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Lunch and Refreshments at Breaks

Mayberry Cafe, Danville, IN; Brad and Christine Born

Pre-Conference BBQ Dinner

Shoup's Catering

Schedule of Presentations

8:15   Registration and check-in

9:00   Welcome. Dennis Liptrap, Chairman of Planning Committee

9:05   Pork sustainability: Where are we, what are the realities, and what role might nutrition play?
Sara Crawford, Eocene Environmental Group, West Des Moines, IA

9:50   Life and loss: Understanding mortality's role in feed conversion efficiency.
Bradley Eckberg, MetaFarms Inc, Eagan, MN

10:35   Break

11:00   Performance responses to supplemental nucleotides in nursery pigs fed low protein diets.
Kolapo Ajuwon, Purdue University

11:30   Timing of introduction of animal by-products in nursery diets affects pig performance.
Merlin Lindemann, University of Kentucky

12:00   Lunch

1:10   Trace minerals: Requirements vs need – The case for iodine in the nursery.
Robert Dove, University of Georgia

1:45   Sow anemia: Is it really that big of a deal?
Crystal Levesque, South Dakota State University

2:20   Break

2:40   Soybean meal net energy value for growing pigs is greater in commercial environments: How can this be? Dean Boyd, Animal Nutrition Research LLC and Aaron Gaines, Ani-Tek Group, Shelbina MO

3:25   Soybean meal or crystalline amino acids in diets for growing pigs: Impact on diet net energy, pig growth performance, and nitrogen retention. Hans Stein, University of Illinois

4:00   Wrap-up and adjourn

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Pork Sustainability:
Where are We, What are the Realities,
and What Role Might Nutrition Play?

Dr. Sara Crawford
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Words like "sustainability" and "regenerative" are nothing new to the U.S. agriculture industries, being that farmers and ranchers have employed sustainable practices and regenerative agriculture for centuries. There has been a steep increase in internet searches for these terms, and others related, since 2018 (Google, 2024). There is no doubt there is increased complexity and programming in the field of sustainability.

Across the globe, there have been both public and private sustainability programs created, which often include reductions in greenhouse gas (GHG) emissions or specific claims related to regenerative agriculture. Oftentimes these programs include representatives from across the supply chain, from farmers and ranchers to retail and foodservice. For instance, the Global Roundtable for Sustainable Beef (GRSB) brought together members of various supply chain sectors to create their sustainability programming and reporting framework (GRSB, 2024). Another example is where, starting in 2019, the National Pork Board created sustainability goals and metrics, which are founded on the long-standing We Care program (NPB, 2024). There are also Consumer Packaged Goods (CPG) companies as well as retail grocery and foodservice companies that have created sustainability claims.

In addition to the various industry groups, governmental regulations, CPG, retail grocery and foodservice programs, there are various certifications and frameworks that have been created in the topic areas of sustainability and regenerative agriculture. Some of these include Certified B Corp, LEED Certification, ISO 14000 and USDA Regenerative Agricultural Designations. While these listed are more well-known, there are many additional frameworks which have been created to address various supply chain needs. With the aforementioned in-mind, it is easy to understand why there are many unknowns and confusion when considering on-farm sustainability and what it means to specific fields, like swine nutrition, and to the producers.

The frameworks and programs created by the various parties are leading to more involvement, and likely data requirements, from the farming operations. As companies review their GHG emissions, the "Scope 3" GHG emissions are those included in the company's GHG emissions footprint, but where they do not have control. For instance, a food manufacturer that has no direct ownership of swine production or pork processing, but sells products with bacon or pizza topping, any step towards-the-farm in the supply chain is considered Scope 3 GHG emissions. This deeper look into supply chain GHG emissions is an example of the "why" the swine industry needs to understand sustainability programming, GHG emissions quantification and what will be asked of pork producers.

While there is pressure coming from the supply chain to quantify impacts and report various frameworks, there are benefits for the swine industry when sustainable practices are employed. When a swine operation is as efficient as possible, it is a benefit to not only "business sustainability" or the economics, but also, very likely, for sustainability metrics as well. It is at this juncture where swine nutritionists can utilize a strong skillset and history of driving efficiency through the system and relate it to new opportunities. There are growing opportunities for funding to make improvements on-farm, such as USDA grants, carbon marketplaces, funding from CPGs, retail grocery and foodservice and others.

Approximately 40% of a swine operation's GHG emissions comes from the feed consumed (or wasted) and the feed manufacturing (NPB, 2015). The remainder of the emissions result from manure and energy used within the barn. With these details in mind, there are important opportunities for swine nutrition professionals to help pork producers meet both financial and GHG emissions reduction goals. As feed efficiency improves, that means less time in the barn for market hogs, which means reduced electricity and fuel usage, less manure generated, less water used

and a lower enteric methane footprint. This aids in meeting the overall goals to reduce GHG emissions from the swine operation. Similarly at a sow unit, improved efficiencies for the sows relate to improvements in sow production variables. Again, this is vital to the business sustainability of an operation, while also improving the overall GHG emissions.

Swine nutritionists fill a critical role in the virtual cycle where swine feed becomes manure, which becomes nutrients for improved soil health, which leads to improved crop yields and feedstuff quality for the feed. As the opportunities continue to develop for requested Scope 3 data reporting and improved GHG emissions at the farm-level, the GHG emissions profile of the feedstuff rations should be considered. Additionally, swine nutrition research is vital for continuing to improve understanding of the emissions factors of individual ration items. An emissions factor is a representative value that attempts to relate the quantity of a pollutant emitted with an industrial activity (EPA, 2024). To improve modeling of the ration related to GHG emissions, emissions factors for each ration item are needed, including feed additives, biologicals, bakery waste, etc.

Finally, swine nutritionists can utilize their already strong connections to pork producers to consult on ration formulation based on various needs. For example, the lowest-cost ration financially may not be the lowest GHG emissions ration. However, there may be an opportunity for cost-share, a marketing stream or investment from within the supply chain to formulate to the lowest GHG emissions ration.

In summary, there have been an influx of public and private sustainability reporting programs and frameworks, into which pork producers may need to report. There is potential for pork producers to participate in, and take advantage of, programs that will provide cost-share, marketing opportunities or grant funding, which can aid in offsetting the cost of new practice adoption or changes in production, like new ration formulations. Swine nutritionists will be critical in providing pork producers information related to how rations influence the GHG emissions footprint of their operation, can provide valuable research findings that which will be used to improve models for GHG emissions quantification, and can be the trusted advisor for those related to the swine industry supply chain.

Life and Loss:
Understanding Mortality's Role
in Feed Conversion Efficiency

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Summary

Mortality in swine production has a significant impact on feed efficiency, directly affecting economic and resource management. When pigs die prematurely, the feed they have consumed up to that point results in no productive output, leading to substantial economic losses for farmers. Additionally, the resources used to care for these animals, including feed, labor, and medical costs, are wasted. High mortality rates also contribute to increased stress among the surviving pigs, which can further decrease their feed efficiency by affecting their health and growth rates. Implementing effective health management, optimized nutrition, and improved housing conditions are crucial strategies to mitigate these impacts and enhance overall feed efficiency in swine production.

Introduction

Feed efficiency, defined as the ability of livestock to convert feed into desired outputs like meat, is a key determinant of productivity and profitability in swine farming. However, mortality disrupts this efficiency by causing direct and indirect losses. Moreover, high mortality rates can induce stress among surviving animals, further compromising their growth and feed conversion rates. Understanding and addressing the factors that contribute to mortality in swine production is essential for optimizing feed efficiency and ensuring sustainable farming practices. This presentation explores the multifaceted impacts of mortality on feed efficiency and discusses strategies to mitigate these effects, thereby enhancing the overall productivity and sustainability of swine operations.

Economic Impact

The economic impact of mortality on feed efficiency in swine production is profound, leading to significant financial losses and inefficiencies. When pigs die prematurely, the feed they have consumed up to that point is essentially wasted, as it does not contribute to the production of marketable meat. This results in a direct economic loss, as the investment in feed does not yield any return. Additionally, the cost of labor, veterinary care, and other resources expended on these animals also becomes a sunk cost. High mortality rates necessitate increased spending on preventative measures and treatments, further straining financial resources. Moreover, the loss of potential income from the sale of these animals can severely impact the overall profitability of swine operations. By improving health management, optimizing nutrition, and enhancing living conditions to reduce mortality, producers can significantly improve feed efficiency and economic outcomes in swine production.

Table 1. Finishing feed conversion by mortality rate by year

Year			Mortality %									
			< 1%	1-2%	2-3%	3-4%	4-5%	5-6%	6-7%	7-8%	8-9%	9-10%	≥ 10%
2019	Feed Conversion Rate		2.69	2.73	2.79	2.84	2.88	2.91	2.96	2.97	2.99	2.97	3.01
2020			2.75	2.79	2.82	2.88	2.92	2.95	2.97	2.98	2.99	3.02	3.03
2021			2.66	2.73	2.77	2.82	2.86	2.90	2.93	2.94	2.95	2.99	3.00
2022			2.71	2.75	2.78	2.82	2.86	2.90	2.92	2.93	2.94	2.94	2.99
2023			2.76	2.71	2.74	2.79	2.83	2.87	2.90	2.91	2.92	2.94	2.96

*Source: MetaFarms, Inc.

Table 2. Closeout group mortality rates by year

Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Nursery	3.60%	3.06%	3.23%	3.13%	3.32%	3.32%	3.81%	4.04%	4.39%	3.88%
Finish	4.40%	4.11%	4.13%	4.22%	4.18%	4.33%	4.64%	4.95%	5.36%	5.40%
W2F (SS)	6.10%	5.65%	5.49%	5.98%	6.30%	5.95%	6.26%	6.79%	6.87%	7.23%

*Source: MetaFarms, Inc.

Table 3. Sow farm mortality rates by year

Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Sow	9.3%	10.4%	11.0%	11.1%	11.8%	11.1%	13.8%	13.4%	14.3%	15.6%
Pre-Wean	17.2%	15.0%	15.4%	16.2%	16.3%	16.1%	16.5%	16.7%	17.0%	17.5%

*Source: MetaFarms, Inc.

Mortality Trends

Mortality trends in swine production have shown varying patterns influenced by factors such as disease outbreaks, management practices, and advancements in veterinary care. Historically, swine producers have faced challenges with high mortality rates due to infectious diseases like porcine reproductive and respiratory syndrome (PRRS) and Porcine Epidemic Diarrhea (PEDv) which have caused substantial losses. To mitigate higher mortality rates swine producers will shore up their biosecurity measures, vaccination programs, and enhanced overall herd management. Despite these advancements, mortality rates can still fluctuate significantly, especially in regions where disease control is difficult or where resources for optimal management are limited. Monitoring these trends is crucial for identifying risk factors and implementing strategies to mitigate them, ensuring healthier herds and more efficient production systems.

Feed Costs

The swine industry, a crucial segment of global agriculture, has faced significant challenges in recent years due to the rising costs of feed. Feed constitutes the largest single expense in swine production, accounting for 60-70% of total production costs. As feed prices escalate, their impact on the swine industry becomes increasingly significant, influencing production practices and profitability.

Management Practices

Effective management practices are essential for lowering mortality in swine production and enhancing overall herd health and productivity. Key strategies include implementing robust biosecurity measures to prevent the introduction and spread of infectious diseases. This involves strict control of farm access, regular sanitation protocols, and quarantine procedures for new animals and outside products that are brought into the farm. Providing balanced and nutritionally complete diets tailored to the specific needs of different growth stages helps boost immunity and overall health. Regular health monitoring and veterinary care, including vaccinations and prompt treatment of illnesses, are vital in preventing disease outbreaks and managing health issues early. Improving housing conditions by ensuring adequate ventilation, appropriate stocking densities, and comfortable bedding can reduce stress and improve welfare. Additionally, training farm staff on best practices

Table 4. Finishing Feed Cost/Lb Gain difference by mortality rate by year

Year	Mortality %										
	< 1%	1-2%	2-3%	3-4%	4-5%	5-6%	6-7%	7-8%	8-9%	9-10%	≥ 10%
2019	$0.2723	$0.2626	$0.2641	$0.2781	$0.2706	$0.2731	$0.2760	$0.2766	$0.2799	$0.2845	$0.2881
2020	$0.2633	$0.2628	$0.2632	$0.2669	$0.2690	$0.2704	$0.2727	$0.2724	$0.2739	$0.2800	$0.2849
2021	$0.3507	$0.3491	$0.3512	$0.3569	$0.3598	$0.3633	$0.3702	$0.3706	$0.3667	$0.3717	$0.3709
2022	$0.4065	$0.4190	$0.4194	$0.4249	$0.4282	$0.4322	$0.4351	$0.4362	$0.4363	$0.4385	$0.4563
2023	$0.4260	$0.3975	$0.4012	$0.4088	$0.4153	$0.4204	$0.4283	$0.4332	$0.4306	$0.4429	$0.4528

*Source: MetaFarms, Inc.

Table 5. Wean-to-Finish (Single-Stocked) feed costs by year

Year	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Corn Cost/Bushel	$6.38	$6.78	$4.62	$3.81	$3.56	$3.41	$3.41	$3.69	$3.54	$5.27
Feed Cost/Lb Gain	$257.54	$225.24	$206.03	$199.49	$208.55	$210.30	$205.33	$267.59	$319.49	$315.49
Feed Cost/Ton	$0.3375	$0.2927	$0.2681	$0.2585	$0.2683	$0.2701	$0.2678	$0.3482	$0.4189	$0.4118

*Source: MetaFarms, Inc.

for animal care and disease prevention ensures consistency and effectiveness in management. By adopting these comprehensive practices, swine producers can significantly reduce mortality rates and improve feed efficiency, leading to more sustainable and profitable operations.

Future Trends & Innovations

Precision farming technologies, such as real-time health monitoring systems and automated feeding systems, are becoming increasingly prevalent. These technologies use sensors and data analytics to monitor individual pigs' health and nutritional needs, allowing for early detection of health issues and eliminating feed flow availability to the pig. Improved biosecurity measures, driven by innovations in farm design and disinfection technologies, further reduce the risk of disease transmission. Recent advances in genetic research and breeding programs are also contributing to the development of more disease-resistant swine breeds. These future trends and innovations collectively aim to create a more resilient and efficient swine production system, ultimately reducing mortality and improving productivity.

Conclusion

The impact of mortality on feed efficiency in swine production is a critical concern that affects economic viability, resource utilization, and overall productivity. Premature loss of pigs leads to significant feed wastage and financial losses, while also increasing stress and health issues among surviving animals. Understanding the direct and indirect consequences of mortality is essential for developing effective strategies to mitigate its effects. Implementing robust health management practices, optimizing nutrition, and improving housing conditions can substantially reduce mortality rates, thereby enhancing feed efficiency. Furthermore, embracing future trends and innovations, such as precision farming technologies and genetic advancements, can provide sustainable solutions to this ongoing challenge. By addressing mortality comprehensively, swine producers can achieve greater efficiency, profitability, and sustainability in their operations.

Performance Responses to Supplemental Nucleotides in Nursery Pigs fed Low Protein Diets

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Summary

The post-weaning period is associated with heightened demand for nucleotides due to insufficient de novo production in the weanling pig and the various stressors which compromise gut barrier function and increase the risk of post-weaning diarrhea (PWD). Increasing evidence supports the benefits of nucleotide supplementation of diets which include improved gut structure and intestinal barrier function, increased cell proliferation, and decreased incidence of PWD. Feeding low protein (LP) diets after weaning improves gut health and reduces PWD but decreases growth performance due to deficiencies in essential amino acids. To address this, various studies have focused on supplementing LP diets with amino acids to restore animal performance while retaining the beneficial effects associated with LP diets. However, the effect of nucleotide supplementation to LP diets on animal performance during weaning has not been determined. In a 35-day study, weanling pigs were fed LP diets with or without nucleotide supplementation. Nucleotide supplementation of LP diets partially ameliorated the negative effects of LP diets while maintaining its benefits. Our results provide information on the advantages of feeding LP diets supplemented with dietary nucleotides after weaning.

Introduction

Nucleotides and their derivatives are fundamental in biological functions, serving as major components for nucleic acids, coenzymes, and energy sources via respiratory pathways (Domeneghini et al., 2006). Cellular proliferation, tissue repair and recovery require elevated nucleotide synthesis (Sánchez-Pozo and Gill, 2002). However, nucleotide synthesis consumes high energy and amino acids such as glutamine, glycine and aspartate. Hence, exogenous supplementation of nucleotides may result in energy and amino acids sparing, allowing these nutrients to be utilized for tissue growth (Kreuz et al., 2020). Under normal conditions, de novo synthesis of nucleotides and recovery via salvage pathway meet the nucleotide requirement of mammals (Hess and Greenberg, 2012). In particular, the gut has limited capability for de novo nucleotide synthesis, relying heavily on the salvage pathway for nucleotide synthesis (Grimble, 1994). Conditions such as weaning heighten nucleotide requirement in pigs due to stress, rapid growth rate, and compromised immune system (Valini et al., 2021). These result in the impairment of energy and nucleic acid

synthesis, making de novo synthesis of nucleotides metabolically expensive (Domeneghini et al., 2006). Therefore, provision of dietary nucleotides becomes crucial in these circumstances, as nucleotides becomes conditionally essential (Domeneghini et al., 2006, Valini et al., 2021).

Feeding low protein (**LP**) diets in nursery pig production is considered a highly effective approach to reduce N excretion and post-weaning diarrhea (**PWD**; Yu et al., 2019). However, various studies have reported that substantial reductions in dietary CP levels may impair growth performance, attributable to deficiencies in essential or non-essential amino acids and resulting in morphological alterations such as decrease in villous height observed in the duodenum and jejunum (Batson et al., 2021). To ameliorate the negative effects of crude protein (**CP**) reduction in diets, LP diets are typically supplemented with crystalline amino acids. For instance, the five essential amino acids (lysine, methionine, threonine, tryptophan, and valine) are generally available in crystalline form for use in diet formulation, and additional reductions in dietary CP can be achieved by meeting the amino acid requirements of pigs (Rocha et al.,

2022). Although nucleotide supplementation has a potential to spare amino acids from use for de novo nucleotide synthesis, the effect of its supplementation on animal performance, in the context of a low protein diet, has not been previously investigated.

Therefore, we hypothesized that nucleotide supplementation of LP diets would ameliorate the negative effects of CP reduction on growth performance while reducing the incidence of PWD and mitigating N excretion and release to the environment. Thus, the objective of this study was to investigate the effects of nucleotide supplementation to LP diets on growth performance, incidence of PWD, nutrient digestibility and protein utilization in weaning pigs.

