25th Annual Midwest Swine Nutrition Conference Proceedings

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Midwest Swine Nutrition Conference

Schedule of Presentations

8:15	Registration and Check-in
9:00	Welcome. Dennis Liptrap, Chairman of Planning Committee
9:05	What Matters Most to U.S. Pig Farmers. *Alex Wibholm, National Pork Board*
9:50	Let's Talk Sows: Amino Acid Considerations for Fetuses and Milk Production. *Le-Anne Huber, University of Guelph*
10:30	Break
11:00	Impact of Microbial Phytase on Plasma Inositol in Weanling pigs. *Hans Stein, University of Illinois Urbana-Champaign*
11:30	The Trade-offs of Zinc Supplementation in Swine Diets for Productivity, Environmental Sustainability, and One Health. *Jinsu Hong, Purdue University*
12:00	Lunch
1:10	Late-Gestation Nutrition in Prolific Sows: An Opportunity to Improve Farrowing Performance, Sow Retention, and Pig Development. *Eric Weaver, South Dakota State University*
1:55	Nutritional and Environmental Enrichment Strategies to Mitigate Aggression in Late-gestation Sows. *Jay Johnson, University of Missouri*
2:25	Break
2:50	The True Cost of Mortality: Quantifying Economic Losses and Management Opportunities in Swine Production. Josh Flohr, Kansas State University
3:20	Wrap-up and Adjourn

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What Matters Most to U.S. Pig Farmers

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Abstract

The U.S. swine industry relies on multiple factors for stability and success, including consumer demand for pork, the health of the swine herd, and people and passion that will drive the industry forward for generations to come. The Pork Checkoff is committed to delivering progress by focusing on three core goals: 1) building long-term value for U.S. pork; 2) improving the health of pigs and people, and 3) creating a stronger, more resilient U.S. pork industry through collaboration with state pork associations and producers. Research and insights are driving NPB's approach to these goals, what the industry can expect in the future, and how producers and stakeholders can be a part of the effort.

About Pork Checkoff

The U.S. pork industry has had a 100% legislative Checkoff program since 1986. Congress created the Pork Checkoff as part of the Pork Promotion, Research and Consumer Information Act of 1985. The 15 appointed members of the National Pork Board (NPB) and the Pork Checkoff staff are responsible for the collection, distribution and program accountability of the Pork Checkoff. NPB executes specific programs in the areas of promotion, research and education. No funds may be used for lobbying or to influence government policy.

Pork Checkoff Priorities

The National Pork Board's Board of Directors approved a bold three-year strategic plan as part of a broader roadmap to guide the organization through 2028. Kicking off in August 2024, the strategic planning process gathered insights from a wide range of producers and industry stakeholders. The path forward is grounded in strategic initiatives to elevate pork's position, presence and consumer appeal:

Goal 1: Drive and increase the long-term value of pork.

-NPB is driving demand and increasing the value of pork by getting more people to choose pork more often. The **Taste What Pork Can Do®** consumer marketing campaign is unapologetic about pork and focuses on the whole hog as an investment to making pork relevant for the next generation.

Goal 2: *Create a stronger, more resilient U.S. pork industry through collaboration with state pork associations and producers.*

-State associations are the U.S. pork industry's boots on the ground, holding close relationships with producers and employees putting in the on-farm work every day. State pork associations serve as a direct link to the next generation of leaders and talent.

Goal 3: Improve the lives of pigs and people.

-NPB is developing a collaborative, producer-led National Swine Health Strategy (NSHS) to strengthen the health of the U.S. swine herd and industry. After gathering input from producers across the country through surveys and listening sessions, a NSHS advisory group of producers, veterinarians and industry stakeholders put forth swine health priorities and objectives for the whole industry to work toward together. The strategy focuses on two primary goals and corresponding objectives:

- Reduce the impact of domestic diseases
  - Eliminate PEDV in the U.S.
  - Eliminate PRRSV in the U.S.
  - Reduce disease spread
- Keep foreign and emerging diseases out
  - Foreign Animal Disease (FAD) prevention and preparedness
  - Monitoring and early detection of emerging diseases

The strategic plan was developed through a multistep, 18-month process led by producers to identify the most important areas for Checkoff dollars and resource investment. This process included input from a wide range of producers and industry stakeholders, producer-led taskforce defined goal and success definitions, and approval by the Board of Directors during the 2025 National Pork Industry Forum.

Driving the Long-Term Value of Pork

Through consumer research, NPB is meeting the consumer where they are and positioning pork to be part of their everyday experience.

The annual per capita consumption of meat is projected to increase by almost 2 pounds per person per year by 2034, and NPB-supported research shows more than 75% of consumers think it's important to meet their daily protein goals. Through NPB's Business Intelligence partnership with foodservice insights partner Datassential, the number of meat eaters increased by 17 percentage points between 2021 and 2024, a significant shift that far surpasses the other variations of dietary patterns. In fact, all other categories, including vegetarians, vegans and flexitarians, declined over the same period. This growth marks a major shift in consumer consumption and behavior. It also sets the stage for pork to meet the increased protein demand among consumers.

Building off meat's momentum, NPB is making a bold investment to build long-term domestic demand for pork through the Taste **What Pork Can Do®** consumer brand campaign. The digital-first campaign focuses on connecting with Gen Z and millennial consumers online and in-store, encouraging them to eat more pork, more often. After months of extensive consumer research, audience analysis and creative development, the campaign launched in May 2025 with audience specific content on channels where consumers already seek inspiration, including social media, streaming services, satellite radio advertisements and online display ads. Through the campaign, NPB is using pork to sell more pork and partnering with retailers, state pork associations and industry partners nationwide to bring the message to life about pork's taste and flavor, nutrition, versatility and convenience.

