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Advances of nutritional technologies and science in pig production

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Abstract

Advances in nutritional technologies and science greatly improved the growth efficiency of pigs by about 30% during the last 40 years. Genetic improvement for lean gain has provided the fundamental basis to increase market weight improving production efficiency. Advances in nutritional technology and science allowed pigs to express their maximal potential for growth. Selected nutritional technologies and science with significant contribution to this improvement could include the concepts and implication of corn and soybean-meal based feeds, phase feeding program, investigation and implication of ideal protein with increased availability of supplemental amino acids, evaluation of ileal digestibility and energy systems (metabolizable energy and net energy; ME and NE) of feedstuffs, fermentation technology allowing effective production of feed additives replacing the use of antimicrobial growth promotors.

Keywords: Feed additives, Ideal protein, Nutritional technology, Phase feeding, Pigs

INTRODUCTION

The advances of technical experience and scientific knowledge in nutrition greatly improved the efficiency of animal agriculture in recent decades. In the area of pig production, enough examples and milestones can be introduced to support this statement.

Over the last 40 years, the efficiency and productivity of pig production have been improved 30.9% and 27.3% for gain to feed ratio and market weight, respectively (Table 1). Improvement in genetic potential for lean gain has provided the fundamental basis to increase market weight improving production efficiency. Nutritional technology and science have supported the pigs to express their genetic potential.

In this article, some of selected milestones in nutritional technology and science with significant contributions to pig production are listed, introduced, and discussed.

SELECTED MILESTONES IN NUTRITIONAL TECHNOLOGY AND SCIENCE CONTRIBUTED TO PIG PRODUCTION

Corn and soybean meal-based feeds

Corn and cereal grains have largely been used in feeding livestock including pigs for their high energy content. Among these, corn has been most popular for its higher energy contents

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Conceptualization: Kim SW.
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Writing - original draft: Kim SW, Deng Z, Choi H.
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Table 1. Changes in growth performance and lean (%) of growing-finishing pigs between 1980s and 2020s

Item	1980s1)	2020s2)	% Change3)
Growth performance4)			
Average daily gain (kg/d)	0.79	0.825)	4.0
Average daily feed intake (kg/d)	2.71	2.156)	−20.6
Gain to feed ratio	0.29	0.38	30.9
Duration (d)	99.3	117.3	18.1
Market weight (kg)	100.0	127.3	27.3
Lean (%, at market weight)	58.1	56.5	−2.7

1)Data were based on 3 references [46–48].
2)Data were based on 2 references [49,50].
3)The percentage changes were determined in the 2020s relative to the 1980s.
4)Averaged initial and final body weight ranged from 22 to 100 kg in 1980s and 27.6 to 127 kg in 2020s, respectively.
5)The ADG in 2020s was adjusted to compare the ADG in 1980s using the coefficient 0.9624 data adapted from Duarte et al. [51].
6)The ADFI in 2020s was adjusted to compare the ADG in 1980s using the coefficient 0.9373 data adapted from Duarte et al. [51].

and affordability than other cereal grains. Protein, however, is not sufficient in corn to meet the requirement for efficient growth of pigs. Corn protein specifically low in lysine and tryptophan that are key essential amino acids for pigs. Various protein supplements, therefore, should have been added to corn for the efficient growth of pigs.

Soybeans have long been used as human foods. Oil extraction for cooking has been one of major use of soybean meals. After the extraction of oil, the left-over is roasted and dried as soybean meal that is high in protein especially key essential amino acids such as lysine and tryptophan. The term, soybean meal, referring cooked meal of defatted soybeans is known to be first coin by Thompson & Morgan (1912) and the use of soybean meal in feeding pigs has been evaluated [1]. Soybean meal is particularly important because lysine and tryptophan are low in protein from corn. Thus, a combinational use of corn and soybean meal has provided ideally balanced essential amino acids for the efficient growth of pigs. Corn and soybean meal-based feeds have been practiced in feeding pigs since 1960's and has been a golden standard in feeding pigs since then [2,3].