Experimental Procedures

Animals, diets, and experimental design

A total of 210 piglets (Duroc × Landrace × Yorkshire) were weaned at 21 d of age and fed ad libitum a common corn–soy nursery diet to achieve a 3-day adaptation. At 24 d old, pigs were allocated to 5 dietary treatments in a completely randomized block design for a 35-d experiment. Each dietary treatment consisted of 7 replicate pens containing 6 piglets per pen (1:1 gilt to barrow ratio). Nucleotides (Nucleosaf 600; Phileo by Lesaffre, Marcq-en-Baroeul, France) were added to the nucleotide supplemented diets. The 5 dietary treatments (Table 1) were: (i) a high protein positive control diet (**PC**) with 24% CP; (ii) a low protein negative control (**NC**) with 16% CP; (iii) NC with 1 g/kg dietary nucleotide inclusion (**NC01**); (iv) NC with 3 g/kg dietary nucleotide inclusion (**NC03**); and (v) NC with 9 g/kg dietary nucleotide inclusion (**NC09**). All diets were corn-soybean meal based, supplemented with lysine, methionine, tryptophan, and threonine, with all LP diets additionally fortified with crystalline isoleucine, and valine to meet the ideal amino acid requirements outlined in National Research Council (NRC, 2012). On d 28, titanium dioxide was added at 5 g/kg to all diets as a marker to assess the apparent total tract digestibility (**ATTD**) of nutrients. Pigs had *ad libitum* access to water and diet during the experiment.

Sample collection and processing

Weekly measurements of body weight and feed intake were conducted over the 35-d period to determine the average daily gain (**ADG**), average daily feed intake (**ADFI**), and gain-to-feed ratio (**G:F**). Fresh fecal samples were collected on days 33, 34 and 35 for determination of the ATTD of nutrients. Fecal samples were immediately stored in -20 °C until subsequent analysis.

On d 32, blood samples (10 mL) were collected from 1 pig per pen. To determine the occurrence and severity of diarrhea, a scoring system ranging from 1 to 4 (1 = normal feces, 2 = soft feces, 3 = mild diarrhea, and 4 = severe diarrhea) was established.

Determination of the ATTD of energy, dry matter, phosphorus, calcium, and nitrogen

Digesta samples were analyzed for dry matter (**DM**) content (Precision Scientific Co., Chicago, IL; method 934.01; AOAC International, 2006), gross energy (**GE**) (Parr 1261 bomb calorimeter, Parr Instrument Co., Moline, IL) and nitrogen (**N**) (TruMac N; LECO Corp., St. Joseph, MI; method 990.03; AOAC, 2000). Samples were also analyzed for phosphorus (**P**) through spectrophotometric analysis (model AS1000; Packard, Meriden, CT; AOAC International, 2006) as described by Zhai and Adeola (2013) and calcium (Ca) using an inductively coupled plasma-optical emission spectrometer (Varian, Model 720-ES) according to the method 968.08 (AOAC International, 2000).

Serum analysis

The concentrations of serum insulin-like growth factor 1 (**IGF-1**), insulin, glucose, and blood urea nitrogen (**BUN**) were measured using commercial kits and procedures followed as provided in the respective manufacturers' instruction: IGF-1 (RayBiotech, Peachtree Corners, GA); insulin (Mercodia, Winston-Salem, NC); glucose (Fujifilm, Lexington, MA) and BUN (Thermo Fisher Scientific, Waltham, MA). The concentration of serum glutathione (GSH) was measured according to a protocol published previously (Rahman et al., 2006).

Statistical analysis

Growth performance, blood characteristics and nutrients digestibility were analyzed by PROC GLM of SAS (v.9.4; SAS Inst. Inc., Cary, NC). Comparisons between diets were performed using the orthogonal contrast analysis. Specifically, the PC was compared to each of the NC diets, whereas the NC was compared to each of the nucleotide supplemented NC diets. Contrast was used as: A) PC vs. NC; B) PC vs. NC01; C) PC vs. NC03; D) PC vs. NC09; E) NC vs. NC01; F) NC vs. NC03; G) NC vs. NC09. Each pen was considered as an experimental unit, and the experimental diets were considered as the fixed effects. The replicate blocks were regarded as the random effects in a randomized complete block design. The contrast coefficients necessary to assess the linear and quadratic effects of increasing nucleotide levels were derived using the IML procedure of SAS. The occurrence of diarrhea was analyzed using the LOGISTIC procedure of SAS. Variability within the data was represented by the pooled standard error of mean, statistical significance was declared at $P \leq 0.05$, whereas P-values between $0.05 < P \leq 0.10$ indicated statistical trends.

Results

Nucleotide supplementation partially alleviated the reduction in growth performance

Compared to PC, NC had decreased overall ADG ($P < 0.05$, Table 2). However, the overall ADFI and G:F did not differ between the two diets. Compared to PC, nucleotide supplemented groups showed a tendency for decreased ADFI ($P = 0.06$). However, the overall ADG, final BW and G:F were not different between the nucleotide supplemented groups and PC. Also, the nucleotide supplemented groups did not differ in overall ADG and final BW from the NC. Pigs fed dietary nucleotides had a tendency ($P = 0.08$) for a linear increase in ADG from d 7 to 14 and a linear increase in ADG from d 21 to 28 ($P = 0.05$). From d 21 to 28, there was a quadratic response ($P < 0.05$) in the G:F of the nucleotide supplemented groups and NC09 tended to have increased overall G:F relative to NC ($P = 0.09$).

Low protein diets reduced the incidence of post-weaning diarrhea

A reduction in the overall fecal diarrhea score was observed in piglets fed NC diet relative to PC ($P < 0.05$, Table 3). Also, the NC09 group had decreased overall fecal diarrhea score relative to PC ($P < 0.05$), while there was no difference relative to NC. There were no linear or quadratic trends of nucleotide supplementation on the overall fecal diarrhea score.

Effects of nucleotides supplementation on ATTD of nutrients

Compared to PC, NC03 had decreased ATTD of DM ($P < 0.05$, Table 4), while NC01 showed tendency ($P = 0.09$) for a decrease. When compared to PC, NC piglets showed a tendency ($P = 0.10$) for decreased ATTD of GE. The NC01 and NC03 groups had decreased ATTD of GE ($P < 0.05$), while NC09 was not different from PC, potentially indicating nucleotide effect at this level of supplementation. There were no differences among the LP diets for ATTD of GE, irrespective of nucleotide supplementation. For the ATTD of N, nucleotide supplemented diets groups were not different from PC, except for NC03 which showed a tendency for a higher N digestibility ($P = 0.07$). There was linear increase in ATTD of N in the nucleotide supplemented groups ($P < 0.05$). No treatment effects were observed for ATTD of Ca and P.

Low protein diets reduced blood urea nitrogen, serum GSH and IGF-1 but had no effects on serum glucose and insulin

Serum concentrations of BUN and GSH decreased with reduced CP level without an effect of nucleotide supplementation ($P < 0.0001$ and $P < 0.05$, respectively). Serum concentration of IGF-1 decreased with reduced CP level ($P < 0.05$), except for NC09, which did not differ from PC. There was a linear increase in serum IGF-1 concentration with nucleotide supplementation ($P < 0.05$). No treatment effects were observed for serum glucose and insulin concentrations.

Discussion

Prior to weaning, piglets obtain substantial intake of nucleotides from sow milk (Perricone et al., 2020). However, weaning diets often lack sufficient concentrations of nucleotides (Weaver and Kim, 2014; Perricone et al., 2020). The importance of sufficient nucleotide supplementation is especially critical in the gut which has limited capacity for *de novo* nucleotide synthesis (Grimble, 1994). Additionally, weaning stress creates a heightened demand for nucleotides, making them conditionally essential due to intestinal inflammation associated with weaning (Correa et al., 2021). Therefore, the current study in which nucleotides were supplemented to a low protein diet at various levels represents a novel perspective on the potential of supplemental nucleotides to support pig growth performance.

The reduction in overall ADG and tendency for a decreased final BW in the NC diet despite supplementation with branched-chain amino acids is consistent with previous findings indicating that LP diets decreased growth performance, irrespective of supplementation with few limiting amino acids (Yue et al., 2008; Spring et al, 2020). However, supplementation with nucleotides tended to linearly increase ADG between days 7 to 14, and significantly increased ADG between d 21 to 28, with the greatest increase observed in the 0.9% nucleotide supplemented group. This is consistent with previous findings indicating that nucleotide supplementation in nursery pigs resulted in linear increase in ADG and other performance improvements (Weaver and Kim 2014; Perricone et al., 2020). Overall, nucleotide supplementation partly ameliorated the negative effects of LP diets on growth performance. However, our findings contradict some previous studies that reported no improvement in growth performance with nucleotide supplementation (Lee et al., 2007; Correa et al., 2021). Discrepancies in findings could be due to differences in diet composition between experiments, supplementation methods, sources and levels of nucleotides used. However, the reduction in ADFI with nucleotide supplementation was unexpected and contrasts with the findings by Perricone et al. (2020)

and Weaver and Kim (2014), who reported that nucleotide supplementation increased ADFI in postweaning pigs. The 9 g/kg nucleotide group (NC09) also showed a tendency for a higher G:F compared to NC, suggesting that a higher level of nucleotide supplementation may be necessary to get an effect on G:F.

The reduction in PWD observed in this study with reduction in CP may indicate that reducing dietary and digesta N content may result in subsequent decrease in undigested N entering the hindgut, reducing the chances of microbial fermentation and proliferation of potentially pathogenic organisms and PWD (Lynegaard et al., 2021). In pigs supplemented with 0.9% nucleotide, the lower incidence of PWD compared to PC may be attributed to both the impact of a LP diet and the additive influence of dietary nucleotides. A previous study found that 1000 and 2000 ppm nucleotides supplementation reduced PWD, as evidenced by a decrease in the number of pigs treated with antibiotic because of PWD (Martinez-Puig et al., 2007). Additionally, Weaver and Kim (2014) reported that nucleotides high in inosine 5' monophosphate reduced the incidence of PWD in post weaning pigs when supplemented at 0.5 g/kg in diet. Thus, nucleotide supplementation in combination with reduced dietary protein may have an additive effect in limiting the incidence of PWD in pigs.

Current results may indicate that reducing dietary CP could lead to some reduction in digestive capacity, especially as it relates to energy and DM digestibility. Thus, this possibility needs to be taken into consideration when designing low protein diets for pigs. Nonetheless, inclusion of nucleotides at 0.9% ameliorated this negative effect. The overall mechanism of the linear increase in ATTD of N observed in the nucleotide supplemented diets is unclear but may be related to observed effects of nucleotides in improving gut structure, intestinal barrier function and immune response and increased cell proliferation (Domeneghini et al., 2006; Martinez-Puig et al., 2007; Valini et al., 2021). This result is consistent with Li et al. (2015) who reported that dietary nucleotide supplementation increased ATTD of N in post weanling pigs.

Concentrations of BUN decreased with reduction in dietary CP and was further reduced with nucleotide supplementation, albeit numerically. This finding aligns with a previous study by Yu et al. (2019) who reported that reduction in dietary CP level resulted in decreased BUN. This result corroborates the results obtained in the ATTD of N and suggests that pigs fed low CP diets had better N utilization efficiency, irrespective of nucleotide supplementation. Therefore, low protein diets may enhance N utilization, leading to some reduction in nitrogenous waste production and environmental pollution from excessive nitrogen release from pig wastes.

Serum IGF-1 serves as an indicator of metabolism and growth as it plays a pivotal role in promoting normal growth and development in mammals (Jones and Clemmons, 1995). Previous studies reported that a reduction in dietary CP resulted in decreased final body weights and serum IGF-1 concentration in growing and post-weaning pigs (Li et al., 2017). In the present study, serum IGF-1 concentration decreased with reduction in dietary CP, but was partially recovered with nucleotide supplementation at 0.9%, showing a linear increase with higher nucleotide supplementation. This may indicate an involvement of IGF-1 in the observed amelioration of growth performance observed at this level of supplementation. This may represent a novel mechanism of nucleotide effect in regulating pig growth.

Conclusion

Feeding low protein diets supplemented with nucleotides after weaning could reduce incidence of PWD and N excretion, improve protein utilization efficiency, and partially ameliorate the negative effects of low protein diets on growth performance. However, additional studies are needed to investigate the underlying mechanism of dietary nucleotides actions.

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Table 1. Ingredient composition of experimental diets, as-fed basis

Ingredients, g/kg	PC	NC	NC01	NC03	NC09
Ground corn	440.20	624.49	604.49	562.49	440.20
DDGS	50.00	50.00	50.00	50.00	50.00
Wheat Bran	20.00	20.00	20.00	20.00	20.00
Soybean meal, 48% CP	350.00	144.00	144.00	144.00	144.00
Soybean oil	35.00	42.00	42.00	44.00	46.29
Soy protein concentrate	41.20	40.00	40.00	40.00	40.00
Ground limestone	15.00	15.00	15.00	15.00	15.00
Monocalcium phosphate	12.00	14.50	14.50	14.50	14.50
Salt	4.00	4.00	4.00	4.00	4.00
L-Lysine HCl	2.00	8.74	8.74	8.74	8.74
DL-Methionine	0.80	1.55	1.55	1.55	1.55
L-Threonine	0.40	3.00	3.00	3.00	3.00
L-Tryptophan	0.20	0.60	0.60	0.60	0.60
L-Isoleucine	0.25	1.27	1.27	1.27	1.27
L-Valine	0.25	2.15	2.15	2.15	2.15
Vitamin premix[1]	2.50	2.50	2.50	2.50	2.50
Mineral premix [2]	0.70	0.70	0.70	0.70	0.70
Selenium premix[3]	0.50	0.50	0.50	0.50	0.50
Nucleotide premix[4]	0.00	0.00	20.00	60.00	180.00
Titanium dioxide premix[5]	25.00	25.00	25.00	25.00	25.00
Total	1000.00	1000.00	1000.00	1000.00	1000.00
Calculated composition, g/kg					
ME, kcal/kg	3354.18	3356.72	3353.32	3356.89	3348.38
CP	236.69	163.82	163.73	163.40	162.72
Ca	8.80	8.57	8.57	8.57	8.57
P	6.66	6.20	6.20	6.19	6.17
Phytate-P	2.51	2.10	2.10	2.09	2.08
STTD P	4.08	4.01	4.01	4.00	4.00
Analyzed composition, g/kg					
GE, kcal/kg	4.09	4.07	4.03	4.08	4.08
CP	22.16	17.95	17.18	17.97	17.36
Ca	11.17	11.97	11.30	11.22	10.21
P	6.25	6.67	6.72	6.20	6.23
Calculated Standard Ileal Digestible Amino Acid Composition, g/kg					
Indispensable AA					
Arg	11.30	6.65	6.64	6.64	6.63
His	4.36	2.82	2.82	2.81	2.81
Ile	7.07	5.12	5.12	5.11	5.11
Leu	13.62	9.71	9.71	9.69	9.65
Lys	10.00	10.00	10.00	10.00	10.00
Met	3.07	2.87	2.87	2.87	2.86
Met + Cys	5.52	4.60	4.60	4.59	4.58
Phe	7.97	5.09	5.09	5.08	5.07
Thr	6.09	5.78	5.78	5.78	5.77
Trp	2.16	1.57	1.57	1.57	1.57
Val	7.56	6.31	6.30	6.30	6.29
Dispensable AA					
Ala	9.34	6.89	6.88	6.87	6.84
Asp	19.44	11.67	11.67	11.66	11.64
Cys	3.05	2.20	2.20	2.19	2.18
Glu	28.76	15.56	15.56	15.56	15.57
Gly	7.74	5.02	5.02	5.01	5.00
Pro	10.90	7.86	7.85	7.84	7.80
Ser	9.18	5.97	5.97	5.96	5.94
Tyr	6.24	4.09	4.09	4.08	4.07

[1]Provided the following quantities per kg of complete diet: vitamin A, 6,600 IU; vitamin D_3, 1,660 IU; vitamin E, 44 IU; menadione, 2.2 mg; riboflavin, 8.8 mg; D-pantothenic acid, 22 mg; niacin, 33 mg; vitamin B12, 0.04 mg.
[2]Provided the following quantities per kg of complete diet: I, 0.26 mg; Mn, 12.0 mg; Cu, 6.33 mg; Fe, 136 mg; Zn, 104 mg.
[3]Provided 0.3 mg Se/kg of complete diet.
[4]Nucleotides product was added to diets as a replacement for corn in a premix to supply added at 0, 1, 3 or 9 g/kg of complete diet.
[5]Provided 5 g TiO2/kg of complete diet.

Table 2. Growth performance of weanling pigs fed low protein diets supplemented with dietary nucleotides from days 0 to 35[1]

Diet	PC	NC	NC01	NC03	NC09	SEM[2]									P-values for Contrasts[3]	
NUCL, %	0	0	0.1	0.3	0.9											
Item							A	B	C	D	E	F	G	Linear	Quadratic
BW, kg															
Day 0	6.07	6.06	6.06	5.97	5.96	0.05	0.91	0.86	0.15	0.11	0.95	0.18	0.13	0.08	0.32
Day 7	6.29	6.19	6.27	6.05	6.19	0.08	0.38	0.91	0.04	0.40	0.45	0.21	0.98	0.82	0.21
Day 14	7.27	7.10	7.14	6.97	7.40	0.16	0.45	0.58	0.19	0.55	0.83	0.57	0.18	0.12	0.24
Day 21	10.06	9.71	9.67	9.62	10.11	0.26	0.34	0.30	0.24	0.90	0.93	0.81	0.28	0.22	0.52
Day 28	13.14	12.98	13.11	13.00	13.68	0.32	0.73	0.96	0.76	0.24	0.77	0.97	0.13	0.12	0.61
Day 35	17.91	16.81	17.13	16.98	17.55	0.40	0.06	0.18	0.11	0.54	0.57	0.76	0.20	0.24	0.90
ADG, g/d															
Day 0-7	34.40	19.53	30.95	20.28	36.54	8.77	0.25	0.79	0.29	0.87	0.35	0.95	0.17	0.23	0.69
Days 7-14	156.02	122.84	129.26	145.57	162.87	18.24	0.22	0.32	0.71	0.80	0.80	0.39	0.12	0.08	0.61
Days 14-21	411.68	378.37	358.73	364.11	377.19	24.38	0.35	0.14	0.21	0.33	0.56	0.69	0.97	0.82	0.72
Days 21-28	434.08	454.49	456.84	457.43	503.78	18.76	0.45	0.41	0.42	0.02	0.93	0.91	0.07	0.05	0.59
Days 28-35	720.41	546.48	591.53	602.92	561.11	33.90	<0.01	0.01	0.03	<0.01	0.34	0.26	0.75	0.86	0.17
Days 0-35	343.47	305.47	317.35	320.31	324.15	10.97	0.02	0.11	0.17	0.23	0.43	0.35	0.22	0.31	0.62
ADFI, g/d															
Days 0-7	163.53	163.04	161.56	148.57	160.51	8.29	0.97	0.87	0.24	0.28	0.90	0.24	0.28	0.30	0.40
Days 7-14	278.45	260.11	238.10	251.86	305.00	20.01	0.72	0.22	0.39	0.30	0.35	0.58	0.15	0.03	0.25
Days 14-21	575.54	570.87	481.51	552.70	532.48	35.56	0.90	0.07	0.77	0.34	0.04	0.67	0.26	0.75	0.94
Days 21-28	935.75	944.06	975.21	1070.44	982.12	53.60	0.92	0.61	0.07	0.45	0.67	0.07	0.49	0.64	0.10
Days 28-35	1188.33	927.70	983.78	977.90	987.41	52.81	0.00	0.02	0.03	0.01	0.44	0.34	0.45	0.61	0.47
Days 0-35	603.08	576.22	565.30	567.74	568.47	12.03	0.13	0.06	0.06	0.06	0.51	0.63	0.64	0.85	0.69
G:F, g/kg															
Days 0-7	211.73	119.18	191.13	136.16	227.49	52.18	0.15	0.79	0.31	0.84	0.21	0.68	0.08	0.14	0.89
Days 7-14	559.68	473.90	545.30	577.82	531.72	51.04	0.25	0.85	0.82	0.71	0.31	0.17	0.41	0.69	0.21
Days 14-21	714.50	664.71	744.14	658.72	708.52	35.22	0.33	0.56	0.30	0.91	0.11	0.91	0.37	0.78	0.74
Days 21-28	463.55	481.13	468.54	427.40	513.55	24.36	0.47	0.89	0.33	0.17	0.54	0.09	0.47	0.26	0.04
Days 28-35	605.59	589.51	601.74	617.72	571.77	28.52	0.70	0.93	0.79	0.42	0.76	0.50	0.65	0.49	0.37
Days 0-35	569.02	530.93	561.28	566.93	570.56	16.41	0.12	0.74	0.93	0.95	0.19	0.14	0.09	0.21	0.34

[1]PC = Positive control diet with adequate CP; NC = Negative control diet with inadequate CP; NC01 = NC diet containing dietary nucleotides at 1.0 g/kg of diet; NC03 = NC diet containing dietary nucleotides at 3.0 g/kg of diet; NC09 = NC diet containing dietary nucleotides at 9.0 g/kg of diet; NUCL = Dietary nucleotides; BW = Body weight; ADG = Average daily gain; ADFI = Average daily feed intake; G:F = Gain to feed ratio.
[2]SEM, pooled Standard error of mean.
[3]Contrasts: A) PC vs. NC; B) PC vs. NC01; C) PC vs. NC03; D) PC vs. NC09; E) NC vs. NC01; F) NC vs. NC03; G) NC vs. NC09.