Improving the Health of Pigs and People

NPB, in collaboration with the National Pork Producers Council (NPPC) and other stakeholders, continues to make progress on the NSHS, a coordinated, science-based approach to protect and strengthen U.S. herd health. According to NPB's 2024 producer survey, 98% of producers believe herd health is important to the future success of the industry. The swine industry faces complex health challenges that require a collaborative approach across the industry. After gathering input from producers across the country through surveys and listening sessions, the NSHS advisory group of producers, veterinarians and industry stakeholders put forth swine health priorities and objectives for the whole industry to work toward together. The strategy focuses on two primary goals:

1. Reduce the impact of domestic diseases
   - Porcine Reproductive and Respiratory Syndrome Virus (PRRSV) Elimination
   - Porcine Epidemic Diarrhea Virus (PEDV) Elimination
   - Reduce the spread of pathogens in the U.S. Pork industry
2. Keep foreign and emerging diseases out
   - FAD prevention & preparedness
   - Monitoring and early detection of emerging diseases

The NSHS is informed by producers, for producers. The outcomes of the strategy will:x

- Foster collaborative efforts across organizations
- Guide future swine health initiatives
- Ensure Pork Checkoff funds are invested in producers' top priorities

Partnering With State Pork Associations

As the Taste **What Pork Can Do®** campaign continues to engage consumers nationwide, NPB is collaborating with state pork associations to expand its reach and drive local engagement. From TV programming to city barbecues and baseball games, state pork associations are helping bring taste and flavor to local markets. Led by local producers and staff members, the U.S. pork industry's state associations are dedicated to what's best for the state's industry. These organizations understand the unique challenges of producers in their state and serve as a vital link to the next generation of leaders that will carry the industry forward.

A More Resilient U.S. Pork Industry

NPB is working to ensure producers see strong returns and consumers see pork as their first choice. To elevate pork's position to be the protein of choice for consumers, NPB is leveraging the taste, and flavor pork offers that consumers value.

Passion is what drives NPB and can collectively drive the industry. The future of the U.S. pork industry is bright.

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Datassential, 2025 Trends Q: Which of the following best describes how you eat today? (n=585 Millennials & n=615 Millennials). Fielded June 2024 for the 2024 America in Transition Keynote Report & October 2021 for the 2021 America in Transition Keynote Report.

NPB Checkoff-Funded Research, Kynetec, Total U.S. — Survey, 2024.

Let's Talk Sows: Amino Acid Considerations for Fetuses and Milk Production

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Abstract

Above maintenance, factorial estimates of amino acid requirements for reproductive sows are based on protein retention in pregnancy-associated tissues and milk for the gestating and lactating sow, respectively, along with maternal growth for immature sows. Such factorial models can be scaled for the productivity level (e.g., litter size, piglet growth rate) of the sow, but may not account for the metabolism of the modern sow nor amino acid use for roles beyond protein retention. The purpose of this review is to discuss factors that should be considered when estimating amino acid requirements for sows in (late) gestation and lactation and the relative importance of Met for metabolic fates beyond protein synthesis. Overall, amino acid requirements should be re-evaluated and feeding programs in gestation and lactation should be dynamic to better meet the needs of the reproductive female.

Introduction

Protein retention in pregnancy-associated tissues and milk are the main drivers of amino acid requirements for the reproductive sow (NRC, 2012). Consequently, amino acid requirements are dynamic throughout the reproductive cycle, increasing in late gestation to account for exponential fetal and mammary development and increasing in lactation following the milk production curve. For young sows, maternal growth also contributes to net protein retention and should be considered in the context of future maintenance requirements, milk production potential, and stayability within the herd (Kloostra et al., 2025). Factorial models can be scaled based on the productivity level of the sow (e.g., litter size and growth rate) to accommodate genetic advancements, however, the apparent efficiency of using standardized ileal digestible (**SID**) amino acids for protein retention in pregnancy-associated tissues and milk are held constant within reproductive phase (NRC, 2012), despite mounting evidence that these efficiency values are also dynamic (e.g., Huber et al., 2015; Ramirez-Camba, 2020; Watzeck and Huber, 2024). Moreover, such factorial models only account for amino acid retention in proteins and do not consider amino acid partitioning toward energy production (i.e., preferential catabolism) or other non-protein fates that can draw a significant proportion of available amino acids (e.g., one-carbon metabolism in the case of Met; Robinson et al., 2016). Thus, the purpose of this review is to discuss factors that should be considered when estimating amino acid requirements for sows in (late) gestation and lactation and the relative importance of Met for metabolic fates beyond protein synthesis.

Amino acid considerations for sows in (late) gestation

Late gestation (i.e. beyond day 85) is a time of accelerated fetal growth and mammary development in preparation for parturition and the ensuing lactation period. Approximately 70% of total fetal weight gain happens during the last third of gestation (McPherson et al., 2004). Significant mammary development also occurs beyond day 90 of gestation, with the number of mammary cells increasing by 4.5X and the mass of mammary parenchymal tissue increasing by 3X between days 80 and 112 of gestation (Sørensen et al., 2002). Consequently, the estimated SID Lys requirements increase by 47% after day 85 (17 g SID Lys/day) versus prior to day 85 (11 g SID Lys/day) for gilts with a litter size of 16 piglets to accommodate exponential protein retention in the fetal and mammary pools (NRC, 2012).

Feeding amino acids or nitrogen below estimated requirements during late gestation most commonly results in reduced sow body weight gain with less consistent reductions in piglet birth weights (e.g., Johannsen et al., 2024), indicating that the sow is adept at buffering dietary inadequacies in order to preserve fetal growth. Using a titration study, however, it was found that feeding SID Lys 15% above the currently perceived requirement for late-gestating gilts beyond day 90 via the addition of soybean meal (22 vs 19 g SID Lys/day) maximized whole-body

nitrogen retention in late gestation and piglet birth weight (Kloostra et al., 2025). Therefore, nutrient requirement models, despite being scalable for modern genetics, may not adequately reflect amino acid requirements for late-gestating gilts.