Phase feeding

For the efficient growth, feeds should contain a sufficient amount of nutrients required by pigs. Nutrient requirements, however, are not consistent in pigs with various growth stages (age) and physiological status. With increasing feed intake, nutrient requirement (contents in feeds) reduces as pigs grow. Therefore, in feeding pigs, multiple feeds are prepared gradually reducing nutrient contents as pigs grow. Reduction of nutrient requirement as pigs grow is continuous process, but in practice, feeds are prepared by reducing nutrient content in multiple phases. Considering practicality, a limited number of phases is used. For nursery pigs (from weaning to around 20–25 kg body weight), typically 2 to 4 phases have been used in pig production. For growing and finishing pigs until marketing, typically 4 to 7 phases have been used in pig production. Implementing the concept of phase feeding greatly improved the efficiency of pig

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production, reduced feed costs, and reduced nutrient waste through manure. The number of phases depends on ability of pig producers. Increasing the number of phases will improve the efficiency of pig growth by providing nutrients as close as requirements. However, increasing the number of phases could increase the feed cost and production cost. With recent technology of real time mixing, it is possible that phase feeding program could further develop to precision feeding of pigs providing feeds with nutrients meeting requirements of pigs individually.

Ideal protein

In pig production, lean gain (increase of body protein) is the primary target of profit. Protein synthesis is predetermined based on genetic code resulting in building a sequence of amino acids. There are specific compositions of amino acids needed for lean gain depending on stage of growth and physiological status of pigs. There have been tremendous research efforts to identify ideal ratios among amino acids (so called 'ideal protein' especially among essential amino acids) for lean growth of pigs. Formulating feeds based on ideal protein concept minimizes the amount of unutilized amino acids and thus also minimizing unneeded amino acid catabolism. Appling ideal protein in feeding pigs has also reduced the use of protein supplements resulting in reduced crude protein in feeds and thus reducing nitrogen waste through manure. Increased availability of feed grade supplemental amino acids greatly encouraged nutritionists to apply ideal protein in feed formulation. For growing pigs, ideal protein is less variable by growth stages [4], whereas ideal protein dynamically changes for sows depending on protein needs for fetal tissues gain, mammary tissue gain, milk production, and contributions from maternal lean tissue mobilization [5–9] (Table 2). The milestone research investigating optimum dietary amino acid pattern and ideal protein was initiated by two research teams at Rowett Research Institute (Bucksburn, Aberdeen, UK) led by Dr. Fuller since 1989 [10,11] and at University of Illinois (Urbana, IL, USA) led by Dr. Baker since 1992 [12].

The concept of ideal protein has provided a fundamental basis of establishing nutrient requirements for pigs and feed formulations. Increased availability of feed grade supplemental amino acids has been critical for the successful implementation of ideal protein in feed formulations.

Table 2. **Dynamic ideal protein for sows during gestation [7,9] and lactation [7,52]**

Ratio to lysine (%)	True ileal digestible amino acids				
	Lysine	Threonine	Valine	Leucine	Isoleucine
Gestation					
D 0 to d 60 of gestation	100	79	65	88	59
D 60 of gestation to farrowing	100	71	66	95	56
Lactation					
0% (maternal tissue mobilization)	100	59	77	115	59
20% (maternal tissue mobilization)	100	61	77	116	59
40% (maternal tissue mobilization)	100	63	78	118	59

Supplemental amino acids

As feedstuffs contain proteins with fixed amino acid composition, it is not possible to perfectly provide ideally balance amino acids by mixing various feedstuffs. It is mostly possible to match the requirements of 2 to 4 key essential amino acids but others would suffice the requirements.

Pure (or crystalline) amino acids have been introduced and produced in food application since early 1900. It is produced by bacterial fermentation followed by purification process. Similar technology has been applied to produce feed grade amino acids. These amino acids are collectively called 'supplemental amino acids' whist other terms including 'crystalline amino acids' and 'synthetic amino acids' have also been used.