Table 3. The overall fecal score of weanling pigs fed low protein diets supplemented with dietary nucleotides from days 0 to 14[1]

Diet	PC	NC	NC01	NC03	NC09	SD[2]	P-values for Contrasts[3]								
NUCL, %	0	0	0.1	0.3	0.9										
Item							A	B	C	D	E	F	G	Linear	Quadratic
Overall fecal score	2.46	1.20	1.69	1.57	1.34	0.39	0.03	0.26	0.60	0.03	0.33	0.16	0.91	0.40	0.64

[1]PC = Positive control diet with adequate CP; NC = Negative control diet with inadequate CP; NC01 = NC diet containing dietary nucleotides at 1.0 g/kg of diet; NC03 = NC diet containing dietary nucleotides at 3.0 g/kg of diet; NC09 = NC diet containing dietary nucleotides at 9.0 g/kg of diet; NUCL = Dietary nucleotides.
[2]SD, Standard deviation.
[3]Contrasts: A) PC vs. NC; B) PC vs. NC01; C) PC vs. NC03; D) PC vs. NC09; E) NC vs. NC01; F) NC vs. NC03; G) NC vs. NC09.

Table 4. Apparent total tract digestibility (ATTD) of nutrients in weanling pigs fed low protein diets supplemented with dietary nucleotides[1]

Diet	PC	NC	NC01	NC03	NC09	SEM[2]	P-values for Contrasts[3]								
NUCL, %	0	0	0.1	0.3	0.9		A	B	C	D	E	F	G	Linear	Quadratic
ATTD, %															
DM	83.12	82.25	81.91	81.33	82.14	0.49	0.22	0.09	0.01	0.16	0.63	0.19	0.87	0.93	0.19
GE	81.32	80.08	79.03	79.09	80.12	0.49	0.10	<0.01	<0.01	0.10	0.15	0.17	0.96	0.48	0.15
Ca	66.57	64.66	67.46	65.49	66.60	1.20	0.27	0.61	0.53	0.99	0.11	0.63	0.26	0.59	0.85
P	46.20	43.92	44.84	43.28	44.20	1.96	0.42	0.62	0.31	0.46	0.75	0.83	0.92	0.43	0.85
N	75.26	74.33	76.98	77.51	76.54	0.91	0.48	0.16	0.07	0.29	0.05	0.02	0.09	0.02	0.39

[1]PC = Positive control diet with adequate CP; NC = Negative control diet with inadequate CP; NC01 = NC diet containing dietary nucleotides at 1.0 g/kg of diet; NC03 = NC diet containing dietary nucleotides at 3.0 g/kg of diet; NC09 = NC diet containing dietary nucleotides at 9.0 g/kg of diet; NUCL = Dietary nucleotides, DM = Dry matter; GE = Gross energy; Ca = Calcium; P = Phosphorus; N = Nitrogen.
[2]SEM, Pooled Standard error of mean.
[3]Contrasts: A) PC vs. NC; B) PC vs. NC01; C) PC vs. NC03; D) PC vs. NC09; E) NC vs. NC01; F) NC vs. NC03; G) NC vs. NC09.

Table 5. Blood serum characteristics of weanling pigs fed low protein diets supplemented with dietary nucleotides[1]

Diet	PC	NC	NC01	NC03	NC09	SEM[2]	Contrasts[3]							P-Value	
NUCL, %	0	0	0.1	0.3	0.9										
Item							A	B	C	D	E	F	G	Linear	Quadratic
GLU, mg/dL	179.68	166.51	157.65	168.81	171.42	8.93	0.30	0.12	0.39	0.55	0.48	0.84	0.70	0.43	0.98
INS pmol/L	48.99	54.34	52.72	54.90	59.18	7.97	0.66	0.76	0.62	0.40	0.96	0.96	0.66	0.59	0.91
BUN mg/dL	11.33	3.40	3.25	3.00	2.68	0.75	<0.0001	<0.0001	<0.0001	<0.0001	0.88	0.70	0.50	0.36	0.82
GSH µmol/L	12.17	7.77	7.76	8.16	7.65	1.02	0.01	0.01	0.01	0.01	1.00	0.79	0.93	0.91	0.72
IGF-1 ng/mL	237.65	215.69	218.64	218.87	228.10	5.66	0.01	0.04	0.02	0.25	0.72	0.67	0.12	0.04	0.86

[1]PC = Positive control diet with adequate CP; NC = Negative control diet with inadequate CP; NC01 = Negative control diet containing dietary nucleotides at 1.0 g/kg of diet; NC03 = Negative control diet containing dietary nucleotides at 3.0 g/kg of diet; NC09 = Negative control diet containing dietary nucleotides at 9.0 g/kg of diet; NUCL = Dietary nucleotides; GLU = Glucose; INS = Insulin; BUN = Blood urea nitrogen; GSH = Glutathione; IGF-1 = Insulin-like growth factor-1.
[2]SEM, Pooled Standard error of mean.
[3]Contrasts: A) PC vs. NC; B) PC vs. NC01; C) PC vs. NC03; D) PC vs. NC09; E) NC vs. NC01; F) NC vs. NC03; G) NC vs. NC09.

Timing of Introduction of Animal Byproducts in Nursery Diets Affects Pig Performance

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Summary

*Voluntary feed intake of pigs can be improved by supplemental flavoring additives that can enhance the taste of feed. To provide information on the potential of umami flavor-stimulating effects of various rendered animal protein byproducts on both feed preference and on performance of nursery pigs, a series of experiments were conducted with poultry byproduct meal (**PBM**) and meat and bone meal (**MBM**). The results of those experiments demonstrated that while preference tests may be interesting and give some information about the discriminatory ability of pigs, they are not definitive indicators of the effect of a feed ingredient, or potentially an additive, on growth performance. Both animal byproducts, PBM and MBM, evaluated in these studies are excellent nutrient sources but consideration should be given to when those ingredients are introduced to a young pig diet.*

Introduction

In general, mammalian taste receptors recognize sweet, sour, salty, bitter, and umami tastes known as the 5 basic tastes. Unlike the first 4 basic tastes mentioned, umami is a primary taste that is responsiveness to the combined saltiness of the sodium component and sourness of glutamate (Yamaguchi and Ninomiya, 2000). It should be noted that the voluntary feed intake (**VFI**) of pigs can be improved by supplemental flavoring additives that can enhance the taste of feed (Whittemore, 1998) and by stimulating porcine umami taste receptors responsive to salty and sour tastes (Ren and Liu, 2019). For instance, Mereu et al. (2017) reported a 3% increase in VFI of nursery pigs from day 0 to 28 postweaning due to dietary supplementation of a umami sensory additive at 900 ppm. Notably, several rendered animal protein byproducts including poultry byproduct meal and meat and bone meal are relatively high in glutamate (Li et al., 2011), implying that the afore-mentioned animal protein byproducts can potentially stimulate umami taste receptors, leading to improved VFI of pigs. In addition to high levels of glutamate, animal protein byproducts are already recognized to be excellent sources of highly digestible amino acids and available phosphorous and an excellent source of metabolizable energy in swine diets (NRC, 2012).

With regard to commercially available rendered animal protein byproducts, poultry byproduct meal (**PBM**) is a high-protein source commonly used in the pet food industry (Yamka et al., 2003). The effects of including PBM in diets for nursery pigs on general performance have been investigated somewhat and improvements in voluntary feed intake (VFI) have been observed in those studies. Different inclusion rates across these studies have given different changes in VFI, suggesting that the inclusion rate may have a "sweet spot". Meat and bone meal (**MBM**) is another byproduct of the rendering industry and a recognized excellent source of amino acids, Ca, and P (NRC, 2012). The effect of including MBM in diets for pigs on general performance has been evaluated historically in many studies. The effects of including various other rendered animal protein byproducts in diets for pigs have also been evaluated. Kim et al. (2001) reported a 7% improvement in VFI of nursery pigs during d 0-21 postweaning due to dietary inclusion of dried porcine solubles (**DPS**) at 6%. In research at the University of Kentucky, Cho et al. (2010) reported a clear preference of nursery pigs during d 0-21 postweaning for a diet containing DPS at 2.5% relative to diets containing DPS at either 0 or 5%. From these studies, it appears that the aforementioned animal protein byproducts from the rendering industry have often improved VFI of both nursery and grower pigs. The observed improvement in VFI of pigs may be associated with an actual taste, and therefore preference, for the animal protein byproducts based on the umami flavor.

A feed preference assay is commonly used to quantify the palatability of feedstuffs available for pigs. If given a choice of diets, pigs will clearly demonstrate a feed preference if they have one. Previous preference studies conducted at the University of Kentucky have reported demonstrable differences in feed preference for a variety of ingredients or levels of ingredients including salt, methionine source, mycotoxin contamination and byproducts. Thus, to provide further information on the potential of umami flavor-stimulating effects of various rendered animal protein byproducts on both feed preference and on performance of nursery pigs, a series of experiments were conducted with PBM and MBM.

Experimental Procedures

Common procedures in all experiments – In all experiments, pigs were provided the experimental diets and water ad libitum. Body weight and feed consumption of pigs were recorded weekly for determination of average daily gain (**ADG**), average daily feed intake (**ADFI**), and feed to gain ratio (**F:G**). In the performance experiments, pens were equipped with plastic feeders mounted on the front of each pen and adjustable-height nipple waterers. In the preference experiments, two feeders, each with one of the two diets in the treatment comparison, were placed in each pen and the location of the feeders was rotated each Monday, Wednesday, and Friday to avoid the potential of feeder location being confounded with potential feed preference exhibited. In the performance experiments, pen served as the experimental unit and data were analyzed by ANOVA using Proc GLM in SAS. In the preference experiments, pen served as the experimental unit and feed consumption values were converted to percentage consumption of each diet. The percentages for each period and for the cumulative time periods were then analyzed as un unpaired *t*-test in Graph Pad Prism (Graph Pad Software, San Diego, CA). The α levels evaluated were 0.05 and 0.01.

Study Series 1 - Performance and preference response of weanling pigs fed graded levels of PBM or MBM **introduced to the diet seven days postweaning.**

Experiment 1 – Performance study with graded levels of PBM

A total of 120 crossbred barrows and gilts [(Yorkshire × Landrace) × Large White] with an initial body weight (**BW**) of 7.2 ± 0.6 kg were allotted to 1 of 5 treatments in a randomized complete block design balanced for BW, sex, and genetic background for a 28-d performance study. All pigs were fed a common diet for 7 d after weaning before the study began. A corn-soybean meal (**SBM**)-based basal diet (**BD**) was formulated based on recommended ideal amino acid ratios and all other essential nutrients to be in slight excess of the NRC (2012) requirement estimates. Diets were for-

mulated in 2 dietary phases: Phase 1 (7 to 11 kg) for 7 d and Phase 2 (11 to 25 kg) for 21 d, respectively. The five dietary treatments included 1) BD, 2) BD + 1.5% PBM, 3) BD + 3% PBM, 4) BD + 4.5% PBM, and 5) BD + 6% PBM. The PBM replaced SBM, synthetic amino acids, dicalcium phosphate, and limestone; Diets 1 and 5 were mixed in large quantities and blended to create Diets 2-4. All pigs were housed by BW within sex to result in 30 pens of 4 pigs per pen for 3 barrow and 3 gilt replicates per treatment.

Experiment 2 – Preference study with PBM and SDPP

A total of 60 barrows and gilts [Yorkshire × Landrace) × Large White] with an initial BW of 6.7 ± 0.4 kg were used in a 4-wk diet preference study to determine if pigs would demonstrate a preference for diets based on the inclusion of PBM or SDDP. All pigs were fed a common diet for 7 d after weaning before the study began. Pigs were blocked by BW within sex and randomly allotted to 1 of 3 dietary treatment comparisons: 1) choice of 0% PBM or 3% PBM; 2) choice of 0% PBM or 3% SDPP, and 3) choice of 3% PBM or 3% SDPP. The 0 and 3% PBM were as in Experiment 1 and the SDPP diet was formulated in a similar manner as that described for the PBM diets in Experiment 1. The pigs were housed 4 pigs per pen for a total of 5 replicates comprised of 3 barrow and 2 gilt replicates.

Experiment 3 – Performance study with graded levels of MBM

A total of 120 crossbred barrows and gilts [(Yorkshire × Landrace) × Large White] with an initial BW of 7.3 ± 0.6 kg were allotted to 1 of 5 treatments in a randomized complete block design balanced for BW, sex, and genetic background for a 28-d performance study. All pigs were fed a common diet for 7 d after weaning before the study began. A corn-SBM-based BD was formulated based on recommended ideal amino acid ratios and all other essential nutrients to be in slight excess of the NRC (2012) requirement estimates. Diets were formulated in 2 dietary phases: Phase 1 (7 to 11 kg) for 8 d and Phase 2 (11 to 25 kg) for 21 d, respectively. The five dietary treatments included 1) BD, 2) BD + 1% MBM, 3) BD + 2% MBM, 4) BD + 3% MBM, and 5) BD + 5% MBM. The MBM replaced SBM, synthetic amino acids, dicalcium phosphate, and limestone; Diets 1 and 5 were mixed in large quantities and blended to create Diets 2-4. All pigs were housed by BW within sex to result in 30 pens of 4 pigs per pen for 3 barrow and 3 gilt replicates per treatment.

Experiment 4 – Preference study with MBM and SDPP

A total of 60 barrows and gilts [(Yorkshire × Landrace) × Large White] with an initial BW of 6.1 ± 0.2 kg were used in a 4-wk diet preference study to determine if pigs would demonstrate a preference for diets based on the inclusion of MBM or SDDP. All pigs were fed a common diet for 7 d after weaning before the study began. Pigs were blocked by

BW within sex and randomly allotted to 1 of 3 dietary treatment comparisons: 1) choice of 0% MBM or 2% MBM; 2) choice of 0% MBM or 2% SDPP, and 3) choice of 2% MBM or 2% SDPP. The 0 and 2% MBM were as in Experiment 3 and the SDPP diet was formulated in a similar manner as that described for the MBM diets in Experiment 3. The pigs were housed 4 pigs per pen for a total of 5 replicates comprised of 3 barrow and 2 gilt replicates.

Study Series 2 - Performance and preference response of weanling pigs fed graded levels of PBM or MBM **introduced to the diet at weaning.**

Experiment 5 – Performance study with graded levels of PBM

A total of 120 crossbred barrows and gilts [(Yorkshire × Landrace) × Large White] with an initial BW of 5.6 ± 0.6 kg were allotted to 1 of 5 treatments in a randomized complete block design balanced for BW, sex, and genetic background for a 28-d performance study. A corn-SBM-based BD was formulated based on recommended ideal amino acid ratios and all other essential nutrients to be in slight excess of the NRC (2012) requirement estimates. Diets were formulated in 2 dietary phases: Phase 1 (7 to 11 kg) for 13 d and Phase 2 (11 to 25 kg) for 15 d, respectively. The five dietary treatments included 1) BD, 2) BD + 1% PBM, 3) BD + 2% PBM, 4) BD + 3% PBM, and 5) BD + 5% PBM. The PBM replaced SBM, synthetic amino acids, dicalcium phosphate, and limestone; Diets 1 and 5 were mixed in large quantities and blended to create Diets 2-4. All pigs were housed by BW within sex to result in 30 pens of 4 pigs per pen for 3 barrow and 3 gilt replicates per treatment.

Experiment 6 – Preference study with PBM and SDPP

A total of 60 barrows and gilts [(Yorkshire × Landrace) × Large White] with an initial BW of 5.9 ± 0.2 kg were used in a 4-wk diet preference study to determine if pigs would demonstrate a preference for diets based on the inclusion of PBM or SDPP. Pigs were blocked by BW within sex and randomly allotted to 1 of 3 dietary treatment comparisons: 1) choice of 0% PBM or 2% PBM; 2) choice of 0% PBM or 2% SDPP, and 3) choice of 2% PBM or 2% SDPP. The 0 and 2% PBM were as in Experiment 5 and the SDPP diet was formulated in a similar manner as that described for the PBM diets in Experiment 5. The pigs were housed 4 pigs per pen for a total of 5 replicates comprised of 3 barrow and 2 gilt replicates.

Experiment 7 – Performance study with graded levels of MBM

A total of 120 crossbred barrows and gilts [(Yorkshire × Landrace) × Large White] with an initial BW of 6.2 ± 0.6 kg were allotted to 1 of 5 treatments in a randomized complete block design balanced for BW, sex, and genetic background for a 28-d performance study. A corn-SBM-based BD was formulated based on recommended ideal amino acid ra-

tios and all other essential nutrients to be in slight excess of the NRC (2012) requirement estimates. Diets were formulated in 2 dietary phases: Phase 1 (7 to 11 kg) for 15 d and Phase 2 (11 to 25 kg) for 13 d, respectively. The five dietary treatments included 1) BD, 2) BD + 1% MBM, 3) BD + 2% MBM, 4) BD + 3% MBM, and 5) BD + 5% MBM. The MBM replaced SBM, synthetic amino acids, dicalcium phosphate, and limestone; Diets 1 and 5 were mixed in large quantities and blended to create Diets 2-4. All pigs were housed by BW within sex to result in 30 pens of 4 pigs per pen for 3 barrow and 3 gilt replicates per treatment.