Mammary development also appears sensitive to amino acid supply in late gestation, particularly toward increases in SID Lys (protein) intake. In the first of a series of studies, mammary development at the end of gestation in gilts was increased by 44% when SID Lys intake was increased 40% above estimated requirements between days 90 and 110 of gestation (26 vs 19 g SID Lys/day) via soybean meal (Farmer et al., 2022). Mammary development in multiparous sows, however, was not influenced by additional SID Lys (protein) intake (Farmer et al., 2023), likely attributed to sows having superior mammary parenchymal mass and greater epithelial proliferation at the end of gestation versus gilts (Farmer et al., 2024). In gilts, it was determined that subsequent milk production was also maximized when fed SID Lys 19% above the estimated requirement during late gestation via soybean meal (23 vs 19 g SID Lys/day; Kloostra et al., 2025). Conversely, feeding SID Lys below estimated requirements during late gestation (12 and 15 vs 18 g SID Lys/day) did not negatively impact mammary development by the end of gestation (Gillies et al., 2025). Thus, the gilt appears to maintain some level of obligatory mammary development when amino acid intake is inadequate in order to promote survival of the offspring after farrowing, as long as the deficiency is not too severe or too prolonged. Therefore, the amino acid feeding strategy employed during late gestation can have lasting impacts on sow performance and nutrient requirement models should consider subsequent lactation performance in late-gestation nutrient feeding recommendations.

Amino acid considerations for lactating sows

Lactation represents the single greatest metabolic burden on the sow. Historically, lactating sows have received controlled or *ad libitum* (or some combination thereof) access to a lactation diet with static nutrient composition, often leading to maternal protein and energy mobilization in order to support milk production. The sow, however, has dynamic feed intake and milk production during the lactation period, suggesting that a static diet composition may not be adequate to maximize lactation performance. It was recently shown that the (weekly) optimal SID Lys-to-net energy ratios for primiparous and multiparous sows were dynamic over the lactation period (Watzeck and Huber, 2024; Gregory and Huber, 2025a). For primiparous sows, the SID Lys-to-net energy ratios necessary to maximize maternal nitrogen retention were at least 5.51 g SID Lys/Mcal net energy in week one when feed intake was low (~3.82 kg/d on a dry matter basis; Gregory and Huber, 2025a). In weeks two and three, however, maternal nitrogen retention was maximized at 4.74 and 4.85 g SID Lys/Mcal net energy when feed intake had recovered (~ 5.62 and 6.40 kg/d on a dry matter basis in weeks two and three, respectively; Gregory and Huber, 2025a). It was interesting to note that in the aforementioned study, the primiparous sow was able to maintain milk nitrogen output, regardless of the dietary SID Lys-to-net energy ratio, such that the main response was for maternal nitrogen retention, which could have long-term implications for sow productivity and retention in the herd when the primiparous sow receives an inadequate SID Lys-to-net energy ratio.

In multiparous sows (average parity 3.1), milk nitrogen output was maximized at 4.28, 4.42, and 4.67 g SID Lys/Mcal net energy in weeks one, two, and three, respectively (Watzeck and Huber, 2024). In the multiparous sow, that is approaching or has achieved mature body (protein) size, both maternal nitrogen retention and milk nitrogen output were influenced by dietary SID Lys-to-net energy ratio (Watzeck and Huber, 2024). When a unique dynamic feeding program was developed to match estimated daily optimal SID Lys-to-net energy ratios for first- and second-parity sows, overall piglet average daily gain and piglet body weight at weaning were improved compared to sows that received a static diet composition (Gregory and Huber, 2025b). Therefore, a static diet composition during lactation is insufficient to maximize milk production of lactating sows, while primiparous sows would benefit from additional protein per unit energy intake, particularly in early lactation.

Non-protein uses of methionine in the reproductive sow

The empirical estimates of Met requirements in the gestating and lactating sow are few and extremely outdated (e.g., Ganguli et al., 1971; Holden et al., 1971). These estimates were used to inform current factorial nutrient requirement models (e.g., NRC, 2012) but may not reflect the metabolism of the modern sow and certainly do not consider SID Met use for fates beyond protein retention. Using a titration study in gestating gilts with whole-body nitrogen retention as the response variable, it was recently determined that the minimum SID Met requirements were 3.8, 4.2, 3.5, and 6.0 g/day between days 38 and 41, 53 and 56, 87 and 90, and 109 and 112 of gestation (Munoz Alfonso et al., 2025), which were relatively greater than the NRC- (2012) estimated requirements of 3.5 and 5.2 g SID Met/day before and after day 90 of gestation, respectively. Beyond protein retention, however, Met also plays a significant role as a methyl donor via S-adenosyl-methionine to generate over 50 different transmethylation products, including creatine and phosphatidylcholine (Brosnan et al., 2011). As a co-

product of transmethylation, homocysteine can either be remethylated to Met or undergo transsulfuration to irreversibly generate Cys (Finkelstein and Martin, 2000). In the neonatal piglet, it was observed that transmethylation consumed a significant proportion of available Met (Robinson et al., 2016), indicating that the dietary need for SID Met might be greater than that required to maximize protein retention. Using primed, continuous stable isotope infusions of [^{13}C]sodium bicarbonate and [1-^{13}C; $^{2}H_3$]Met however, it was determined that the whole-body partitioning of available Met toward transmethylation was preserved in late gestation when SID Met was supplied 50% below estimated requirements for late-gestating gilts, whereas whole-body protein synthesis was reduced when gilts were fed Met-deficient diets (Munoz Alfonso et al., unpublished). Interestingly, remethylation was only increased by 25% for gilts fed the Met-deficient versus Met-adequate diet, indicating that remethylation was insufficient to rescue Met availability for protein synthesis either due to substrate availability (e.g., methyl donors) or enzymatic capacity.