Feed grade lysine became available from a large-scale bacterial fermentation since 1960s. Production of lysine allowed the reduced use of protein supplements (such as soybean meal) in pig feeds. Use of lysine at 0.1% would allow to reduce soybean meal by 4% unit in typical pig feeds (as an example of the reduction of soybean meal from 24% to 20%: 4%-unit reduction). In the meantime, methionine has been produced through chemical process as bacterial fermentation would be poorly efficient to produce methionine containing sulfur. Methionine has well been used in pig feeding whereas poultry production is the major user of feed grade methionine. Soon after the introduction of lysine, additional feed grade amino acids have been produced including threonine and tryptophan. Availability of these 4 feed-grade amino acids tremendously reduced the use of protein supplements resulting in reducing crude protein in feeds at least by 6% unit (compared to no use of supplemental amino acids). More recently, feed grade valine (since 2008), arginine (since 2014), isoleucine (since 2015), and histidine (since 2017) have been available allowing further reduction of crude protein in pig feeds whist meeting amino acid requirements.

Currently, at least 8 feed grade supplemental amino acids are available and extensively used in pig production. The global use (demand) of lysine was over 2.5 million t in 2023 with 3-fold increase since 2005 (Fig. 1). Supplemental amino acids allowed the reduced use of protein supplements, reduction of crude protein in feeds, reduced feed cost, and reduced nitrogen excretion through manure without compromise in production efficiency.

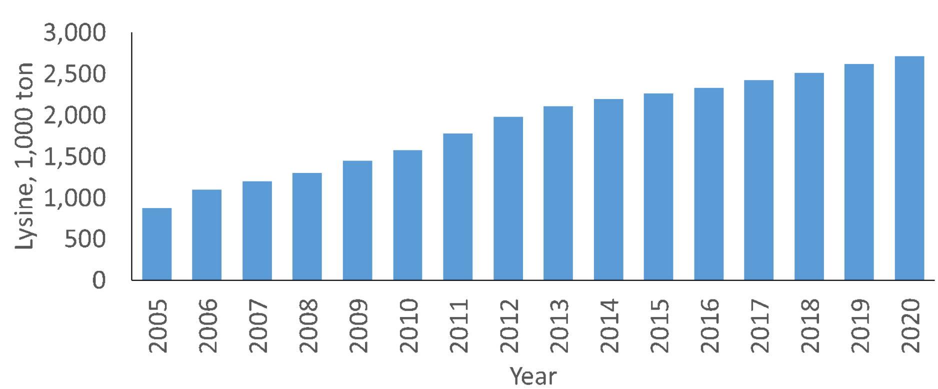

Fig. 1. Global lysine use (1,000 ton).

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Evaluation of ileal digestibility

A proper supply of amino acids [13] in adequate quantities is critical for the maintenance and maximal growth of pigs. Amino acid requirements in pigs and amino acid composition in feedstuffs have been changed to digestible amino acid contents for pigs. The total tract digestibility of amino acids in pigs have measured using the fecal index method, first suggested by Kuiken et al. [14]. However, the total tract digestibility method has limitations that undigested amino acids can be broken down by fermentation by microorganisms in the large intestine, resulting in an overestimation of digestibility of amino acids [15,16].

Ileal cannulation technique in pigs has been adapted to measure accurate ileal digestibility of amino acids in pigs [17]. Ileal cannulation technique allows for the direct collection of ileal digesta, minimizing microbial fermentation influence on amino acids, as well as reducing the need to sacrifice pigs for ileal digesta sample collection. Ileal digestibility can be divided into apparent, true, and standardized ileal digestibility (SID). Apparent ileal digestibility (AID) reflects both non-digested dietary amino acids and total endogenous losses of amino acids, which do not result in the net disappearance of amino acids from the small intestine prior to the distal ileum. The major concern with using AID is that AID values lack additivity in mixed diets, especially feedstuffs with lower amino acid content due to high proportion of the endogenous losses to undigested amino acids [18]. To overcome the additivity issue and to supply a proper quantity of amino acids for pigs, total endogenous losses of amino acids can be excluded to determine the true ileal digestibility (TID) of feedstuffs [19,20].

The TID accounts for total endogenous losses of amino acids, including specific and basal endogenous losses. However, measuring total endogenous losses of amino acids is challenging due to the varying levels of specific endogenous losses of amino acids caused by different feedstuffs. This challenge makes it difficult to apply TID to the wide range of feedstuffs commonly used in pig feeds, and TID is less accurate for ensuring additivity in mixed diets.