Experiment 8 Preference study with MBM and SDPP

A total of 60 barrows and gilts [(Yorkshire × Landrace) × Large White] with an initial BW of 6.5 ± 0.2 kg, were used in a 4-wk diet preference study to determine if pigs would demonstrate a preference for diets based on the inclusion of MBM or SDDP. Pigs were blocked by BW within sex and randomly allotted to 1 of 3 dietary treatment comparisons: 1) choice of 0% MBM or 2% MBM; 2) choice of 0% MBM or 2% SDPP, and 3) choice of 2% MBM or 2% SDPP. The 0 and 2% MBM were as in Experiment 7 and the SDPP diet was formulated in a similar manner as that described for the MBM diets in Experiment 7. The pigs were housed 4 pigs per pen for a total of 5 replicates comprised of 3 barrow and 2 gilt replicates.

Results and Discussion

*Experiments 1 and 2 – Evaluation of **PBM** when offered 7 days postweaning*

The decision to start the experiments 7 days postweaning was to allow the pigs to get "on feed" and remove some of the variation that occurs in performance on the first week postweaning as well as to concentrate on periods when ADFI would be somewhat higher than is observed in the first 7 days. The results of the performance test (Table 1) did not demonstrate any increase in ADFI related to any level of inclusion of PBM. In fact, there was a linear decline in both ADFI and ADG ($P < 0.05$) with increasing level of PBM with no statistical difference in F:G. The preference test results (Table 2) indicated a clear preference ($P < 0.01$) for the BD over both PBM and SDPP. When PBM and SDPP were compared to each other, the pigs demonstrated a preference for the PBM ($P < 0.05$). Given that SDPP is regarded as an excellent ingredient for young pigs, and one that is generally associated with an increase in ADFI in the nursery, the preference results were not expected and raised questions about why the results occurred.

*Experiments 3 and 4 – Evaluation of **MBM** when offered 7 days postweaning*

The results of the performance test (Table 3) did not demonstrate any differences in ADFI, ADG, or F:G related to any level of inclusion of MBM. The performance re-

Table 1. Effect of feeding graded levels of poultry byproduct meal beginning 7 days postweaning on growth performance of pigs[1]

	Poultry byproduct meal, %						P-value	
Item[2]	0	1.5	3.0	4.5	6.0	SEM	Linear	Quad
BW, kg								
d 0	7.15	7.17	7.19	7.15	7.18	0.011	0.367	0.276
d 28	25.32	25.10	24.51	24.68	24.18	0.762	0.024	0.880
ADG, kg	0.649	0.640	0.617	0.621	0.608	0.012	0.025	0.771
ADFI, kg	0.989	0.953	0.934	0.930	0.894	0.026	0.016	0.937
F:G	1.53	1.49	1.51	1.48	1.47	0.033	0.261	0.926

[1]Data are least squares means.
[2]BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; F:G = feed to gain ratio; and SEM = standard error of the mean. The pig BW and feed disappearance were determined on a weekly basis to calculate ADG, ADFI, and F:G.

Table 2. Percentage feed consumption of nursery pigs when offered a choice of 2 diets beginning 7 days postweaning[1]

0 vs. 3% poultry byproduct meal	60.1 vs. 39.9**
0 vs. 3% spray-dried plasma protein	72.1 vs. 27.9**
3% PBM vs. 3% SDPP	61.2 vs. 38.8*

[1]Each mean represents 5 observations (3 barrows and 2 gilts) per treatment comparison for 28 days. *$P < 0.05$; **$P < 0.01$.

Table 3. Effect of feeding graded levels of meat and bone meal beginning 7 days postweaning on growth performance of pigs[1]

	Meat and bone meal, %						P-value	
Item[2]	0	1	2	3	5	SEM	Linear	Quad
BW, kg								
d 0	7.33	7.34	7.33	7.34	7.33	0.006	0.669	0.741
d 29	25.27	25.76	25.87	25.52	25.19	0.359	0.598	0.191
ADG, kg	0.617	0.631	0.635	0.626	0.612	0.012	0.641	0.191
ADFI, kg	0.925	0.921	0.939	0.925	0.925	0.022	0.955	0.771
F:G	1.49	1.45	1.47	1.48	1.50	0.019	0.360	0.142

[1]Data are least squares means.
[2]BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; F:G = feed to gain ratio; and SEM = standard error of the mean. The pig BW and feed disappearance were determined on a weekly basis to calculate ADG, ADFI, and F:G.

Table 4. Percentage feed consumption of nursery pigs when offered a choice of 2 diets beginning 7 days postweaning [1]

0 vs. 2% meat and bone meal	82.2 vs. 17.8**
0 vs. 2% spray-dried plasma protein	76.8 vs. 23.2**
2% MBM vs. 2% SDPP	56.5 vs. 43.5

[1]Each mean represents 5 observations (3 barrow and 2 gilt replicates) per treatment comparison for 29 days. *$P < 0.05$; **$P < 0.01$.

sults were amazingly flat. The preference test results (Table 4) again indicated a clear preference ($P < 0.01$) for the BD over both MBM and SDPP. When MBM and SDPP were compared to each other, while there was no statistically significant difference, the pigs again, as with the PBM, demonstrated a numerical preference for the MBM.

It should be noted that in a preference test, that if a pref-erence or difference if feed intake is observed, it cannot be determined whether the pigs favored one diet or whether they disfavored the other diet. The clear "disfavor" of the SDPP diet compared to the BD in this second experiment suggested that the results of the first two preference studies were probably correct and not an aberration. The most probable explanation appeared to be that the pigs would have been accustomed to the plain corn-SBM diet fed during the first 7 days postweaning and were preferring the taste to which they had become accustomed. The decision was then made to repeat the studies but to begin immediately postweaning.

*Experiments 5 and 6 – Evaluation of PBM when offered **at weaning***

The results of the performance test (Table 5) when this byproduct was offered at weaning were remarkably different than when it was offered 7 days postweaning. When offered at weaning, there was no reduction in ADFI and ADG. In fact, while ADG for all levels of inclusion when offered 7 days postweaning were less than that pf pigs fed the BD (Table 1), when the PBM was offered at weaning, the ADG for all levels of inclusion were numerically greater than the BD. Consistent with the performance results of Table 1 is the fact that all F:G response values were numerically better than the values for the BD-fed pigs. When comparing the preference results for diets offered at weaning (Table 6) to those when diets were offered 7 days postweaning (Table 2), there are several things to note. First, the clear discrimination for the BD diet over the PBM diet is no longer present, there is still a discrimination against the SDPP diet ($P < 0.01$), and there still remains a preference for the PBM diet over the SDPP diet ($P < 0.01$) that is actually a bit stronger numerically when the diets were offered at weaning. While the performance results were not as surprising as those observed when PBM was offered 7 days postweaning, the preference results related to the SDPP were still unexpected and did not resolve all questions.

*Experiments 7 and 8 – Evaluation of MBM when offered **at weaning***

The results of the performance test (Table 7) did not demonstrate any differences in ADFI or ADG, again being very flat. However, there was a quadratic improvement in the F:G with increasing levels of MBM in the diet. The preference test results (Table 8) were very clear with strong preferences (P < 0.01) exhibited in all three comparisons. The only difference in the responses compared to those when the diets were offered 7 days postweaning (Table 4) is that pigs at weaning showed a strong preference (P < 0.01) for the MBM diet compared to the SDPP diet.

Conclusion

Growth performance and feed preferences of pigs in response to the inclusion of animal byproducts clearly depends on when the products are introduced to the diet. However, the fact that preferences for the basal diet without the byproducts compared to diets with the byproducts can be clearly and statistically evident (i.e., 60:40 to 80:20, P < 0.01) but there be no difference in ADFI or ADG when pigs are not given a choice of diets, demonstrates that while preference tests may be interesting and give some information about the discriminatory ability of pigs, they are not definitive indicators of the effect of a feed ingredient, or potentially an additive, on growth performance. Both animal byproducts, PBM and MBM, evaluated in these studies are excellent nutrient sources but consideration should be given to when those ingredients are introduced to a young pig diet.

Table 5. Effect of feeding graded levels of poultry byproduct meal beginning at weaning on growth performance of pigs[1]

| Item[2] | Poultry byproduct meal, % | | | | | SEM | P-value | |
	0	1	2	3	5		Linear	Quad
BW, kg								
d 0	5.63	5.62	5.62	5.63	5.62	0.008	0.554	0.707
d 28	16.78	17.31	17.49	17.73	17.60	0.511	0.262	0.416
ADG, kg	0.398	0.417	0.424	0.432	0.428	0.018	0.259	0.409
ADFI, kg	0.585	0.608	0.576	0.608	0.594	0.027	0.885	0.825
F:G	1.48	1.46	1.36	1.41	1.39	0.038	0.116	0.251

[1]Data are least squares means.
[2]BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; F:G = feed to gain ratio; and SEM = standard error of the mean. The pig BW and feed disappearance were determined on a weekly basis to calculate ADG, ADFI, and F:G.

Table 6. Percentage feed consumption of nursery pigs when offered a choice of 2 diets beginning at weaning[1]

0 vs. 2% poultry byproduct meal	54.2 vs. 45.8
0 vs. 2% spray-dried plasma protein	77.4 vs. 22.6**
2% PBM vs. 2% SDPP	75.9 vs. 24.1**

[1]Each mean represents 5 observations (3 barrow and 2 gilt replicates) per treatment comparison for 28 days. *P < 0.05; **P < 0.01.

Table 7. Effect of feeding graded levels of meat and bone meal beginning at weaning on growth performance of pigs[1]

| Item[2] | Meat and bone meal, % | | | | | SEM | P-value | |
	0	1	2	3	5		Linear	Quad
BW, kg								
d 0	6.21	6.21	6.21	6.19	6.21	0.013	0.603	0.571
d 28	17.31	17.34	17.17	17.31	16.90	0.389	0.444	0.723
ADG, kg	0.396	0.397	0.391	0.397	0.382	0.014	0.457	0.709
ADFI, kg	0.553	0.549	0.522	0.540	0.526	0.019	0.350	0.577
F:G	1.40	1.38	1.33	1.36	1.38	0.022	0.566	0.054

[1]Data are least squares means.
[2]BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; F:G = feed to gain ratio; and SEM = standard error of the mean. The pig BW and feed disappearance were determined on a weekly basis to calculate ADG, ADFI, and F:G.

Table 8. Percentage feed consumption of nursery pigs when offered a choice of 2 diets beginning at weaning[1]

0 vs. 2% meat and bone meal	71.3 vs. 28.7**
0 vs. 2% spray-dried plasma protein	83.4 vs. 16.6**
2% MBM vs. 2% SDPP	74.4 vs. 25.6**

[1]Each mean represents 5 observations (3 barrow and 2 gilt replicates) per treatment comparison for 28 days. *P < 0.05; **P < 0.01.

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Trace Minerals: Requirements vs Need – The Case for Iodine in the Nursery

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Summary

Several trace minerals improve the growth rate of swine when supplemented at concentrations higher than published requirements. These include copper, zinc, iron, and manganese. Recent data from the University of Georgia indicates that iodine should be included in this list. Increasing dietary iodine levels up to 14 ppm improved growth rate and increased thyroid hormone activity in nursery pigs. Published trace mineral requirements for swine are adequate to prevent deficiency symptoms but may not be adequate for maximal growth rates.

Introduction

Historically, energy and protein requirements in swine have been determined based on the concentration needed for maximal growth and efficiency. However, vitamin and trace mineral requirements were determined solely by the amount of vitamin or mineral needed to prevent deficiency symptoms and to stabilize metabolic processes in the animal. These differing criteria for the determination of a requirement are often overlooked by nutritionists.

Over the past 75+ years it has been shown that feeding pigs diets that contained trace mineral levels above the published requirements can improve growth and reproductive efficiency. The beneficial impacts of "pharmacological" levels of copper and zinc are well established and recognized (Cromwell, 1989; Stahly et. al., 1980; Shelton, et. al. 2011, Hill, et. al. 2000). More recently neonatal and nursery pigs have been shown to respond to increased levels of iron and manganese supplementation (Edmunds et. al, 2022, Qi, et. al., 2024; Xiong, et. al., 2024). In most studies these minerals were fed at levels which were 6 (Mn) to 30 (Zn) times the dietary concentration needed to prevent deficiency symptoms.

The NRC (2012) sets the iodine requirement as 0.14 mg/kg of diet. This requirement is based on the work of Simombing et. al (1974) who found that thyroid size was near normal at about 0.14 mg/kg dietary iodine and Cromwell et. al. (1975) who found the iodine requirement was between 0.086 and 0.132 mg/kg dietary iodine. At these dietary iodine concentrations, iodine deficiency symptoms

were eliminated, and growth rate was similar to controls. It should be noted that highest dietary concentration of iodine in these studies was 0.4 mg/kg dietary iodine (Simombing et. al. 1974; Cromwell et al., 1975).

Recently completed studies at the University of Georgia would indicate that nursery pigs respond to supplemental iodine at levels up to 100 times (14 mg/kg) the current published NRC requirement. Iodine is unique in that it directly impacts the basal metabolic rate as a component of the thyroid hormones and consequently increased thyroid hormone activity may impact the need for and utilization of other nutrients.

Experimental Procedures

A total of 180 weaned piglets (PIC LO3 x 337, 21 +/- 3 days, 5.8 +/- .8 kg, 80 piglets in trial 1, 100 piglets in trial 2) were randomly blocked by sex and weight and assigned to pens. Barrows and gilts were equally distributed with 2 barrows and 2 gilts per pen. Within each weight block, pens were randomly assigned to one of 5 dietary treatments. Pigs were housed in an environmentally controlled nursery with *ad libitum* access to feed and water. Experimental diets were formulated to meet or exceed NRC (2012) recommendations for all nutrients except iodine (Table 1). Supplemental iodine was added to the diets at 0.0, 0.14, 1.4, 14.0 and 140.0 mg of I/kg of diet as potassium iodide. Experimental diets were fed in 3 phases over the 35 d study, with phase 1 being fed d 0-10, phase 2 d 10-21, and phase 3 d 21-35. Piglet weights, and pen feed intake were recorded on d 0, 7, 10, 21,

Table 1. Basal diet composition and analysis

Ingredient, %	Phase 1	Phase 2	Phase 3
Corn	23.14	43.48	62.83
Soybean meal	18.64	27.01	32.34
Oats	10.00	5.00	
Hamlet Protein 300	10.00	5.00	
Whey	15.00	5.00	
Lactose	10.00	5.00	
Fish meal	5.00	3.00	
Fat	3.35	2.90	1.33
Lysine	0.40	0.30	0.35
Methionine	0.16	0.11	0.12
Threonine	0.11	0.06	0.05
Limestone	0.74	0.85	0.84
Dicalcium Phosphate	0.64	0.91	1.55
Salt	0.20	0.25	0.35
Vitamin premix[1]	0.25	0.25	0.25
Mineral premix[2]	1.00	1.00	1.00
Zinc Oxide	0.37		
Nutrient Content, calculated			
ME[3], kcal/kg	3400.00	3400.00	3330.00
Crude Protein, %	23.19	23.06	21.36
Lysine, SID %	1.50	1.35	1.20
Total Sulfur Amino Acids, SID %	0.82	0.74	0.68
Tryptophan, SID %	0.25	0.24	0.23
Threonine, SID %	0.88	0.79	0.73
Calcium, %	0.85	0.80	0.80
Phosphorus, STTD	0.45	0.40	0.40

[1] Vitamin premix: supplied per kg of diet: vitamin A (4,134 IU); vitamin D (1,653 IU); vitamin E (66 IU); vitamin K (3.3 mg); riboflavin (8.27 mg); niacin (49.6 mg); vitamin B12 (0.033 mg); pantothenic acid (27.6 mg); ADM Alliance Nutrition, Quincy IL 62305.
[2] Mineral premix: supplied per kg of diet: copper (20 mg/kg Cu from CuSO4); zinc (100 mg/kg Zn from ZnO); iron (100 mg/kg Fe from FeSO4); manganese (24 mg/kg from MnSO4); selenium (0.3 mg/kg Se from Na2SeO3.
[3] ME is defined as metabolizable energy.

28 and 35. Blood samples and fecal swabs were collected on d 21 and 35 for the determination of thyroid hormones and microbiome changes. Data were analyzed using Proc GLM in SAS utilizing the pen as the experimental unit. Initial body weight was used as a covariate for growth parameters. Linear and quadratic effects were made using appropriate contrast statements in Proc GLM.

Data and Interpretation

Pigs used in this study grew as expected and demonstrated no signs or symptoms of a clinical iodine deficiency or toxicity. One piglet was removed from the study on d 7 due to an unrelated injury.

During the first 10 d of the study, pigs fed increasing levels of dietary iodine had a linear (P <0.03) increase in body weight, average daily gain (ADG) and average daily feed intake (ADFI, Table 2). Gain:Feed ratio (G:F) was not affected (P >0.3) by iodine supplementation. Pigs fed 14 mg/kg iodine had the numerically highest body weights, ADG, and ADFI. In the present study, pigs responded very rapidly to changes in the dietary iodine concentrations possibly indicating a metabolic demand for iodine.

During days 10-21 of the study pigs fed increasing levels of iodine had a linear (P < 0.03) increase in body weight, however there were no significant (P > 0.10) differences in ADG, ADFI or G:F associated with the increasing dietary iodine concentration. There were numerical increases consistent with the first 10 d of the study. There appeared to be more variation in piglet performance during this phase, especially in feed intake. This may be related to the transition from the high-lactose phase 1 diet to the more corn-based phase 2 diet, perhaps indicating an interaction between the resident microbial population activity and dietary iodine concentrations.

From day 21 to the end of the study on day 35, pigs fed increasing concentrations of dietary iodine exhibited a linear increase (P < .04) in body weight, ADG and ADFI. During this phase, pigs fed the 14 mg/kg dietary iodine (100x NRC) had an ADG that was 37 g/d greater than those fed the 0.14 mg/kg dietary iodine (1x NRC) and 63 g/d greater ADG than those pigs fed no supplemental iodine. Increasing levels of dietary iodine had no effect (P > 0.1) on G:F. There was a trend (P <0.07) for a quadratic effect on feed intake during this period. Pigs fed the 1.4 mg/kg dietary iodine had the highest feed intake during this period.