In the lactating primiparous sow, comparable patterns were observed whereby the estimated SID Met requirements to maximize total nitrogen retention (including milk) were similar to those estimated by the NRC- (2012) model in early lactation (days 5 to 9; 10.2 vs 10.9 g SID Met/day) but relatively greater than model-estimated values in peak lactation (days 17 to 21; 17.0 vs 15.0 g SID Met/day; Kozole et al., 2026). Using the same primed continuous infusions of [^{13}C]sodium bicarbonate and [1-^{13}C; $^{2}H_3$]Met in peak lactation, it was determined that even when SID Met was provided 20% below estimated peak-lactation requirements, the whole-body transsulfuration and transmethylation fluxes were preserved, despite transmethylation consuming 42% of whole-body methionine flux (Kozole et al., unpublished). In the aforementioned study, remethylation occurred very efficiently with 95% of homocysteine returning to Met (Kozole et al., unpublished). Therefore, for the gestating and lactating primiparous sow, providing SID Met to maximize nitrogen retention should also be sufficient to meet the whole-body non-protein Met needs for transmethylation. The supply of methyl donors, including folate and choline, however, should also be considered in the estimates of SID Met requirements.

Conclusions

The amino acid requirements of the reproductive sow are dynamic and in order to maximize amino acid utilization for protein retention during gestation and lactation, feeding programs should also dynamically supply amino acids. Specifically, a phase-feeding or top-dressing approach should be employed during gestation, especially for gilts, to maximize piglet birth weight and mammary development, to ultimately support maximum milk yield in the subsequent lactation period. During lactation, the lysine-to-net energy ratio should be altered uniquely for primiparous and multiparous sows in order to maximize milk nitrogen output and piglet growth. Finally, the non-protein uses of SID Met certainly consume a significant proportion of dietary supply, but it appears that both the gestating and lactating sow prioritize such Met fates, indicating that providing Met to maximize nitrogen retention is sufficient to also meet non-protein Met needs. Overall, feeding sows with static diets is not adequate to maximize reproductive performance, despite the fact that the sow is very good at buffering dietary deficiencies. Future research should work to redefine dietary amino acid requirements for both protein retention and non-protein fates, while also considering long-term performance and longevity implications for the reproductive sow.

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Impact of Microbial Phytase on Plasma Inositol in Weanling Pigs

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Abstract

Inositol is a ring-formed sugar that is needed for a number of physiological functions in the body including energy utilization, maintenance of the immune system, and integrity of cell membranes. Inositol can be synthesized by pigs from glucose and it has not been considered a limiting nutrient. However, results of recent research have demonstrated that pigs do not maintain pre-weaning levels of plasma inositol during the initial 4 to 6 weeks post-weaning and during this time, they may be immunologically compromised due to reduced plasma inositol. However, inositol is also present in phytate where it forms the ring-structure that chelates with up to 6 phosphate groups. Therefore, if phytase is added to diets, the ester bonds connecting the six phosphate groups to inositol will be hydrolyzed, which liberates the inositol in phytate. This inositol can then be absorbed, which enables weanling pigs to maintain plasma inositol at pre-weaning levels throughout the post-weaning period.

Introduction

In plant-based feed ingredients, most of the phosphorus (**P**) is bound to phytate (myo-inositol hexakisphosphate, IP6; Cowieson et al., 2011; Lee et al., 2023). The portion of total P that is bound to phytate varies among feed ingredients. Corn contains 0.24 to 0.27% total P of which around 70% is phytate P, whereas soybean meal (**SBM**) contains 0.65% total P with approximately 60% as phytate P (Lee et al., 2023). Animal proteins, including spray-dried plasma and whey powder, contain no phytate because phytate is absent from animal tissues. Likewise, highly processed ingredients such as fermented SBM have reduced phytate-P compared with conventional SBM due to phytate degradation during fermentation (Rojas and Stein, 2012). Therefore, diets for weanling pigs typically contain less phytate than diets for growing pigs because they include animal protein sources and highly processed ingredients that contain little or no phytate. Because swine have low activity of endogenous phytase, the hydrolysis of phytate is limited and, therefore, the availability of P is reduced (Holloway et al., 2019). Phytase is the enzyme that hydrolyzes phytate to lower inositol phosphate, and exogenous phytase has been added to swine diets to increase P digestibility and reduce P excretion at a standard level of 500 phytase units (**FTU**)/kg (Moita and Kim, 2022).

Phytase and phytate

Phytate is the main storage form for P in plant ingredients (Cowieson et al., 2011) and it is composed of a complex structure with up to six phosphate molecules bound to a myo-inositol ring (Holloway et al., 2019). Pig diets may contain between 0.2 to 0.3% of phytate-P depending on the feed ingredients that are used in the diets and the processing conditions (Rodehutscord and Rosenfelder, 2016). Phytate is generally considered an anti-nutritional factor because it reduces the availability of nutrients to the pigs (Bedford and Walk, 2016). Phytate has 12 ionizable reactive sites, which results in a strongly negative charge at the pH range throughout the gastrointestinal tract and, therefore, phytate can chelate bind di- and trivalent cations such as Zn2+, Cu2+, Ni2+, Co2+, Mn2+, Fe2+, and Ca2+ in very stable complexes, reducing the availability of those minerals (Dersjant-Li et al., 2015). The extent to which any of those minerals inhibit the hydrolysis of phytate differs among cations, with Zn^{2+} having the greatest inhibitory effect, followed by Fe^{2+}, Mn^{2+}, Fe^{3+}, Ca^{2+}, and Mg^{2+}. Differences among minerals are primarily associated with the stability of the phytate-mineral complex, solution pH, and the phytate-to-mineral molar ratio (Angel et al., 2002). As phytate remains relatively soluble under acidic conditions, complex formation is limited in the stomach and occurs primarily in the small intestine, where the higher pH favors the interaction between phytate and mineral ions (Angel et al., 2002). Because Ca is present in animal diets in greater concentrations than other cationic minerals,

phytate primarily forms complexes with Ca in the small intestine and can chelate up to six Ca atoms (Selle et al., 2009).