To address these challenges, Mariscal Landin [21] first introduced the term SID. This method involves collecting digesta at the end of the ileum and correcting for only basal endogenous losses of amino acids [22,23]. For measuring basal endogenous losses of amino acids, N-free diets or diets containing protein source with an assumed 100% digestible were provided to pigs. Those methods to get basal endogenous losses of amino acids for SID were relatively simple, less costly, and less variable to determine the endogenous losses of amino acids. Therefore, the SID has become the most appropriate method for evaluating the digestibility of amino acids based on current research findings [24].

Evaluation of metabolizable energy (ME) and net energy (NE)

Energy is not a nutrient, but energy is crucial for pigs to utilize nutrients. Energy content in feeds has an impact on the voluntary feed intake of pigs, consequently energy should be considered when determining the nutrient requirements of pigs. Pigs derive energy from digesting and absorbing carbohydrates, fats, and proteins from feeds, which are oxidized to support the maintenance, growth, and reproduction of pigs. The total gross energy (GE) in feeds undergoes digestion, absorption, oxidation, and excretion processes, with only the remaining energy being available to pigs. The available energy is categorized into digestible energy (DE), metabolizable energy (ME), and net energy (NE) [25].

The DE is the total energy consumed minus the energy lost in feces, representing the energy absorbed by the animal, which is easy to measure and has been widely used to express energy requirements and the energy content of feedstuffs for pigs. ME is the DE minus the energy lost in gases and urine. In pigs, the energy lost in gases is minimal (0.1% to 3% of DE), thus, ME primarily considers urinary energy losses. However, ME does not account for heat increment. Heat increment is the heat produced by the digestion and metabolism of nutrients and fermentation in the gastro-intestinal tract of pigs [26]. ME system can also lead to overestimating the energy value of high-fiber and high-protein feedstuffs and underestimating that of high-fat and high-starch feedstuffs [27]. Fats and starch produce less heat increment, whereas proteins and dietary fibers produce more heat increment [28]. Consequently, the high production of adenosine triphosphate (ATP) in fats and glucose is more likely stored as lipids compared with amino acids and dietary fiber [29]. Thus, NE system can provide accurate available energy to pigs and have gradually recognized and used in pig production. The NE system have allowed to increase in the use of alternative feedstuffs such high dietary fiber coproducts, to reduce protein contents in diets with increasing amino acid supplementation in feeds, and to mitigate environmental pollution. Despite theoretical advantages of NE system, the system requires ongoing refinement to address these issues [30]. This is because NE system had challenges, such as difficulty for accurately measuring maintenance energy requirements or fasting heat production (NEm), growth and reproduction energy requirements (NEp), and changes in energy metabolism by certain condition [31,32].

Fermentation technology

With the rapid development of animal agriculture, demands for feed additives, such as enzymes, amino acids, probiotics, and postbiotics have increased dramatically over the last decades. Properly using these feed additives improve swine production efficiency and the profitability of producer. Fermentation plays a key role in the production of feed additives in the swine industry.

Fermentation is a process that the substance is broken down by microorganisms. Enzyme products is typically produced by using the microorganisms with providing suitable nutrient and controlled conditions, then the end products, enzymes, are subsequently isolated through centrifugation or filtration [33]. Majority of enzyme producer use submerged fermentation technology because of the scalability, better control of environmental conditions, and high productivity. However, solid-state fermentation is getting more attention by the researchers due to the advantages [34]. Compared to liquid fermentation, solid-state fermentation has advantages such as lower wastewater generation, higher product stability, lower energy consumption during fermentation, and ease to transfer the end products [35]. Fermentation is becoming one of the most dominant methods to produce amino acids due to the cost-efficient and sustainable production. Modern technologies, such as gene modification and genome analysis, help the industry to improve the capacity of the strain producing enzymes [36]. In addition, innovative

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separation techniques, such as the nanofiltration membranes, can be used to reduce the cost of downstream processing [13]. The conventional batch fermentation is widely used in probiotics production. Cell viability is an important parameter to evaluate the quality of probiotics. Several technologies have been studied to improve cell viability, such as sublethal stresses during fermentation [37]. Postbiotics are bioactive compounds produced by beneficial microorganisms or released by bacterial lysis that exert some benefits to the consumer. Lactic acid bacteria is considered the common bacteria producing postbiotics [38].