Over the entire 35 d study, increasing the concentration of dietary iodine resulted in a linear (P 0.01) increase in body weight gain, with those pigs fed the 14 mg/kg dietary iodine completing the study 1.22 kg heavier than those fed the NRC level of 0.14 mg/kg dietary iodine and 1.96 kg heavier than those pigs fed no supplemental iodine. Average daily gain and ADFI were also linearly increased (P < 0.01) with increasing concentrations of dietary iodine. Throughout the study, pigs fed 14 mg/kg of dietary iodine

Table 2. The effect of dietary iodine on the growth performance of nursery pigs

| | Dietary Iodine, mg/kg | | | | | | P-Value | | |
	0	0.14	1.4	14	140	SEM	Iodine	Linear	Quadratic
Body Weight, kg									
d 0	5.74	5.83	5.79	5.86	5.81	0.05	0.57	0.33	0.56
d 10	7.05	7.33	7.32	7.56	7.30	0.09	0.01	0.02	0.37
d 21	11.56	11.93	12.13	12.67	11.97	0.24	0.02	0.03	0.91
d 35	19.18	19.92	20.46	21.14	20.24	0.35	0.01	0.01	0.43
ADG, g/d									
d 0-10	130	154	155	176	152	9	0.03	0.03	0.44
d 10-21	410	414	435	459	422	17	0.22	0.19	0.67
d 21-35	550	576	597	613	595	17	0.14	0.03	0.34
d 0-35	384	405	420	440	414	11	0.02	0.01	0.46
ADFI, g/d									
d 0-10	262	306	287	338	296	14	0.01	0.02	0.39
d 10-21	795	792	822	838	836	39	0.82	0.26	0.74
d 21-35	1014	1099	1128	1112	1097	28	0.04	0.04	0.07
d 0-35	731	779	791	819	782	17	0.01	0.01	0.21
G:F									
d 0-10	0.51	0.52	0.56	0.54	0.53	0.02	0.61	0.33	0.74
d 10-21	0.55	0.54	0.55	0.58	0.52	0.03	0.86	0.85	0.44
d 21-35	0.56	0.54	0.54	0.57	0.56	0.01	0.59	0.52	0.60
d 0-35	0.55	0.54	0.55	0.55	0.55	0.01	0.89	0.50	0.87

Table 3. The effect of dietary iodine on thyroid hormone concentrations on d 21 and d 35 in the nursery

| | Dietary iodine, mg/kg | | | | | | P-values | | |
	0	0.14	1.4	14	140	SEM	Iodine	Linear	Quadratic
d 21									
T4, nmol/L	63.9	63.6	66.3	71.3	68.4	2.2	0.09	0.02	0.87
T3, nmol/L	1.65	1.62	1.63	1.71	1.71	0.06	0.79	0.31	0.86
T4:T3	39.6	40.1	42.2	43.0	41.5	1.6	0.52	0.18	0.85
d 35									
T4, nmol/L	48.4	51.4	58.3	59.3	59.9	2.2	0.01	0.01	0.03
T3, nmol/L	1.65	1.31	1.49	1.39	1.40	0.16	0.62	0.40	0.25
T4:T3	36.6	41.3	40.9	45.2	44.6	1.7	0.01	0.01	0.03

On d 21, plasma thyroxine (T4) was linearly increased (P <0.02) as dietary iodine concentrations were increased., with pigs fed 14 mg/kg dietary Iodine having the highest plasma T4 concentration (Table 3). Neither plasma triiodothyronine (T3) nor the T4:T3 ratio were affected (P > 0.18) by increasing concentrations of dietary iodine on day 21. On d 35, plasma T4 and the T4:T3 ratio were both linear (P < .01) and quadratic (P <0.03) responses to increasing dietary iodine concentrations. The T4 response appears to plateau starting at 1.4 mg/kg of dietary iodine while the T4:T3 ratio decrease when pigs are fed 140 mg/kg dietary iodine. Plasma T3 concentrations were not affected (P >0.40) by increasing dietary iodine concentrations at d 35.

Specific information on the metabolism of T3 and T4 in swine is minimal (Slebodzonski, 1965). In most mammals, including swine, it is thought that T4 functions as a pro-hormone and has a significantly longer half-life than T3. A majority of the thyroxine that is produced by the thyroid gland is circulated to the cells, where it is converted to T3, which has 3-4 times the activity of T4 (Chemburkar, et.al., 2010). Thus, it is not surprising that little change in plasma T3 concentrations was observed, in this study. Thyroxine appears to be much more responsive to changes in dietary iodine concentrations.

Thyroid stimulating hormone (TSH) was not measured in this study. However, it is hypothesized that the decrease in plasma T4 and the decrease in performance seen in those pigs fed the 140 mg/kg dietary iodine was a result of the down regulation of TSH resulting in excretion of the excess iodine in the urine and feces. The hypothalamic-pituitary-thyroid axis is very tightly regulated and excess T4 would result in decreased levels of TSH, which would decrease T4 synthesis in the thyroid. The data from this study indicates that 14 mg/kg (100x NRC, 2012) dietary iodine resulted in the best growth performance and the highest concentration of T4.

consistently had the highest ADG and ADFI. Pigs fed 140 mg/kg dietary iodine (1000x NRC) had numerically lower ADG and ADFI than the pigs fed 14 mg/kg dietary iodine. While no clinical signs or symptoms of iodine toxicity were seen, 140 mg/kg dietary iodine was above what was needed to support growth performance and feed intake. Increases in ADG tended to follow the increases in ADFI, therefore, no improvements (P > 0.10) in G:F were seen at any time during the study.

Conclusion

Trace minerals play an important role in the growth and development of swine, especially nursery pigs and stressed pigs. Numerous minerals have been shown to improve growth rate when supplemented at levels above what is required to prevent deficiencies. This study indicates that the addition of up to 14 mg/kg iodine to the nursery diet increases growth performance and T4. Iodine has an important role in the maintenance of the basal metabolic rate of the animal. Additional dietary nutrients may be needed by the young pig to maximize growth in the presence of higher dietary iodine levels.

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Sow Anemia:
Is It Really That Big of a Deal?

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Summary

Current mineral requirement estimates are based on studies conducted more than 30 years ago. In particular for iron, despite diet supplementation 30% or more above current recommendations approximately 50% of gestating sows are expected to have blood hemogoblin concentration below levels deemed to reflect anemia (i.e. < 10 g/dL) indicating a high proportion of gestating sows are anemic. A similar incidence of sow anemia has been reported in the U.S., Europe, and China. Further, the incidence of sow anemia increases with increasing parity. The direct cause of sow anemia is not known and is less likely related to iron supply considering current diet supplementation levels; further reports of additional iron supplementation of sows (oral or injection) had limited impact on sow blood hemoglobin content. Some degree of anemia may be expected following parturition considering blood loss during farrowing; however, recovery of sow blood hemoglobin prior to, and during, the subsequent pregnancy declined with parity. Recent evidence indicates that a possible complication of an anemic state is prolonged farrowing and thus anemia in sows has also been associated with increased incidence of stillborn piglets potentially providing a partial explanation for increase stillborn rate with parity. While the direct cause of anemia in sows is unknown, the practical implications of this condition on sow reproductive performance indicates efforts to understand, and thus develop mitigation strategies, could benefit overall pork production.

Introduction

The concept of anemia in pigs was recognized almost a century ago in relation to low iron status of piglets at birth combined with low iron content of sow's milk (Willman et al., 1933). Since then, there has been extensive investigation into strategies to mitigate suckling pig anemia. However, trace mineral requirement estimates of the breeding herd in the most updated NRC (2012) were based primarily on studies conducted prior to 1980 and do not take into account the body weight of the animal, its production level (including metrics such as total born), changing metabolic needs during gestation and lactation, or parity. In part due to the outdated information on sow mineral needs, industry levels of iron inclusion within mineral premixes into sow diets are several times higher than the published recommendations. For example, in a recent survey of vitamin and trace mineral levels in US swine diets (Faccin et al., 2023), the average dietary iron content (mg/kg) was 1.37-fold higher than NRC (2012) requirement estimates with the 25th and 75th percentile at 1.2 and 1.48-fold higher, respectively. Despite fortification of iron in sow diets that are above recommended levels, sow hemoglobin (Hb) concentration (an indirect marker of iron status) was below the cutoff value for anemia (i.e. <10 g/dL) in approximately 50% of U.S. breeding females with a greater prevalence of anemia observed in older parity sows and during lactation (Bhattarai et al., 2019a; Castevens et al., 2020; Noblett, et al., 2021; McClellan et al., 2024). The prevalence of anemia in sows is not restricted to US herds. In a survey of 637 sows across farms in the European Union, 47% were anemic (blood Hb < 10 g/dL) at weaning (Sperling et al., 2021). In the Hunan province of China, average blood Hb at 5 timepoints in gestation was < 10 g/dL for parity $2-6$ based on samples from over 500 sows (Guo et al., 2022).

Some degree of anemia is not surprising considering the current sow is approximately 13 kg heavier at first breeding (gilt at breeding = 123 vs 136 kg) and farrows 4+ more pigs/litter (10 vs 14.5 total born) than the sow from 40 years ago when the requirements were established but the typical gestation diet is provided at a similar daily proportion $(1.8 - 2.4$ kg) with similar nutrient concentrations (3300

kcal/kg ME; 0.55 – 0.60 % SID lysine; 100 - 113 mg/kg iron) (Hoppe, 1985). Considering the example of a gilt at breeding provided 1.8 kg feed/d, iron intake on a kg body weight basis is 10% lower but fetal output is at least 40% greater in the current female.

Sow anemia

The prevalence of anemia reported by Castevans et al. (2020) and Noblett et al. (2021) was based on single point of time assessment across individuals thus an explanation for the higher prevalence in older parity sows could not be determined. Recently, a group of gilts was monitored for changes in Hb concentration throughout gestation and lactation over 2 – 3 successive parities (McClellan et al., 2024). Similar to the previous work, sow Hb concentration declined over gestation where anemia rates peaked in late gestation (i.e. d 92 ± 2), with a high prevalence of anemia persisting during lactation for all parities. However, this work also noted that the decline in Hb concentration during gestation and lactation was greater in parity 2 than parity 1 and 3. As a result, sows were able to recover from low Hb concentration within 5 days after weaning from the first parity but recovery was lesser from the second parity, thus in parity 3, sows spent much of gestation and all of lactation in an anemic state (Figure 1). Greater prevalence of anemia during late gestation and lactation may be expected considering changes in blood serum volume and packed red cell volume that occur in late gestation and lactation due to demands for fetal development and milk synthesis (Anderson et al., 1970; Mahan et al., 2009). It is estimated plasma volume increases 30% during gestation with addi-tional increase in lactation (Jezkova et al., 1977). Blood loss during farrowing may also provide some explanation for the prevalence of anemia around farrowing where in humans the loss of red blood cells may exceed the production of new red blood cells (Braunstein, 2022) although the information related to actual blood loss in sows at farrowing is limited and doesn't necessarily explain the decline with sow age considering litter sizes and weight (hence placental size) is similar in parity 2+ sows.

It is generally presumed that anemia in sows is due to iron deficiency (Castevens, 2020) thus the most common approach to mitigating the condition is dietary supplementation. Despite dietary iron above requirement estimates, iron absorbed from the diet may fall short of whole-body iron demands across consecutive pregnancies; however, attempts to increase sow iron supplies through diet supplementation have had limited success. For example, oral supplementation of AA-chelated iron (300 mg/day or 650 mg/day) for 3 weeks in late gestation (Egeli et al., 1998) or inorganic iron (256 mg/kg diet) throughout gestation (Buffler et al., 2017) or an injection of iron (2500 mg) at 56 and 69 days of gestation (Bhattarai et al., 2019c) failed to enhance sow hematologic variables. Although provision of heme iron or lactoferrin throughout gestation improved iron content in sow serum and placental iron (Xing et al., 2023). The combination of dietary iron levels above requirement estimates and the lack of response to supplemental iron (oral or injected) suggest that sow anemia is related to iron metabolism rather than dietary iron supply. Anemia caused by low iron supply is defined as microcytic and characterized by smaller than normal red blood cells in circulation, hence lesser capacity to carry iron (Chaudhry and Kasarla, 2022). Anemia can also be caused by low Hb content when red blood cell size is within the normal range (i.e. normocytic) or abnormally large red blood cells with low Hb content relative to their size (i.e. macrocytic) (Moreno et al., 2009). While laboratory tests are available to help characterize the type of anemia in humans (Short and Domalgaski, 2013), similar laboratory standards and analytical expertise are severely lacking in pigs making development of effective intervention strategies challenging.

While the prevalence of anemia in sows is well established, the implications of sow anemia on her own reproductive performance or on the developing and suckling piglet is less well understood.
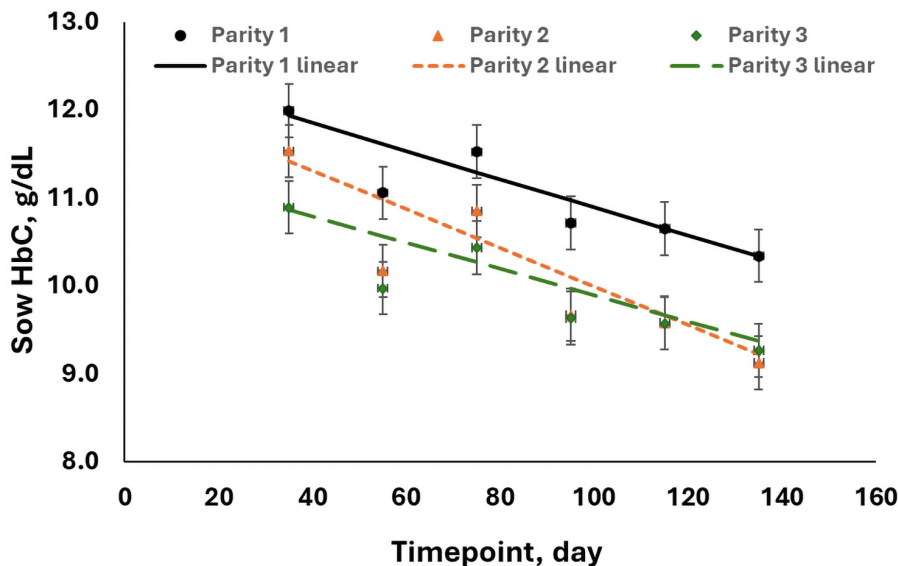

Figure 1. Slope-ratio comparison of sow HbC values across gestation and lactation time points based on sow parity. Day 0 represents day of breeding.
Parity 1: sow HbC = 12.4 + (−0.016 × d), R^2 = 0.17;
Parity 2: sow HbC = 12.2 + (−0.023 × d), R^2 = 0.37;
Parity 3: sow HbC = 11.3 + (−0.015 × d), R^2 = 0.37

Implications on sow and piglet outcomes. A common concern with low sow iron status relates to iron status of piglets, particularly at weaning. Sperling et al. (2019) note that despite iron supplementation to suckling piglets, 15 – 17% were still anemic at weaning, with higher prevalence of anemia in piglets from older sows (parity 6+) and parity 1 and 2 sows. McClellan et al. (2024) also report higher incidence of anemia at weaning in piglets from the first parity compared to second or third litters in a longitudinal study tracking a cohort of gilts across 3 parities. The reduction in prevalence of piglet anemia at weaning in mid parity sows may be related to greater placental iron transfer during pregnancy with greater parity (Guo et al., 2022) and in part may explain the increased prevalence of anemia with parity. However, it is possible that beyond 5 pregnancies, maternal iron levels are sufficiently limited such that transfer to fetuses is also limited. Guo et al. (2022) report a limited positive linear correlation (r = 0.328) between sow Hb at day 110 of gestation and placental iron content at farrowing suggesting that greater sow iron status results in greater placental transfer. In addition, the authors report declining placental iron content at parturition with advancing parity supporting limited capacity for iron transfer to reproductive tissues during pregnancy with age.

Another potential consequence of low sow iron status relates to incidence of stillborn piglets. Some recent work has reported a relationship between sow Hb and stillborn incidence (Bhattarai et al., 2019b; Noblett et al., 2021). Based on late gestation sow Hb from sows across 5 commercial sow farms, the number of stillborn piglets was greater in anemic than non-anemic sows and that if sow Hb was increased from 10 to 11 g/dL the incidence of stillborn could be reduced by a factor of 0.74 (Noblett et al., 2021). The authors speculate the mechanism of action may relate to impaired uterine contractions.

There is evidence in humans that anemia is linked to prolonged labor or dystrophic dystocia (Traylor and Torpin, 1951; Zilliacus and Putkinen, 1952). In sows, longer farrowing duration is associated with increased incidence of stillborns possibly due to greater risk of hypoxia in piglets
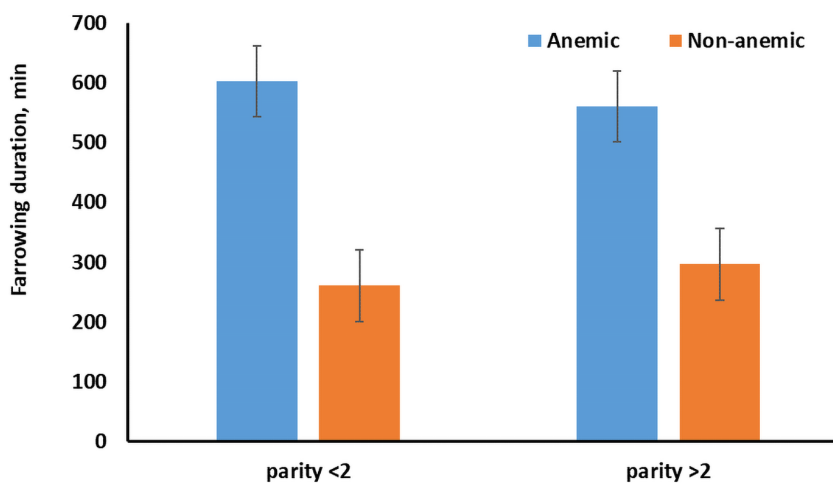

Figure 2. Farrowing duration by parity group and anemia status. Sows were deemed anemic when late gestation blood hemoglobin was ≤ 10 g/dL.

Table 1. Hemoglobin concentration (HbC) ranges by farrowing duration

Category	1	2	3	4	SEM	P-value[1]
HbC range, g/dL	≤9.0	9.1 – 9.9	10.0 -11.0	>11	-	-
Sows, n	13	40	29	19	-	-
Farrowing duration, min	750[a]	510[b]	306[c]	246[c]	54	<0.0001

[1]Different superscripts [a,b,c] within the same row indicate differences at $P < .05$

Table 2. Feeding time and prefarrowing feed intake for anemic vs non-anemic sows[1]

Variable	Anemic	Non-Anemic	SEM	P-Value
Time elapsed since last feeding[2] (min)	301.6	231.2	0.9	0.150
Pre farrowing feed intake (kg)	3.2	2.9	0.3	0.525

[1]Anemia was defined as blood hemoglobin at <10 g/dL.
[2]Feed drops occurred simultaneously for all sows six times a day, at 5 am, 8 am, 11 am, 2 pm, 5 pm, and 8 pm, respectively. The total daily feed was distributed across these time periods, with the first two accounting for 20% each, and the remaining four for 15% each. The maximum amount of feed distributed per meal was up to 4.84 kg. There was an additional 0.11 lb "stimulation" drop at the beginning of each new period. Sows were allowed to consume 20% more than their assigned parity curve.