Phytate not only chelates minerals, potentially creating a deficiency, but also impairs digestion, which may reduce the digestibility of amino acids (**AA**) and energy (Bedford and Walk, 2016). One possible mechanism is that even at a low pH in the stomach, most of the dietary AA are positively charged, and as a result, insoluble protein-phytate complexes may be formed, reducing the efficiency of gastric digestion (Farhadi et al., 2019). In addition, to increase the solubility of these complexes, the pig may respond by increasing gastric acid secretion and lowering stomach pH (Yu et al., 2012). However, a more acidic environment may stimulate mucin secretion to protect the gastric epithelium (Onyango and Adeola, 2012), and because mucin is rich in threonine, serine, and proline (Lien et al., 1997), increased mucin production may increase endogenous AA losses and contribute to reduced AA digestibility.

Utilization of P from phytate and lower inositol phosphates requires the stepwise cleavage of phosphate groups from the inositol ring (Lagos et al., 2023). This hydrolysis is catalyzed by phytases and other phosphatases (Sandberg and Andlid, 2002). Phytases are not specific for phytate and can further catalyze the hydrolysis of lower inositol esters. Lower inositol phosphates can also be catalyzed by other phosphatases that cannot hydrolyze phytate (Rodehutscord and Rosenfelder, 2016). Standard phytase doses (e.g. 250-500 FTU/kg) may be sufficient to cleave phytate to IP4, but insufficient to target full IP4 hydrolysis, which may result in the accumulation of IP4 or IP3 in the intestinal tract (Mesina et al., 2019; Lagos et al., 2023). Previous data indicate that these lower esters retain antinutritional properties because they can bind minerals and interfere with proteolytic activity (Liu et al., 2009; Yu et al., 2012; Beeson et al., 2017). Therefore, further hydrolysis of IP4 and IP3 concentrations may contribute to improvements in nutrient digestibility and growth performance observed with high phytase inclusion rates.

The negative impact that phytate can have on nutrient utilization has increased interest in using phytase in concentrations greater than those required to meet the P requirement of pigs (Holloway et al., 2019). Increasing phytase inclusion beyond conventional levels facilitate the full hydrolysis of these lower esters and the release of the inositol ring (Moran et al., 2017; Laird et al., 2018; Moran et al., 2019; Lagos et al., 2023). Ileal concentrations of phytate decreased as phytase increased from 0 to 4,000 FTU/kg, whereas ileal inositol concentrations increased more than 35-fold, indicating extensive phytate breakdown (Lagos et al., 2023). These observations indicate that the benefits of high doses of phytase may be beyond improvements in P availability, as the release of myo-inositol may provide additional physiological benefits to the pigs.

Role of inositol in the body

Inositols are a group of cyclic sugar alcohols that can exist in nine stereoisomeric forms, and among them, myo-inositol (referred to as inositol) is the most predominant and biologically important isomer in nature (Gonzalez-Uarquin et al., 2020; Quarta et al., 2025). Although inositol was historically classified as a member of the vitamin B complex and was often referred to as vitamin B8, it is no longer considered a true vitamin because mammals can synthesize inositol endogenously from glucose (Regidor and Schindler, 2016; Antonowski et al., 2026). The synthesis begins with glucose entering the glycolytic pathway, where it is converted to glucose-6-phosphate. Glucose-6-phosphate is then converted to inositol-1-phosphate by the enzyme inositol-1-phosphate synthase, which represents the rate-limiting step in the inositol biosynthesis (Chen and Xiong, 2010; Sánchez-Hidalgo et al., 2021). Inositol monophosphatase then removes the phosphate group to generate free inositol (Antonowski et al., 2026). This synthesis occurs primarily in the kidneys, but other tissues such as liver, brain, and testis also synthesize inositol, but at much lower amounts compared with the kidneys (DiNicolantonio and O'Keefe, 2022). In addition to endogenous synthesis, pigs may obtain inositol from dietary ingredients, through the complete hydrolysis of phytate by phytase which releases free inositol that can be absorbed and utilized by the body, or by recycling from inositol phosphates and phosphatidylinositol (Gonzalez-Uarquin et al., 2020).

Inositol has a role in many physiological processes. Inositol is a precursor of phosphatidylinositol and its phosphorylated forms (i.e. PIP, PIP2, PIP3), which participate in signaling cascades such as the PI3K/Akt and PLC-IP3/diacylglycerol pathways (Antonowski et al., 2026). The PI3K/Akt pathway regulates cellular growth, protein synthesis, glucose uptake, and insulin sensitivity (Manning and Cantley, 2007; Hers et al., 2011), whereas the PLC-IP3/diacylglycerol pathway regulates intracellular Ca signaling through the generation of IP3 and diacylglycerol. Upon activation, IP3 stimulates Ca release from the endoplasmic reticulum, while diacylglycerol activates protein kinase C, together influencing hormone secretion, metabolism, immune responses, and other cellular processes (Nishizuka, 1992; Berridge, 1993). Inositol phosphates, including IP3, IP4, and IP6 also function as signaling molecules involved in cell signal transduction and the regulation of diverse physiological processes such as muscle contraction, neurotransmission, and immune cell activation (Irvine and Schell, 2001).

Why is inositol important for weanling pigs

Weaning is one of the most stressful periods during the production cycle because it involves nutritional, environmental, physiological, and immunological changes. These changes result in reduced feed intake, impaired intestinal function, and activation of inflammatory responses, which can negatively affect growth performance (Pluske et al., 1997; Lallès et al., 2007). Recent research indicates that inositol may play an important role during this transition period because newly weaned pigs appear unable to maintain pre-weaning plasma inositol levels unless phytase is included in the diet (Moran et al., 2019; Lagos et al., 2021; Guan et al., 2025). Supplementation of microbial phytase increased phytate degradation and plasma inositol concentrations in weanling pigs. In pigs fed a diet without phytase, plasma inositol concentrations decreased from approximately 49 μM before weaning to 20 μM at 14 days post-weaning, which is a reduction of nearly 60%, whereas pigs fed phytase maintained plasma inositol concentrations within or above the pre-weaning range (Lagos et al., 2021). Pigs not receiving phytase did not recover pre-weaning plasma inositol concentrations until approximately 42 days after weaning (Lagos et al., 2021). Similar data have been reported from more recent experiments, which indicates that plasma inositol concentrations can be maintained at preweaning levels if pigs are fed diets containing phytase, whereas pigs fed diets without phytase experienced a reduction of approximately 50% in plasma inositol concentration (Guan et al., 2025; Mallea et al., 2025).