Beside feed additives, feedstuffs or feeds can be improved by using fermentation technology. Fermentation not only helps to provide high-quality feedstuffs or feeds but also aids in the breakdown of toxins, anti-nutritional compounds, and harmful microorganisms present in the raw materials [39]. There are two main fermentation technologies for feedstuffs or feeds, including liquid fermentation, and solid-state fermentation. The former involves mixing feed and water in certain proportions in a tank and storing them at a certain temperature for a period of time. In the initial stage of fermentation, the characteristics include low levels of lactic acid bacteria, yeast, and lactate, with a high pH, and significant proliferation of enterobacteria. The second stage reaches a stable state, characterized by high levels of lactic acid bacteria, yeast, and lactate, low pH, and a reduction in the number of enterobacteria [40]. Yeast (*Saccharomyces cerevisiae*) and fungi (*Aspergillus oryzae* and *Aspergillus niger*) are typically involved in the solid- state fermentation system to facilitate the fermentation processes because of less water used in this system [41]. These two microorganisms not only reduce oxygen in the fermentation environment during the early stage, but also release a large amount of enzymes (e.g., cellulase, phytase), vitamins, and growth factors for microorganisms. In addition to fungi, bacteria are also used for solid-state fermentation, including *Lactobacillus* and *Bacillus*. Furthermore, different enzymes are used either alone or in combination with microorganisms to promote fermentation process, including proteases, carbohydrase (cellulase, xylanase), phytase. Some of these solid-state fermentation products are added to swine diet to replace high-cost feedstuffs such as fishmeal, blood plasma, and poultry meal without negatively affecting growth performance of animals [42].

Bioactive compounds as feed additives

One of the most effective feed additives (non-nutritive supplements) would be antimicrobial growth promotors (AGP, antibiotics) with consistent improvement in weight gain and growth efficiency [43]. Due to concerns with occurrence of bacterial resistance to antibiotics, their non-therapeutic uses in animal feeding have been restricted and banned in several countries including the EU (2006), Korea (2011), China (2016), and the USA (2017). Restricting the use of AGP triggered the efforts of developing alternative feed additives and provided opportunities for their use in pig feeds. Some of successful feed additives possess antimicrobial properties mimicking the function of AGP and also those improving intestinal health to be ready for pathogenic challenges. Feed additives with antimicrobial properties include phytogenics (or phytobiotics including herbal extracts and essential oils), medium chain fatty acids (including lauric acid and myristic acid), acidifiers (including formic acid and benzoic acid), and selected minerals (including ZnO and $CuSO_4$). Feed additives with properties maintaining good intestinal health include prebiotics (such as fructose oligosaccharides, galactose oligosaccharides, and mannose oligosaccharides), probiotics (mostly *Bacillus* spp, and *Lacobacillus* spp), postbiotics (bacterial cell walls, and yeast cell components), and feed enzymes (with properties to hydrolyze antinutritional compounds and allergenic compounds). There are enormous research efforts have been poured in the evaluation of feed additives. In 2022 and 2023, about 25% to 35% of 1,000 research presentations made in conferences held in the USA were directly related to intestinal health evaluating feed additives replacing the role of AGP [44,45].

CONCLUSION

The efficiency and profitability of pig production have been improved greatly over last decades. In this article, selected nutritional technologies and science advances improving the efficiency of pig production have been reviewed. Introduction of the concepts and implication of corn and soybean-meal based feeds and phase feeding contributed to structure nutritional management of pigs. Research advances to characterized ideal protein with increased availability of supplemental amino acids greatly improved production efficiency, reduced feed cost, reduced nutrient waste, and improved health of pigs. Advances in nutritional technologies evaluating ileal digestibility and energy systems (ME and NE) have expanded opportunities to implement precision feeding and also to use new feedstuffs and coproducts. Enhanced development of fermentation technology allowed effective production of feed additives including feed enzymes, probiotics, and postbiotics and also allowed effective processing of feedstuffs to improve digestibility and to eliminate antinutritional compounds and allergens. Restriction and ban of the use of AGP have opened opportunities of these feed additives and processed feedstuffs especially for young pigs to maintain intestinal health and therefore improve production efficiency of pig production.

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