(Oliviero et al., 2010; Feyera et al., 2018). Recent work in our lab recording farrowing duration on 101 sows showed that anemic sows had almost 2x greater farrowing duration than non-anemic sows (Table 1) and that this prolonged farrowing in anemic sows was consistent regardless of parity (Figure 2). The increase in farrowing duration was not explained by differences in litter size (anemic = 16.7 total born; non-anemic = 16.6 total born) or piglet birth weight (anemic = 1.49 kg; non-anemic = 1.45 kg). Oliverio et al. (2010) suggest a farrowing duration threshold of 300 min to reduce risk of piglet hypoxia based on sows with average litter size of 12.7 piglets. This upper limit fits well with our data where sows with late gestation Hb >10 g/dL had farrowing duration at or below 300 min while those with Hb < 10 g/dL had average farrowing duration above 500 min (Table 1) despite no differences in total born. Time from last feeding to farrowing and feed intake on the day of farrowing were also measured and were not different between anemic and non-anemic sows (Table 2).

In addition to greater risk of stillborn, prolonged farrowing duration may negatively influence sow post-partum recovery (Hasan et al., 2018) and fertility (Oliviero et al., 2013). Certainly, prolonged farrowing increases the likelihood of a sleeving event by barn staff which can increase risk of uterine infections, fever incidence, or off-feed events after farrowing. Anecdotal evidence from our work suggests a higher proportion of sow removals, including deaths or culls, among anemic sows compared to non-anemic sows, highlighting the potential broader implications of anemia on sow welfare and productivity.

In conclusion, although anemia itself is an 'old' concept in pig production, the prevalence of anemia in pregnant and lactating sows has more recently been acknowledged. There is increasing evidence that sow anemia has negative consequences on sow reproductive performance (i.e. stillborns) and is not a result of inadequate iron intake. Further, the prevalence of sow anemia may contribute to reduced sow health culminating in sow removal. Efforts to understand the type of anemia prevalent in sows will aid in developing effective solutions and improve overall sow productivity.

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Soybean Meal Net Energy Value for Growing Pigs is Greater in Commercial Environments: How Can This Be?

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Summary

This paper provides credible net energy (NE) estimates for soybean meal (SBM) based on recent indirect calorimetry (IC) and growth assay procedures. The latter was in remarkable agreement (<1.0% difference) with the calorimetric gold standard; both exceeding calculated estimates reported from international composition tables by 8-15%. The empirical studies were conducted in academic facilities with strict environmental control. This setting lacks pathogen induced immune stress that would increase maintenance energy use for protective functions and bias the NE estimate. The growth assay was then used to determine the veracity of the SBM NE estimate in the commercial environment, with the expectation of a similar value. However, this yielded an estimate of 3302 kcal NE/kg SBM dry matter (DM), which exceeded our previous growth assay estimate from an academic equivalent setting (2492) by 32%. This increase in 'apparent SBM NE' (est. +810 kcal/kg DM) does not represent a difference in classic NE estimates. We assert that the IC estimate for SBM NE (2517) represents that because it is based on SBM substrate energetics. However, applying the growth assay in the commercial setting was the means of detecting a role for SBM that we had not anticipated. SBM appeared to cause greater total diet NE use for growth since caloric efficiency improved with increasing SBM level; SBM NE being fixed. Since SBM NE was known, we proposed that the apparent SBM 'NE' value in the commercial setting is the sum of (1) classic ingredient energetics, and (2) conservation of total dietary energy for growth; SBM mediating an 'uplift' in diet NE for growth. The abundance of health-promoting compounds in SBM may have prevented diversion of energy from growth to expand protective functions to combat environmental stress (e.g. pathogen-induced immunity). We describe this combination of NE provision and diet NE conservation as Productive energy (PE). Our observations are aligned with subsequent research results by commercial systems. Consequently, practicing nutritionists are increasingly applying SBM PE values when formulating diets for commercial conditions.

Introduction

This paper sustains the recent estimates of SBM NE presented by the Stein laboratory (Sotak-Peper et al., 2015; Rodriquez et al., 2020; Lee et al., 2022). Their most recent estimate was determined using indirect calorimetry (IC) with group housed pigs, fed ad libitum. The IC method is considered to be the gold standard for ingredient NE estimates, but their housing and feeding procedure is an essential feature (Lee et al., 2022). This estimate is remarkably similar to our growth assay estimate (Boyd and Rush, 2018); respective estimates being 2517 and 2492 kcal NE/kg SBM DM. Both exceed SBM NE values from 4 international composition tables by 8-15% (Boyd and Gaines, 2023).

This paper extends our understanding of how SBM NE varies in practice and that SBM improves the efficiency of total dietary NE use under commercial conditions. In the case of the former, we believe that SBM NE value varies in relation to the protein content (CP) of SBM. Private sector estimates for SBM NE in relation to SBM CP were published by Pope and co-workers (2023; 44.0 to 48.0%). This is not generally recognized but is consistent with Brazil ingredient composition tables for SBM (Rostagno et al., 2017). A complete picture of SBM amino acid content and NE must be understood in order to properly value SBM at different protein levels and against alternative protein and amino acid alternatives (Pope et al., 2024).

There also appears to be a difference between SBM NE values, derived in the academic setting with strict environmental control, and realized 'SBM NE' values observed in the commercial setting, where pathogens and other stressors exist (Boyd and Gaines, 2023). This apparent difference does not represent a conflict in the SBM NE value because the Stein lab estimates represent classic substrate energetics. The apparent uplift in total diet NE from SBM (apparent SBM NE) may involve conservation of total dietary energy use for growth (hypothesized by Boyd and Gaines, 2023). It is conceivable that the health-promoting compounds in SBM may temper the need for a protective response to pathogen or other stressors present in the commercial environment (Petry et al., 2024). This hypothesis had its origin with the report that SBM dramatically ameliorates the effect of respiratory stress on growth in pigs (Boyd et al., 2010; Boyd et al., 2023).

We applied the term *Productive Energy* (PE) to account for the increase in 'realized NE' from the total diet that is attributable to SBM in the commercial environment. Nutritionists in large systems are increasingly applying SBM PE when formulating commercial diets. This paper advances the application of this scientific finding into practice by guiding SBM PE into commercial formulation.

Recent empirical estimates of SBM NE are credible

The papers that were published by the Stein lab on SBM NE (cited above) involved a total of 27 samples from 4 regions of the U.S. Estimates were computed from their experimentally determined DE using the Noblet equation 1-8 (NRC, 2012), with the exception of one sample that was estimated by IC. NE values computed from DE (26) averaged 2499 kcal/kg SBM DM (range, 2391-2625), while the IC estimate was 2517 kcal/kg DM (**Figure 1**).
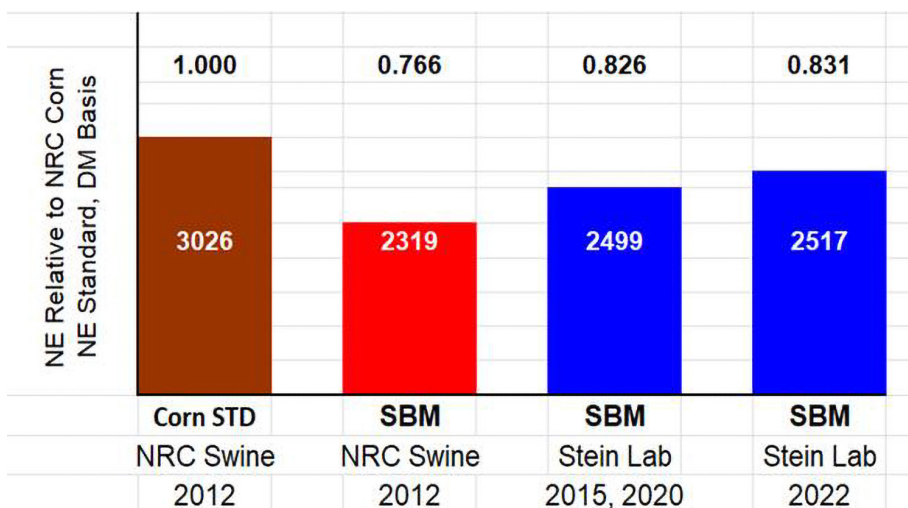
SBM NE values published by the 4 international composition tables (INRA, 2004; CVB, 2016; Brazil – Rostagno et al., 2017) including the NRC (2012) are 8-15% below those reported by the Stein lab; the NRC estimate being the closest (2319 kcal NE/kg DM) and the CVB estimate being the most deviant. These comparisons were based on SBM CP in the 46.5 to 48.4% range, which is important because SBM NE appears to increase as SBM CP increases (Rostagno et al., 2017).

The SBM NE value of 2502 kcal/kg DM is compelling going forward because it is based on the average result for the 3 Stein lab publications that involved 27 samples. This estimate is appropriate for SBM in the 46.6 to 48.1% CP range.

Hanor growth assay agreement with recent SBM NE values

Results from our growth assay were remarkably similar to SBM NE values published by the Stein group; both being conducted in academic or comparable conditions. Our assay yielded an estimate of 2492 kcal NE/kg SBM DM (47.6% CP SBM; Boyd and Rush, 2018) and deviated from Stein lab estimates by less than 1% for DE (2499 kcal NE) and IC derived estimates (2517).

We conducted the growth assay in a small research facility that Hanor used to test concepts before moving to the scale and complexity of a commercial facility. The experimental setting involved small group size (24 pens, 10 mixed sex pigs/pen) and good environmental conditions (temperature, population density), similar to an academic setting. Pigs were sourced from a sow farm that was PRRSv positive, but stable. There were no clinical signs of disease during the test. The assay was conducted for 28 d with pigs over the 101 to 165 lbs phase of growth.

The NE for SBM was computed, assuming that the caloric density or efficiency of the gain was constant for pigs fed the reference and test diets. Given a constant caloric gain, unknown SBM NE was computed to be the value required to deliver the observed feed conversion efficiency (FCE). FCE is a discriminating measure of how diet NE is affected by substituting the SBM of unknown NE for a carefully defined corn reference of known NE. The assumption of constant caloric efficiency of gain requires that growth rate remained constant across diets for the test period, which was delivered on. This procedure was described by Boyd and Rush (2017); essential nuances provided by Boyd and Gaines (2023).

Figure 1. Recent empirical estimates of SBM NE from the Stein lab compared to NRC (2012) corn and SBM

Growth assay validation of ingredient NE – private sector primer

The growth assay has been extensively used by several nutrition companies for more than 35 years to validate experimental NE estimates and to calibrate NE prediction algorithms. Drs. Wesley Snyder and Larry DeGoey were using the growth assay by the mid-1980's to validate NE values for selected ingredients that the Rostock institute of animal nutrition published NE values for. Cargill–Provimi expertly applied the growth assay to calibrate algorithms for dynamic ingredient NE prediction and have a remarkable 'tool' for comparing commercial ingredient sources. Ingredient NE values must be proven to be in agreement with pig growth if they are to be credible.

The Hanor application of the growth assay, referred to as the Snyder growth assay, is methodology disclosed to the lead author nearly 40 years ago. Drs. Wes Snyder and Larry DeGoey of Ralston Purina developed and used this technique extensively. Corn is used as the standard or known NE ingredient. It is chemically analyzed for CP, fat, starch and ADF. Starch digestibility and protein solubility are also confirmed prior to computing NE (NRC, 2012). Corn particle size is in the order of 525 to 625 microns so a particle size adjustment to NE is not made.

We expect the growth assay estimate for SBM NE to be in agreement with reliable academic estimates <u>unless</u> immune stress or other stressors become a factor. This is a significant elevating factor to maintenance energy need (Demas et al., 2011).

The ultimate application of pig growth assay is to prove that total diet NE describes the variation in gain and FCE 'well enough'. There is a public example of this from the Schinckel lab, in collaboration with PIC USA (Schinckel et al., 2012). Their test was extensive, involving 4472 pigs represented by 4 sire lines, both sexes and 2 marketing weights. Two diet types with computed NE and ME were fed (low and high energy). The study showed that diet NE accounted for more variation in growth response than ME. It also showed that diet NE value was not correct for one or more ingredients (e.g., wheat midds). The SBM NE value that was used for formulation was ≥7% too low (similar to NRC, 2012), based on Stein lab estimates.

SBM NE believed to increase as SBM CP increases

The NE of SBM is believed to increase in direct proportion to increasing SBM CP content (44 to 48% CP interval). Algorithms used by 2 international composition tables (Rostagno et al., 2017; CVB, 2016) and a prominent nutrition firm project that SBM NE increases by 20-24 kcal NE/kg DM for each 1.0% increase in SBM CP. We derived and published NE estimates for SBM over the 44 to 48% CP range. They are presented on a DM basis in **Table 1** and represent suggested minimum NE values for SBM in relation to SBM CP content (Pope et al., 2023).

The estimates were derived in collaboration with a private sector nutrition partner and compared to Hanor growth assay information. They used their prediction equation for NE; being developed and calibrated by pig growth assay using FCE as the criterion. NE estimates were generated for each SBM CP level with model input held constant for selected components (i.e. moisture, fat, NDF, ADF, ash, protein digestibility). The Hanor and Stein lab data were comparable but limited to a narrow range of SBM CP. The resulting NE regression of estimates was linear over the 44.0 to 48.0% interval (**Table 1**). In addition, interval increases in SBM NE for each 1.0% increase in SBM CP level were relatively similar to increases observed for regressed Brazilian and CVB data.

Compared to 48.0% CP SBM as the reference point, 44.0% CP SBM is expected to contain about 4.0% less NE for growing pigs. The caloric advantage associated with increasing SBM CP may seem counter-intuitive, but it depends on the component being displaced by CP. SBM NE would increase if CP displaced complex carbohydrates that have low DE value, in contrast to displacement of simple sugars. In general, global SBM sources with higher CP have higher NE than lower CP levels (DM basis) notwithstanding variations in oil, fiber etc. (personal communication with Dr. Chad Pilcher).

The positive association between SBM CP level and SBM NE needs to be verified to help commercial nutritionists be more discriminating in applying NE specifications to the wide range of SBM CP sources encountered.

First observation that SBM 'NE' value is greater in commercial settings

The first observation that SBM NE value was greater for pigs in the commercial environment than for the academic setting occurred when conducting the growth assay commercial facilities at Hanor (barns retrofitted for research). The apparent NE estimate for the commercial environment

Table 1. Net energy estimates by SBM crude protein level (DM basis)

Item	SBM Crude Protein Content, %				
	44.0	45.0	46.0	47.0	48.0
Kcal NE/kg SBM DM	2401	2441	2474	2486	2501
NE ratio to 48.0 CP	0.960	0.976	0.989	0.994	1.000

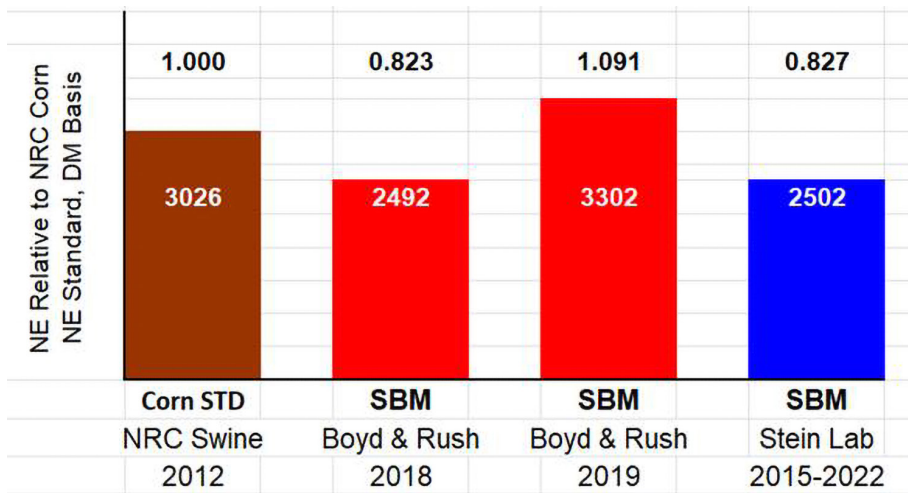[1] NE estimates adapted from publication by Pope et al., 2023

Figure 2. Growth assay estimates for SBM NE in the academic setting and commercial environment compared to Stein lab estimates

was unexpected, being more than 30% greater (3302 kcal NE/kg SBM DM) than our estimate from the academically similar facility (2492 kcal NE/kg SBM DM; Boyd and Rush, 2018). This magnitude of difference (**Figure 2**), combined with a lack of rationale for the result, caused us to categorize the study as flawed and it was indefinitely tabled (ca. 2012).

The commercial growth assay involved two barns, each capable of housing 1250 pigs in 25 pens. The site consisted of 8 barns that normally housed 10,000 pigs in total. Experimental pigs were derived from a sow farm that was PRRSv and mycoplasma pneumonia positive, but serologically stable. Pigs were healthy during the test with no clinical signs of either enteric or systemic disease. The growth assay involved 100 pens with 19 pigs each. Males and females were penned separately for the 28-d assay (80 to 145 lbs bodyweight). Response to increasing increments of SBM (exchanged for corn, amino acids) was similar for each sex (P > 0.15).

Results of the study were re-evaluated after recognizing that an apparent increase in SBM energy value might be due to functional compounds in SBM. We learned that increasing SBM levels of pigs beset with respiratory disease had significant improvements in caloric efficiency of gain (Boyd et al., 2010). It was not clear how much pathogen-induced inflammation and immune stress a population-dense commercial setting would impose. We become open to the energetic cost of inflammation and immune cell infrastructure (Humphrey and D'Amato, 2007; Demas et al., 2011) and potential for SBM to temper these stresses (Smith and Dilger, 2018; Smith et al., 2020; Petry et al., 2024).

We opened the 'flawed data file', analyzed and filed a report, which was our first observation that SBM NE was 'apparently' greater in the commercial setting (Boyd and Rush, 2019).

Confirmation that SBM 'apparent NE' is greater in commercial settings

We collaborated with swine nutritionists from the C.P. (Charoen Pokphand) group – China to study SBM energetics under commercial conditions (Dr. Gary Stoner, Sr. VP Nutrition and R&D). The Snyder growth assay was used in two studies, each involving more than 800 pigs, 4 SBM levels and 18-19 pigs/pen. The first study involved a 21-d test over the 104 to 148 lbs phase of growth, and the second involved a 42-d assay from 148 to 242 lbs body weight. Greater detail is provided in Boyd and Gaines (2023).

In both studies, FCE improved as dietary SBM level increased (**Figure 3 a, b**). SBM NE was estimated to be 3389 kcal/kg DM in the first experiment. In principle, diet FCE could not have improved unless SBM NE was greater than the corn it replaced, and FCE could not have improved at the rate shown (-0.0042 FCE units for each 1.0% SBM added) unless SBM NE was 3389 kcal/kg SBM. This is equivalent to 1.10 x the C.P. China corn NE on a DM basis.