From the above experiments it was concluded that newly weaned pigs have a limited ability to maintain pre-weaning inositol status and may, therefore, benefit from phytase-derived inositol. Indeed, inositol may be a conditionally indispensable nutrient during the post-weaning period because the metabolic demand for inositol immediately after weaning may exceed the pig's capacity for endogenous synthesis (Moran et al., 2019). A dosing appears to be a result of a combination of the reduced anti-nutritional effects of phytate and increased generation of inositol, with these benefits being particularly evident during the immediate post-weaning period.

Whereas the positive effects of phytase-derived inositol on growth performance have been consistently observed, the physiological mechanisms associated with these responses have not been fully elucidated. One proposed mechanism involves the role of inositol in glucose metabolism and insulin signaling. Phytase supplementation increased the abundance of glucose transporter type 4 (GLUT4) in skeletal muscle plasma membranes (Lu et al., 2019). The GLUT4 is a glucose transporter primarily expressed in skeletal muscle and adipose tissue that responds to insulin stimulation. Under normal physiological conditions, insulin promotes the movement of GLUT4 to the plasma membrane, increasing glucose uptake from the bloodstream into tissues (Kahn, 1996). Because myo-inositol is involved in signaling pathways associated with insulin action, it has been proposed that some of the growth-promoting effects of inositol may be related to enhanced glucose uptake and utilization, as well as improved nutrient partitioning and protein accretion (Cowieson et al., 2015; 2017).

An additional implication of increased inositol availability may be the modulation of inflammatory responses. Pigs fed phytase had reduced plasma concentrations of tumor necrosis factor-alpha on day 28 after weaning compared with pigs fed the control diet (Mallea et al., 2025). Reduced concentrations of tumor necrosis factor-alpha indicate a reduced systemic

similar concept has also been proposed for poultry, where inositol has been described as a semi-essential nutrient that may become limiting under certain physiological conditions despite the existence of endogenous synthesis pathways (Gonzalez-Uarquin et al., 2020). This indicates that periods of rapid growth or physiological stress may increase the dependence of pigs on dietary or phytase-derived sources of inositol.

Maintaining plasma inositol concentrations after weaning may have important implications for growth performance because increasing phytase inclusion not only elevates circulating inositol concentrations (Moran et al., 2019; Guan et al., 2025; Mallea et al., 2025) but also improves feed efficiency and growth performance in young pigs (Laird et al., 2016; Moran et al., 2017; Laird et al., 2018; Holloway et al., 2019; Lu et al., 2019; Moran et al., 2019; Lagos et al., 2021; Mallea et al., 2025). Supplementation of 2,500 FTU/kg phytase improved average daily gain (**ADG**) and gain to feed (**G:F**) ratio regardless of levels of dietary energy and amino acids demonstrating that the response was independent of nutrient deficiency and likely related to the extra-phosphoric effects of phytase. A linear increase in ADG and G:F was reported in weanling pigs as dietary phytase increased from 0 to 12,500 FTU/kg (Veum et al., 2006). Likewise, a dose-dependent improvement in ADG and G:F in weaning pigs supplemented with up to 15,000 FTU/kg phytase have been observed (Kies et al., 2006). Similar improvements in growth performance have also been observed under commercial production conditions, where supplementation with phytase at super-dosing levels improved feed efficiency and growth performance in weanling pigs, with the greatest responses observed at approximately 2,500 FTU/kg phytase (Moran et al., 2017). The enhanced growth performance may be partially explained by the complete hydrolysis of phytate and release of inositol (Moran et al., 2019; Lagos et al., 2021). Therefore, the improvements in growth performance associated with phytase super-

inflammatory status, which may allow nutrients and energy to be redirected from immune activation toward growth. Because activation of the immune system is energetically expensive, a reduction in inflammatory signaling may improve nutrient utilization and contribute to better feed efficiency. Inositol may also exert anti-inflammatory effects by reducing oxidative stress and suppressing activation of nuclear factor-κB (NF-κB), a key regulator of inflammatory responses (Quarta et al., 2025).

Phytase supplementation consistently increases plasma inositol concentrations in weanling, growing, and finishing pigs (Laird et al., 2016). However, improvements in growth performance have been observed mainly in weanling pigs, whereas increased availability of inositol in growing and finishing pigs has not consistently translated into improvements in ADG or G:F (Laird et al., 2016; Holloway et al., 2019). In poultry it was also observed that dietary inclusion of 0.1% inositol improved broiler feed efficiency, with the greatest response observed during the starter period, whereas improvements were less pronounced during the grower phase (Żyła et al., 2013).

Conclusions

Inositol has a number of important functions in the body, but in pigs more than six weeks post-weaning there is usually sufficient synthesis of inositol from glucose-6 phosphate to maintain plasma inositol at levels needed for normal body functions. However, it is apparent that newly weaned pigs do not have the ability to synthesize sufficient inositol and inclusion of microbial phytase, therefore, is needed to maintain pre-weaning levels of inositol in plasma. It is likely that at least 1,000 phytase units, and possibly more, is needed to liberate the inositol present in phytate, which allows pigs to absorb the inositol from phytate, and therefore, maintain pre-weaning levels of plasma inositol. By providing microbial phytase at generous levels in the post-weaning diets, pigs will not only maintain plasma inositol levels but also have improved growth performance and sometimes also reduced diarrhea.