Results for experiment 2 agreed, in principle, with results of the first assay. SBM NE computed to be 3031 kcal/kg DM, which is 0.983 x the C.P. corn NE on a DM basis. Both studies agreed with our original finding that SBM improves total diet NE use beyond that predicted by classic substrate energetics.

Since our original finding that realized NE from SBM in the commercial environment was confirmed by the C.P. China group, other public – private sector companies have disclosed similar results in principle. Chief among them is the collaboration of Kansas State University and JBS Foods – Pork Division, who conducted studies on 2 commercial research sites, involving more than 6000 nursery pigs (Cemin et al., 2020). It is noteworthy that the original observation of increased SBM NE value in the commercial setting was so repeatable: 5 studies in 4 locations by 3 groups on 2 continents.

These results have been replicated by other companies with commercial research facilities. The Maschhoffs recently reported a study to estimate the relative energy value of SBM to corn. They determined a value of 102% for growing pigs (90 to 150 lbs) and 105% for late finishing pigs (200 lbs to harvest). In both studies, caloric efficiency improved as SBM level increasingly replaced corn in the diet (2024, United Soybean Board Project No. 2311-107-0202). These estimates are likely underestimates because the corn reference was finely ground (240 microns using flow agent) with
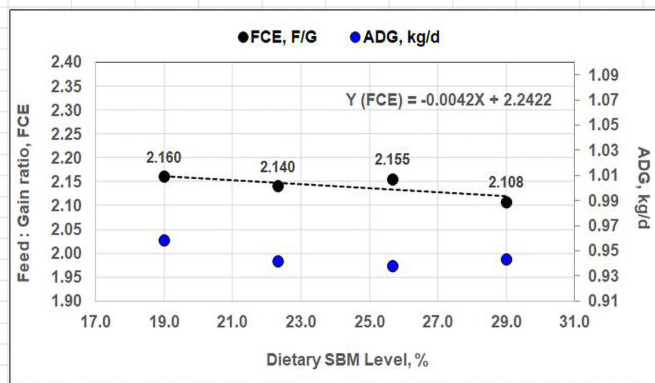
a.) Growth assay (21-d) over the 47 to 67 kg (104-148 lbs) phase of growth.

The C.P. corn NE standard was estimated to be 3084 kcal/kg DM; the SBM NE was computed to be 3389 kcal/kg DM. Growth rate (ADG) was not different (P = 0.786); FCE tended to respond linearly (P = 0.102). See Boyd and Gaines (2023) for detail.
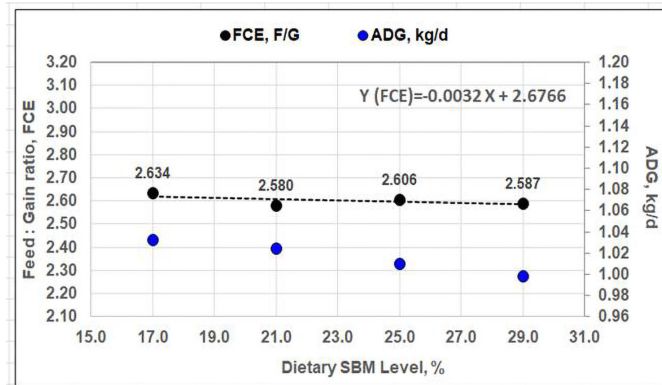
b.) Growth assay (42-d) over the 67 to 110 kg (148-242 lbs) phase of growth.

The corn NE as described for Figure 3a; the SBM NE was computed to be 3031 kcal/kg DM. Growth rate (ADG) and FCE were not different (P = 0.227, P = 0.388, respectively).

Figure 3. Feed conversion response to increasing replacement of corn with SBM in growing pig diets in a commercial environment using the Snyder growth assay (provided courtesy of Dr. Gary Stoner, Sr. VP Nutrition and R&D, C.P. [Charoen Pokphand] group – China).

diets fed in pellet form. The corn reference is normally in the range typically used for meal diets (525 to 625 microns).

Estimating the increase in total diet NE use for growth by SBM

We estimated that the increase in 'apparent SBM NE' not accounted for by classic substrate NE, is in the order of 810 kcal/kg SBM DM). This is based on the difference between the Hanor growth assay values for the two environments. This 32% increase in the apparent SBM NE estimate does not represent a difference in SBM NE estimates. The Stein lab IC estimate for SBM NE (2517 kcal/kg SBM DM) is based on classic substrate energetics. Applying the growth assay in the commercial setting was the means of detecting SBM influence on energetics that is not accounted for by classic ingredient NE. The incremental increase in total diet NE use for growth that is due to SBM has its basis in other physiological mechanisms (**Figure 4**).

The growth assay confirmed Stein lab estimates for SBM NE, where pathogen stress was not a complicating factor (Boyd and Rush, 2018). It was also the means of detecting SBM influence on dietary energetics that are not accounted for by classic ingredient NE.

We believe that this is the first example in animal nutrition where a feed ingredient has been shown to increase the total diet NE partition for a productive purpose (improved

efficiency of energy use). SBM has such an abundant and diverse set of health-improving compounds that are known to counter metabolic and immune stress challenges (anti-inflammatory, anti-oxidation, anti-viral, improve existing immune cell function; Petry et al., 2024).

Productive energy term applied to SBM

In view of the SBM-related increase in dietary NE use for growth in the commercial setting, that cannot be accounted for by classic energetic measures, we applied the term '*productive energy*' (PE, Boyd and Gaines, 2023).

This term is applied specifically to SBM to describe the realized NE deriving from it in the diet. PE is the sum of (1) classic substrate NE, and (2) total diet NE that is conserved
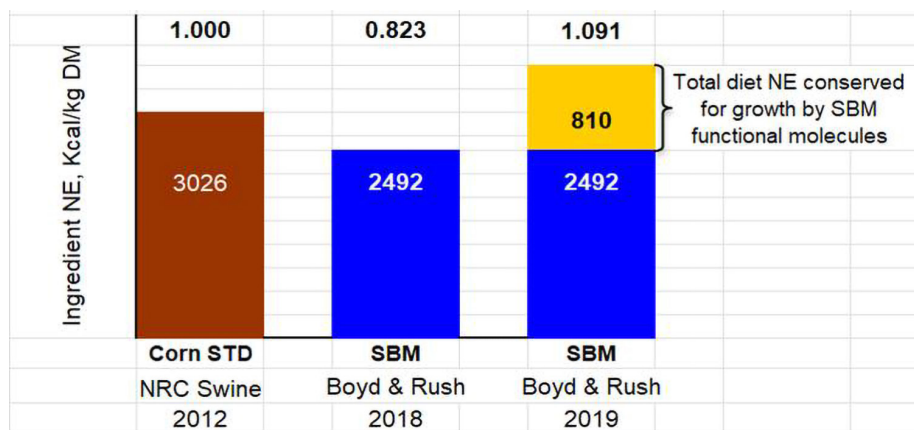

Figure 4. Illustration of the productive energy concept that emerged with SBM NE studies in the Commercial Environment (NE value is contained in each bar and is expressed on a DM basis). The SBM NE to NRC corn ratio is shown above each bar. The incremental increase in 'apparent SBM NE' was estimated as the difference between the academic-equivalent (2492 kcal/kg DM; Boyd and Rush, 2018) and commercial environment (3302 kcal/kg DM; Boyd and Rush, 2019); the difference being 810 kcal NE/kg DM.

from processes other than growth (**Figure 4**). In this sense, PE does not interfere with classic substrate NE. It quantitatively accounts for apparently conserved total diet NE that would have been diverted from growth; perhaps because of stressors in the commercial setting. This increment is 'significant' for SBM and must be taken into account when formulating commercial diets.

Where does SBM PE come from and is it fixed or variable?

Although it is possible that a difference in DE might be a factor, our hypothesis is based on how efficiently ME is used for growth (NEg). We propose that the apparent conservation of dietary NE for growth may arise by preventing expansion of maintenance energy (NEm); energy that would have been used for protective actions to counter stressors. Replacement of corn with SBM dramatically increases diet content of functional molecules that have the ability to thwart and suppress immune and metabolic stresses (Petry et al., 2024) given that stressors such as inflammation and building immune cells require significant NE.

Maintenance energy needs are known to increase with low sanitation (+10.2%, van der Meer et al., 2020) and to dramatically increase with significant inflammation (+39.8%, Huntley et al., 2018). Under these circumstances, less diet energy is available for growth (NEg). Huntley and coworkers (2018) illustrated this principle elegantly and quantitatively. Increased energy partition for protective immune response to inflammation (+30.2%) coincided with an 18.3% decrease in growth rate.

This illustrates that energy that is accounted to maintenance is not fixed. While NEm needs for pigs in a high health environment are relatively low and predictable (equation developed under controlled conditions; van der Meer et al., 2020), the NEm requirement in a commercial environment would be less predictable because of stressors (type, magnitude) that are not present in academic facilities (e.g. pathogens, biogases). The studies cited show that immune stress expands maintenance energy needs, proving that maintenance energy need is not static, thereby leaving less NE for gain (Huntley et al., 2018). We illustrated the concept of a dynamic NEm value in relation to SBM (**Figure 5**).

Finally, although the SBM NE is a fixed value based on substrate energetics, the SBM PE value is expected to vary with the commercial environment. A population-dense pig barn with no evidence of respiratory disease or concentrated biogases may have a lower SBM PE value than a barn where pigs have respiratory disease. A commercial barn in the winter that is closed to the cold typifies the latter. Open barns in the spring and fall months might exhibit a lower SBM PE benefit.

Integrating SBM PE specification into diet formulation format

Nutritionists in large systems are increasingly applying SBM PE when formulating commercial diets. The co-author conducted a survey of nutritionists from the Top 11 Pork Powerhouses (ca. 3 million sows) and learned that the SBM to corn energy value used by them in formulation ranges from 87 to 105% of corn NE, with an overall average of 97%.

It was interesting to learn that at least 5 of these companies have conducted internal growth assays to determine SBM PE value.

Principles to consider when integrating SBM PE into the formulation system:

• Apply the Stein lab SBM NE value (2502 kcal NE/kg DM; overall average) to university and academic similar controlled environments of low pen and building pig density and absence of clinical signs of respiratory disease.

• Apply the SBM PE as the NE specification for SBM (e.g., SBM PE = 100% corn NE value). The logical range for SBM PE is 95 to 100% of corn NE value (DM basis).

• Translate the PE and NE DM specification for SBM and corn to an as-fed moisture basis for the mill. Corn and SBM moisture content typically differ.
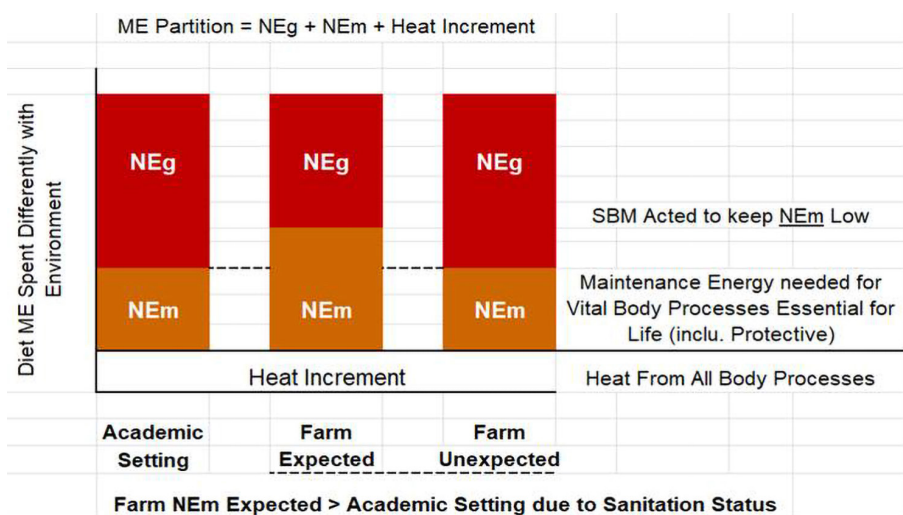

Figure 5. Illustration of dynamic maintenance energy need for environments differing in sanitation status. Proposed SBM mediation of Farm NEm. Academic setting expected to have NEm need unaffected by unsanitary influence. Farm environment expected to have greater NEm need due to lower sanitation (van der Meer et al., 2020). Less NE would be available for growth (NEg). Proposed that SBM mediates a lower than expected NEm (unexpected) given observed increase in NE for growth. Digestion may be affected, but diet NE 'uplift' is large; suggesting that internal systems may present greatest opportunity (multitude of inefficient processes).

- If the formulation is based on SID Lysine then proceed to formulate.
- If the formulation is based on SID Lysine:NE specifications utilizing the PIC Lysine curve then see the New PIC tool (published July 2024). Tool translates/corrects the SID Lysine:NE specification based on the SBM PE to Corn NE chosen.
- The point is to maintain the SID Lysine curve but to recalculate the SID Lysine:NE specification assuming test diets used the SBM PE value, thus preventing the Lysine curve from elevating.

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Soybean Meal or Crystalline Amino Acids in Diets for Growing Pigs: Impact on Diet Net Energy, Pig Growth Performance, and Nitrogen Retention

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Summary

The net energy of soybean meal has been estimated directly or indirectly in a number of recent experiments in the United States and other countries. In all experiments, without exception, it has been concluded that soybean meal contains more net energy than currently indicated in official feed ingredient tables. The reason for the greater net energy in soybean meal compared with current book values is likely that the digestible energy in soybean meal is underestimated in feed ingredient tables and the retention of nitrogen in modern genotypes of pigs is greater than in older genotypes, which results in a greater net energy of the protein fraction in soybean meal. As a consequence, a net energy value of soybean meal of at least 90% and maybe 100% of the net energy of corn can be assumed, which means that there is no measurable increase in net energy of diets if soybean meal is replaced by corn and crystalline amino acids.

Introduction

The use of crystalline amino acids (**AA**) in diets for pigs has gradually increased over the last few decades due to the availability of more AA at competitive prices. Because soybean meal (**SBM**) is the most commonly used source of AA in diets for pigs in the United States, the increased use of crystalline AA has reduced the need for inclusion of SBM in diets. Indeed, as a common grower diet is formulated with none, 3, 4, or 5 crystalline AA, the inclusion rate of SBM in a grower diet is reduced from 34.5 to 18.75% (Table 1). In terms of growth performance, protein deposition, and carcass quality, it has generally been considered of no consequence if the AA were furnished by SBM or by other sources of AA as long as requirements for digestible AA were met. However, use of crystalline AA instead of SBM usually reduces diet crude protein concentration, and therefore also reduces nitrogen excretion, and it has been generally accepted that lower protein diets are beneficial for intestinal health and also contain more net energy (**NE**) than diets based on only corn and SBM. However, some of these assumptions are not based on strong scientific evidence, and results of recent research have left doubts about

some of the previously assumed effects of using crystalline AA instead of SBM in diets for pigs.

The NE of SBM and other ingredients are usually calculated using prediction equations based on digestible nutrients in the ingredient or based on the concentration digestible energy (**DE**) corrected for nutrient concentrations (Noblet et al., 1994; NRC, 2012). In these prediction equations it is assumed that the NE value of crude protein is much lower than the energy value of starch and ingredients high in crude protein, therefore, have lower calculated NE than ingredients high in starch. As a consequence, the NE of SBM is assumed to be much lower than the NE of corn but results of recent research in the United States and other countries have failed to verify that the NE of SBM is much lower than in corn.

There is, therefore, a need for reviewing the assumptions that SBM in diets for growing pigs can be reduced without negative consequences for growth performance and protein retention and that NE in low-SBM diets is greater than in diets based only on corn and SBM. It is the objective of the current contribution to review and discuss results of some recent experiments conducted at the University of Il-

Table 1. Influence of crystalline AA on diet concentration of soybean meal in a typical diet for growing pigs

Item	Dietary protein, %			
	20.0	16.4	15.4	13.4
Ingredient, %				
Ground corn	60.40	70.27	71.40	75.11
Soybean meal	**34.50**	**24.00**	**22.80**	**18.75**
Soybean oil	2.50	2.50	2.50	2.50
L-Lys-HCl	-	0.32	0.35	0.47
DL-Met	-	0.08	0.09	0.12
L-Thr	-	0.08	0.10	0.15
L-Trp	-	-	0.01	0.03
L-Val	-	-	-	0.07
Vitamins, minerals	2.60	2.75	2.75	2.80
Analyzed nutrient, %				
Dry matter	88.49	89.73	88.16	88.55
Crude protein	20.02	16.36	15.38	13.40
Gross energy	3,976	3,936	3,924	3,963
Indispensable amino acids				
Arg	1.25	0.94	0.98	0.93
His	0.50	0.40	0.41	0.39
Ile	0.85	0.69	0.69	0.65
Leu	1.58	1.35	1.39	1.32
Lys	1.07	1.09	1.08	1.11
Met	0.28	0.28	0.31	0.36
Phe	0.95	0.77	0.79	0.75
Thr	0.70	0.63	0.67	0.64
Trp	0.34	0.23	0.26	0.25
Val	0.92	0.75	0.75	0.80

Table 2. Growth performance and carcass characteristics of pigs fed diets containing different levels of crude protein[1]

Item	High-protein	Medium-protein	Low-protein	SEM	P-value
Initial weight, kg	9.67	9.61	9.64	-	-
Final weight, kg	138.49	140.07	137.77	2.02	0.920
Average daily feed intake, kg	2.49	2.49	2.47	0.05	0.715
Average daily gain, kg	0.97	0.98	0.96	0.01	0.929
Gain:Feed	0.39	0.39	0.39	0.01	0.567
Fat thickness, cm	2.29	2.86	2.76	0.338	0.075
Loin eye area, cm^2	60.27	58.05	53.65	0.015	0.058

[1]Diets were fed in a 5-phase sequence from approximately 10 to 138 kg. Within each phase, high protein diets were formulated without crystalline AA, medium protein diets were formulated with crystalline lysine, methionine, and threonine, and the low protein diets were formulated with crystalline lysine, methionine, threonine, tryptophan, and valine.

linois to determine the impact of reducing SBM in diets for growing pigs.

Impact of dietary soybean meal and crystalline amino acids on growth performance and nitrogen retention

In two recent experiments, growth performance and nitrogen balance of pigs fed diets with different levels of crude protein and crystalline AA were determined to test the hypothesis that reducing diet concentration of SBM has no negative impact on growth performance or nitrogen balance as long as diets are fortified with crystalline AA to meet minimum requirements for digestible AA. In Exp. 1, three dietary sequences were fed to pigs from around 10 kg to market weight at around 138 kg. There were five dietary phases from 10 to 25 kg, 25 to 50 kg, 50 to 75 kg, 75 to 100 kg, and from 100 to 138 kg. Within each phase, all diets were formulated as high-, medium-, or low-protein diets, but all diets within the same phase met the same minimum requirements for standardized ileal digestible AA (NRC, 2012). Within each phase, diets were formulated either without crystalline AA, with 3 crystalline AA (i.e., Lys, Met, and Thr), or with 5 crystalline AA (i.e., Lys, Met, Thr, Trp, and Val). As the concentration of crystalline AA was increased, the concentration of SBM in the diets was reduced. As an example, in diets fed from 25 to 50 kg, SBM was included in the diets at 32.75, 22.40, or 16.00% to yield diets containing 20.0, 16.0, or 14.0% crude protein, respectively.