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The Trade-offs of Zinc Supplementation in Swine Diets for Productivity, Environmental Sustainability, and One Health

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Abstract

Pharmacological zinc oxide (ZnO) supplementation is considered the most cost-effective strategy for preventing post-weaning diarrhea in U.S. swine production and has been widely adopted to improve nursery pig health and growth performance during the first 2–3 weeks post-weaning. However, growing concerns about environmental zinc accumulation and its potential contribution to the development of antimicrobial resistance (AMR) have resulted in regulations on the use of pharmacological ZnO. Traditionally, optimal zinc supplementation levels have been recommended based primarily on growth performance and the prevention of post-weaning diarrhea. However, these recommendations should be re-evaluated by considering not only pig growth performance and health but also overall swine productivity, swine production sustainability, environmental impacts on agricultural ecosystems, and AMR risk. Therefore, a systems-based approach is needed to establish optimal dietary zinc supplementation strategies that meet the nutritional requirements of nursery pigs, support post-weaning health and overall swine productivity, minimize environmental zinc accumulation and AMR risk, and contribute to sustainable swine production.

Introduction

Zinc (Zn) is a nutrient required by all living organisms including pigs for optimal growth and health because it plays vital catalytic, structural, and signaling functions (Ryu and Aydemir, 2020). Furthermore, Zn provides antimicrobial effects to significantly reduce the post-weaning diarrhea and promote growth of weaned pigs when supplemented at pharmacological levels (2,000 to 3,000 mg/kg) in the form of zinc oxide (ZnO). However, 80 – 90% of ingested zinc is not retained and excreted in manure that is applied to croplands where it accumulates at variable rates depending on soil and crop factors. Excess soil zinc may lead to decrease crop yields and ecotoxicity (Monterio et al., 2010), moreover, excessive dietary Zn may contribute to the antimicrobial resistance (AMR) of pigs and potential public health concern (Poole, 2017). Considering the trade-offs between newly weaned pig health, the environment, and public health, many countries have been proactively implementing regulations to reduce the amount of zinc supplementation in swine diets.

Zinc supplementation levels in nursery pig diets

The NRC (2012) recommends a dietary zinc requirement of 100 mg/kg for piglets weighing 5 to 11 kg and 80 mg/kg for piglets weighing 11 to 25 kg (Table 1). In 2022, the European Union (EU) imposed regulations restricting the Zn content in pig diets to 150 mg/kg and prohibiting diets containing pharmaceutical Zn concentrations. In 2018, China decreased the authorized level of zinc supplementation in pig diets from 2,250 to 1,600 mg/kg for the first 2 weeks of the postweaning period, and restricted zinc concentration to 110 mg/kg in all other stages of the pig's lifecycle (Li et al., 2024). Currently, there are no regulations on zinc supplementation levels in the U.S., and it is a common practice to add pharmacological concentrations of Zn in weaned pigs' diets (2,000 to 3,000 mg/kg) for 2 to 3 weeks of the post-weaning period to prevent post-weaning diarrhea. As a result, dietary zinc supplementation levels used in U.S. nursery pig production are substantially higher than those reported in other countries. In the U.S., average dietary zinc concentrations are approximately 3,032 and 2,081 mg/kg in Nursery phase 1 and phase 2

Table 1 Recommended zinc supplementation levels and current zinc practices in nursery pig diets.

Item	Recommended dietary Zn concentration, mg/kg			
	U.S. [1]	Brazil [2]	China [3]	E.U. [4]
Nursery 1 – 5 to 7 kg BW	100	123	110	150
Nursery 2 – 7 to 11 kg BW	100	123	110	150
Nursery 3 – 11 to 25 kg BW	80	110	70	150
Zn regulation or practice	No regulation; Pharmacological ZnO (2,000-3,000 mg/kg Zn) for first 2-3 weeks postweaning		Limit at 110 mg/kg (~25 kg BW piglet); Pharmacological ZnO (~1600 mg/kg) for first 2 weeks postweaning	Regulation: 150 mg/kg
	Average zinc supplementation level, mg/kg			
	U.S. [5]	Brazil [6]	China [7]	E.U. [8]
Nursery 1 – 5 to 7 kg BW	3032	2225	425	150
Nursery 2 – 7 to 11 kg BW	2081	1876	534	150
Nursery 3 – 11 to 25 kg BW	401	996	95	150

References: [1] NRC, 2012; [2] Rostagno et al., 2017; [3] NY/T 65-2004; [4] CVB, 2020; [5] Flohr et al., 2016; [6] Dalto and da Silva, 2020; [7] Yang et al., 2021; [8] European Commission, 2016.

diets, respectively, compared with 425 to 534 mg/kg in China and 150 mg/kg in the E.U.

Trade-offs of pharmacological use of ZnO

Pork production and its supply chain comprise a complex system of diverse stakeholders, processes, and resources influenced by economic, environmental, social, and cultural factors. Given the complexity of this pork production system, a holistic approach is essential for addressing the multifaceted challenges of modern swine production. Systems thinking provides a valuable framework for understanding interactions among swine production, animal health, environmental sustainability, and public health, enabling the identification of leverage points where targeted interventions can improve overall system performance. Pharmacological use of ZnO in nursery pig diets has long been used to reduce post-weaning diarrhea, improve growth performance and gut health, decrease mortality, and enhance the productivity and profitability of swine production (Figure 1). In addition, pharmacological zinc can reduce the need for antibiotic treatments during the post-weaning period or later grower-finisher period, whereas excessive zinc use has raised concerns because of its potential contribution to AMR. Environmentally, improved growth performance and feed efficiency may reduce nutrient excretion per unit of pork produced, but large amounts of unabsorbed zinc are excreted in manure, leading to zinc accumulation in agricultural soils and potential adverse effects on agroecosystems. It should be noted that a recent epidemiological study (Nielson et al., 2025) reported that discontinuation of ZnO use led to a 17% increase in antimicrobial usage among Danish swine farms between 2022 and 2023, primarily due to a higher incidence of gastrointestinal disease treatments in weaned pigs, highlighting potential unintended consequences of such regulatory actions. Consequently, the trade-offs between the benefits of pharmacological zinc supplementation for swine productivity and health and its potential impacts on environmental sustainability and AMR remain incompletely understood.