Results demonstrated that there were no differences among treatments in overall growth performance from 10 to 138 kg (Table 2). Likewise, there were no differences in loin quality traits, belly quality, or backfat color. There was, however, a tendency ($P < 0.10$) for a reduction in loin eye area and there was also a tendency ($P < 0.10$) for an increase in back fat thickness as dietary crude protein was reduced. The tendency for a reduced loin eye area indicates that pigs fed the low-protein sequence of diets, while being able to maintain growth performance, were not able to maintain the same protein synthesis as pigs fed the diet sequence with greater protein concentration. A follow-up experiment was, therefore, conducted to test the hypothesis that pigs fed low protein diets have reduced nitrogen retention compared with pigs fed diets with greater protein intake even if diets are balanced for digestible AA. The same diets as used in phase 1 of the growth performance experiment were used in the nitrogen retention experiment and pigs had an initial body weight of 17.75 kg when they were placed in metabolism crates and fed experimental diets for 12 days with urine and feces being collected for 4 days after a 7-day adaptation period. Results of this experiment indicated that although nitrogen retention as a per-

centage of nitrogen intake increased ($P < 0.001$) as dietary crude protein was reduced, the total daily nitrogen retention calculated as gram per day was reduced (linear, $P < 0.001$) as the protein level was reduced (Table 3). It is likely that it is the reduced daily nitrogen retention that is the reason for the reduced loin eye area that was observed in the growth performance experiment. Thus, results of both experiments indicated that even when diets are carefully formulated to meet the same concentrations of digestible indispensable AA, protein synthesis is not always maintained in the low-protein diets.

Table 3. Nitrogen balance of pigs fed diets containing different levels of crude protein[1]

Item	High-protein	Medium-protein	Low-protein	SEM	P-value
Feed intake, kg/d	1.00	0.99	1.03	-	-
N intake, g/d	36.68a	29.53b	27.36c	0.64	<0.001
N excretion in feces, g/d	4.06a	3.48ab	3.14b	0.43	<0.001
N excretion in urine, g/d	8.39a	4.33b	2.96b	0.48	<0.001
Absorbed N, g/d	32.60a	26.06b	24.25bc	0.54	<0.001
Retained N, g/d	24.11a	21.81ab	21.19b	0.69	<0.001
ATTD of N, %	88.89	88.24	88.46	1.30	0.606
N retention, % intake	66.03b	73.56a	77.64a	2.31	<0.001
N retention, % absorbed	74.16b	83.32a	87.76a	1.74	<0.001

[1]Diets were fed to pigs with an initial body weight of 17.5 kg. High protein diets were formulated without crystalline AA, medium protein diets were formulated with crystalline lysine, methionine, and threonine, and the low protein diets were formulated with crystalline lysine, methionine, threonine, tryptophan, and valine.

To further investigate the impact of reducing dietary crude protein and SBM on growth performance, carcass composition, and nitrogen balance, two additional experiments were conducted. The same diets were used in both experiments. A control diet was formulated based on corn and SBM without any crystalline AA. This diet met all nutrient requirements for growing pigs (NRC, 2012). Three additional diets were formulated by reducing the inclusion rate of SBM and adding 3 crystalline AA (i.e., Lys, Met, Thr); 4 crystalline AA (i.e., Lys, Met, Thr, Trp); or 5 crystalline AA (i.e., Lys, Met, Thr, Trp, Val) to the diet. Concentrations of standardized ileal digestible indispensable AA were at or above requirements (NRC, 2012) in all diets, but the concentration of crude protein was reduced from 20.0% to 16.4, 15.4, and 13.4%, respectively, by including 3, 4, or 5 crystalline AA in the diets. In the growth performance experiment, 176 growing pigs (initial body weight: 32.2 ± 4.2 kg) were used. On d 1, 16 pigs were randomly chosen and euthanized and the composition of nutrients and energy in the body of these pigs was determined. The remaining 160 pigs were allotted to the four diets using a randomized complete block design. There were 4 pigs per pen (2 gilts and 2 barrows) and 10 replicate pens per diet. Diets were provided to pigs on an *ad libitum* basis for 28 d. At the conclusion of the experiment, one pig in each pen that had a BW that was closest to the pen average was slaughtered after an overnight fast. To determine body composition, the pig body was partitioned into three parts (i.e., carcass, blood, and viscera). The weight of each part was recorded and samples from each part were then analyzed for fat and nitrogen. By subtracting the concentration of nutrients in the 16 pigs that were sacrificed at the beginning of the experiment from the weight of each nutrient in the pigs sacrificed at the end of the experiment, body retention of lipid and nitrogen during the experimental period was calculated. Results indicated that average daily gain and average daily feed intake were not affected by dietary treatments, which resulted in no differences in gain to feed ratio (Table 4). Retained protein, lipid,

Table 4. Growth performance and deposition of protein, fat, and energy in growing pigs[1,2]

| Item | Dietary protein, % | | | | SEM | Contrast P-value | |
	20.0	16.4	15.4	13.4		Linear	Quadratic
Initial BW, kg (on d 1)	32.17	32.29	32.20	32.18	-	-	-
Final BW, kg (on d 29)	61.31	60.64	60.62	61.70	2.20	0.908	0.378
ADG, kg/d	1.04	1.01	1.02	1.06	0.04	0.912	0.339
ADFI, kg/d	2.12	2.21	2.15	2.23	0.07	0.133	0.914
G:F	0.493	0.460	0.473	0.474	0.014	0.296	0.275
Protein deposition, g/d	125.85	119.56	123.27	114.11	9.96	0.259	0.722
Lipid deposition, g/d	137.29	138.13	121.86	123.06	15.09	0.224	0.748
Energy deposition, Mcal/d	1.95	2.04	1.88	1.75	0.17	0.146	0.113
Energy intake, Mcal/d	8.41	8.68	8.42	8.85	0.29	0.184	0.609
Energy efficiency for growth[3], %	22.78	23.39	22.26	19.57	1.54	0.088	0.083
Blood urea N, mg/dL	16.10	10.30	8.10	5.00	0.93	< 0.001	0.886
Bacteria protein in colon, μg/g	963.14	817.07	868.43	710.05	74.30	0.030	0.700

[1]Data are least square means of 10 observations for all treatments.
[2]The diet with 20.0% crude protein was based on corn and soybean meal and no crystalline AA, but in diets contianing 16.4, 15.4, or 13.4% crude protein, the inclusion of soybean meal was reduced and lysine, methionine, and threonine; lysine, methionine, threonine, and tryptophan; or lysine, methionine, threonine, tryptophan, and valine were included to maintain equal concentrations of digestible indispensable AA.
[3]Energy efficiency for growth (%) was calculated by dividing energy deposition by energy intake and multiplying by 100.

Table 5. Nitrogen balance, apparent total tract digestibility (ATTD) of energy, and concentrations of energy in experimental diets fed to growing pigs, as-fed basis[1,2]

Item	Dietary protein, %				SEM	Contrast P-value	
	20.0	16.4	15.4	13.4		Linear	Quadratic
Intake							
Feed, kg/d	1.07	1.07	1.08	1.11	0.04	0.375	0.523
N, g/d	34.39	28.13	26.65	23.70	0.93	< 0.001	0.622
Nitrogen excretion							
Fecal nitrogen, g/d	4.57	3.79	4.23	4.23	0.22	0.241	0.082
Urine nitrogen, g/d	6.76	4.04	3.46	1.93	0.47	< 0.001	0.999
N balance							
N absorbed, g/d	29.83	24.33	22.43	19.47	0.88	< 0.001	0.895
N retained, g/d	23.06	20.30	18.96	17.54	0.59	< 0.001	0.892
N retention, % intake	67.09	72.05	71.26	73.89	1.31	< 0.001	0.686
Biological value, % absorbed[3]	77.28	83.41	84.73	90.02	1.53	< 0.001	0.336

[1]Data are least square means of 10 observations for all treatments.
[2]The diet with 20.0% crude protein was based on corn and soybean meal and no crystalline AA, but in diets containing 16.4, 15.4, or 13.4% crude protein, the inclusion of soybean meal was reduced and lysine, methionine, and threonine; lysine, methionine, threonine, and tryptophan; or lysine, methionine, threonine, tryptophan, and valine were included to maintain equal concentrations of digestible indispensable AA.
[3]Biological value was calculated by dividing nitrogen retained (g/d) by nitrogen absorbed (g/d) and multiplying by 100.

and energy were also not significantly affected by dietary treatment, but energy efficiency tended to decrease (quadratic, $P < 0.10$) as dietary protein was reduced. In the nitrogen balance experiment using the same four diets as in the growth performance experiment, 40 growing pigs (initial body weight: 20.5 ± 2.4 kg) were allotted to a randomized complete block design with four diets and 10 replicate pigs per diet for a total of 10 replicate pigs per diet. Pigs were housed individually in metabolism crates and fecal and urine samples were collected quantitatively for 5 days after 7 days of adaptation. Results indicated that daily nitrogen intake was reduced (linear, $P < 0.001$), and daily nitrogen in feces tended (quadratic, $P < 0.10$) to be reduced as dietary protein was reduced (Table 5). Daily nitrogen excretion in urine was also reduced (linear, $P < 0.001$) as dietary protein decreased. However, although nitrogen retention calculated as percentage of intake increased (linear, $P < 0.001$), absorbed nitrogen and retained nitrogen calculated as gram per day were reduced (linear, $P < 0.001$) as dietary protein decreased.

Combined, results of the above four experiments indicate that although growth performance can be maintained in diets based on corn, crystalline AA, and reduced levels of SBM, nitrogen retention, and therefore, protein synthesis appears to be compromised, which will result in reduced carcass leanness. These observations are in agreement with results by Kerr and Easter (1995) and Le Belego and Noblet (2002) who also observed reduced nitrogen retention of pigs fed diets with reduced concentrations of SBM. Likewise, reduced carcass leanness was also observed as dietary crude protein was reduced although growth performance was not changed (Kerr et al., 1995).

Theoretical and actual impact on net energy of using crystalline amino acids instead of soybean meal

According to current book values, the NE of soybean meal is much less than that of corn. As an example, on a dry matter basis, the NE of corn is 3,026 kcal/kg and the NE of soybean meal is 2,319 kcal/kg (NRC, 2012). The reason for this difference primarily is that the equation used to calculate NE assumes a large negative effect of crude protein on NE (Noblet et al., 1994; NRC, 2012). Indeed, the gross energy and the DE is greater in SBM than in corn (NRC, 2012), but because of the assumed negative effect of crude protein on NE, the calculated NE is only 77% of the NE of corn (Table 6). As illustrated in Table 1, the inclusion of corn will increase as dietary SBM is reduced, and concentrations of crystalline AA are increased in a diet. As a consequence of the assumed difference in NE between corn and SBM, the theoretical NE of a diet will increase if SBM is reduced, and the inclusion of corn is increased. However, in several recent experiments, the NE of SBM was greater than the value estimated by NRC (2012) and NE values ranging from 82 to 125% of the NE of corn have been reported (Li et al., 2017; Cemin et al., 2020; Lee et al., 2021). If those values are correct, it would be assumed that the theoretical increase in NE obtained by increasing corn and reducing SBM in a

Table 6. Comparison of gross energy, digestible energy, metabolizable energy, and net energy in corn and soybean meal, kcal/kg dry matter [1]

Item	Corn	Soybean meal
Gross energy	4,454	4,730
Digestible energy	3,908	4,022
Metabolizable energy	3,844	3,661
Net energy	3,026	2,319

[1] All values calculated from NRC (2012).

diet because of inclusion of crystalline AA may not be realized in practical diets. An experiment was, therefore, conducted to test the hypothesis that the negative effect on diet NE of using SBM in diets is less than calculated from current NRC (2012) values. A diet based on corn, SBM, and L-Lysine was formulated and 5 additional diets in which the concentration of SBM was gradually reduced and inclusion of crystalline AA was increased were also formulated. All diets were formulated to meet the AA requirement for pigs from 30 to 115 kg. The concentration of corn increased from 69.3 to 85.4% and the concentration of SBM was reduced from 27.0 to 9.4% as the inclusion of crystalline AA increased. Diets were fed to group housed and ad libitum fed pigs housed in calorimeter chambers and the concentration of NE was determined for each diet. Results indicated that there were no differences among diets in NE (Table 7) and the hypothesis that the NE of SBM is greater than previously thought was, therefore, confirmed. Indeed, because NE did not change as dietary corn increased and SBM was reduced, results indicated that the NE of SBM may be close to the NE of corn. It was also noted that the observed NE of all diets, regardless of the level of SBM in the diet, was greater than the calculated values, further indicating that SBM may contribute more NE to diets than calculated from current book values. This last observation is also in agreement with results of other recent experiments (Ochoa et al., 2024; Lee et al., 2024).

In the experiment referenced in Table 4, where four diets containing 20.0, 16.4, 15.4, or 13.4% crude protein were formulated by reducing SBM from 34.5 to 24.0, 22.8, or 18.8% and increasing corn and crystalline AA, the NE of each diet was also calculated using the comparative slaughter procedure. Results of this calculation demonstrated that NE of diets did not increase as the concentration of SBM was reduced and the determined NE of the diet based on corn and SBM and no crystalline AA was greater than the NE calculated from NRC (2012), which was also observed in the previous experiment (Cristobal et al., 2024a). Results of the second experiment, therefore, confirmed that the NE of SBM likely is close to the NE of corn when fed to group housed pigs allowed ad libitum intake of feed. These results are also in agreement with recent data from Ochoa et al. (2024) who also reported that the NE of a diet based on corn and SBM is greater than the value calculated from a theoretical prediction equation that assumes a large negative effect of diet crude protein on NE.

Table 7. Effects of dietary crude protein and reducing soybean meal and protein on calculated and measured concentrations of net energy in diets and measured total heat production and fasting heat production from group-housed pigs

Item	Dietary crude protein, % :	16.4	14.6	12.7	11.6	10.6	9.6	SEM
	Soybean meal, %:	27.0	19.1	16.7	14.2	11.8	9.3	
Energy in diets, kcal/kg								
Calculated net energy		2,500	2,546	2,561	2,575	2,588	2,600	-
Measured net energy[1]		2,646	2,605	2,663	2,631	2,665	2,634	47
Heat production, kcal/kg body weight$^{0.6}$ per day								
Total heat production[1]		384	375	378	376	390	377	20
Fasting heat production[1]		223	220	235	218	238	221	17

[1]There were no differences among diets on measured net energy, total heat production, or fasting heat production.

Reasons for increased net energy in soybean meal

There are two main reasons why SBM contains more NE than calculated from previously developed prediction equations. The first reason is that the digestible energy in SBM is greater than estimated in current book values. As an example, in an average of 22 sources of SBM, the DE was 239 kcal greater than NRC (2012), which was in agreement with results of previous experiments conducted at the University of Illinois (Sotak-Peper et al., 2015). A greater DE in SBM also results in a greater NE value and an increase in DE of 239 kcal per kg corresponds to an increase in calculated NE of approximately 170 kcal per kg.

The second reason for increased NE in SBM is that modern genotypes of pigs are more efficient in retaining nitrogen in the body than older genotypes. Indeed, one of the reasons for the assumed negative impact of diet crude protein on NE is that it has been assumed that growing pigs only retain between 45 and 50% of absorbed nitrogen in the body (Noblet et al., 2004). This estimate corresponds to a retention of 40 to 45% of consumed nitrogen and is in agreement with data published in the 1970's and 1980's (Gatel and Grosjean, 1992). However, as pig genetic companies have placed more emphasis on selection based on lean deposition, pigs have become more efficient in retaining nitrogen in the body, and later data indicated that pigs were able to retain between 50 and 60% of consumed nitrogen (Kerr and Easter, 1995; Otto et al., 2003). Recently, data from nitrogen balance experiments in which modern genotypes of pigs fed a corn-soybean meal-based diet without crystalline AA were used, pigs retained between 60 and 70% of consumed nitrogen (Corassa et al., 2024; Ochoa et al., 2024; Cristobal et al., 2024b). Thus, the genetics of pigs have become much more efficient in utilizing dietary nitrogen for protein synthesis and the quantities of AA that need to be deaminated with a subsequent excretion of nitrogen via the urea cycle is, therefore, less in modern genotypes of pigs than in older genotypes. Because deamination of AA and excretion of nitrogen are energy requiring processes, the theoretical energy contribution from dietary protein increases as nitrogen retention increases. As an example, if nitrogen retention increases from 45 to 70% of nitrogen intake, the NE of soy-

bean meal will increase by approximately 165 kcal per kg. It is, therefore, likely that the increased nitrogen retention that is observed in modern genotypes of pigs contributes to the increased NE of SBM that has been consistently observed in experiments conducted in recent years.

If it is assumed that the increased DE of SBM results in an increased NE of 170 kcal per kg compared with current book values and that the greater capacity for nitrogen retention contributes and additional 165 kcal per kg, the increased NE of SBM due to these two factors is 335 kcal NE per kg. If this value is added to the current estimate for NE in SBM (i.e., 2,319 kcal per kg dry matter; Table 6), a NE of 2,654 kcal per kg dry matter is obtained, which corresponds to around 88% of the NE in corn. This value is in reasonable agreement with some recent estimates for NE in SBM (i.e., Li et al. 2017; Lee et al., 2021) and is also in agreement with observations that the NE of a corn-SBM diet is close to 100 kcal per kg greater than calculated (Ochoa et al., 2024; Lee et al., 2024). It is, however, noted that NE values estimated from the gain to feed ratio obtained in growth assays usually give greater estimates for NE in SBM (Cemin et al., 2020). The reason for this discrepancy is not completely clear but may be related to changes in body composition and body energy concentration that is not realized by simply determining gain to feed ratio of a group of growing pigs.

Conclusions

Results of numerous experiments conducted in recent years have demonstrated that the NE of SBM is greater than current book values. It is likely that this is a result of a greater concentration of DE in SBM than previously thought as well as a greater energy value of the protein fraction in SBM due to the greater nitrogen retention in modern genotypes of pigs compared with older genotypes. In experiments conducted to determine NE in SBM or in corn-SBM diets using indirect calorimetry or the comparative slaughter procedure, NE values for SBM between 90 and 100% of corn have been obtained, which is reasonably close to theoretical calculations of NE in SBM fed to modern genotypes of pigs. However, in a number of experiments conducted to calculate NE in SBM from the gain to feed ratio of pigs used in growth assays, the NE of SBM has been estimated to be between 100 and 125% of corn. Whereas these latter values may overestimate the NE of SBM because changes in body composition are not included in the estimates, it should be noted that in all experiments conducted to determine NE of SBM or in corn-SBM based diets, a greater NE than current book values has been obtained. Because no values less than current book values have been reported, it is unlikely that the values reported from recent experiments are due to normal random variations around a common mean value.

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Notes

Notes

Notes

Number of Years of Sponsorship from 2001 to 2024

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