Effects of pharmacological ZnO on growth performance and postweaning diarrhea

A meta-analysis of 26 studies reported inconsistent growth performance responses to pharmacological supplementation of ZnO for weaned pigs (Sales, 2013). Hansen et al. (2023a) reported that 1,400 mg/kg of zinc in diets is required to optimize the growth performance of weaned pigs, while 1,100 mg/kg of zinc in diets significantly reduce the diarrhea during the first week post-weaning. In addition, doses of 1,500 ppm immediately after weaning are considered as physiologically required when considering that the average daily feed intake and subsequent zinc intake of newly weaned pigs do not cover the requirement for 2 -5 days postweaning. Based on these findings, approximately 1,100 mg/kg optimized growth performance, whereas 1,500 mg/kg was more effective for preventing post-weaning diarrhea. In contrast, the current EU limit of 150 mg/kg dietary zinc is likely insufficient to effectively prevent post-weaning diarrhea.

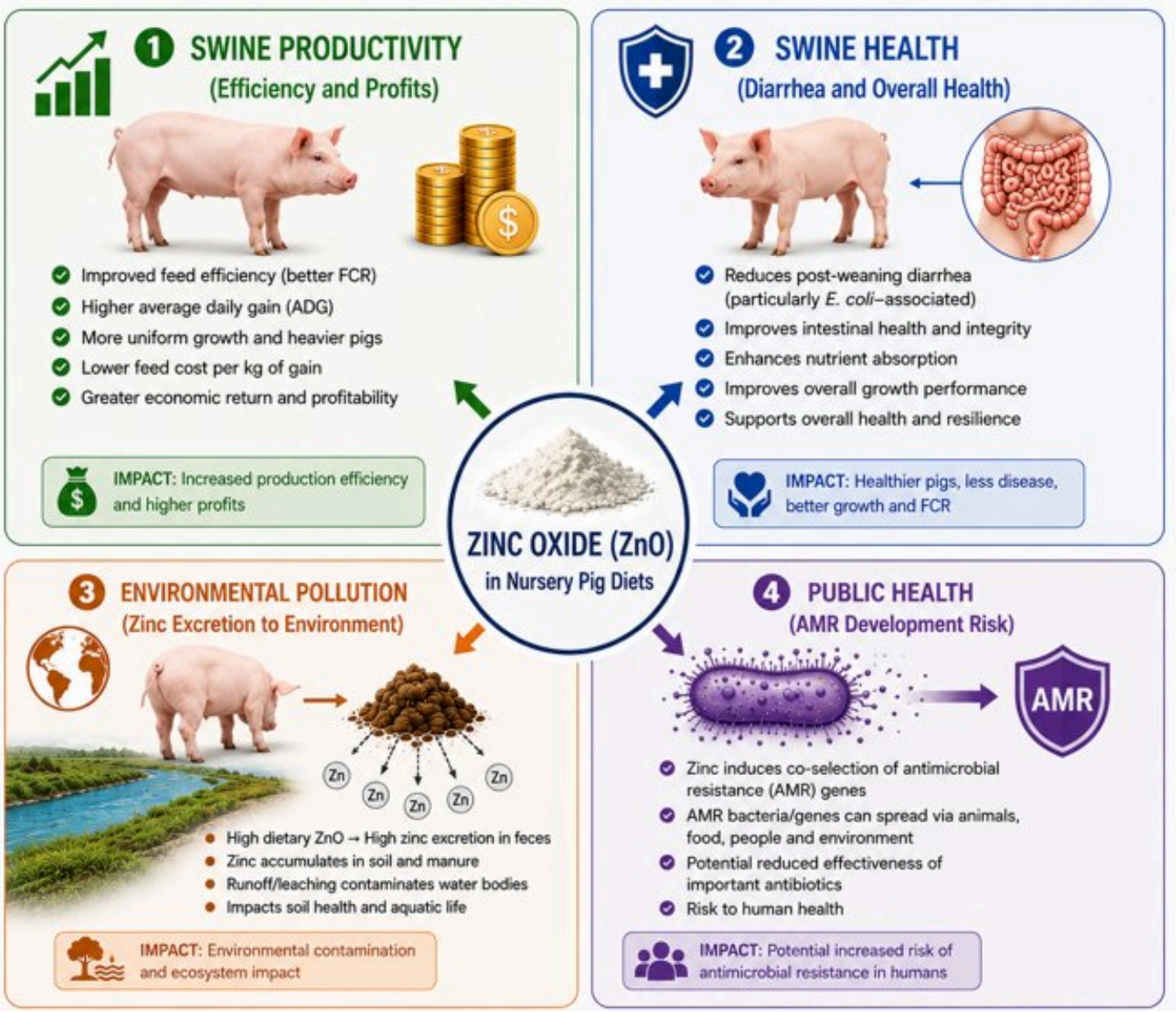

Figure 1 Systems thinking framework illustrating the role of zinc use in nursery pig diets within swine production systems (generated by ChatGPT)

Recently, the Purdue swine research group conducted a 5-week zinc balance trial using 64 weaned pigs (Walpole and Hong, unpublished). Four dietary treatments were evaluated: 1) Control (EU level, 150 mg/kg of Zn), 2) Low ZnO (1,000-750-500 mg/kg of Zn), 3) 3) Intermediate ZnO (2,000-1,500-1,000 mg/kg of Zn), and 4) High ZnO (3,000-2,000-1,000 mg/kg of Zn) during Nursery Phases 1 (0 to 1 wk), 2 (1 to 3 wks), and 3 (3 to 5 wks), respectively. Potentiated ZnO (HiZox®, Animine, France) was used as the zinc source. Higher dietary Zn intake linearly increased ($P < 0.05$) the ADG and ADFI for d 22 to 28, whereas there was no difference in BW and G:F ratio. Quadratic responses ($P < 0.05$) were observed for fecal dry matter on days 7, 14, and 28, with pigs fed the intermediate ZnO treatment having greater fecal dry matter than those fed the control or high ZnO treatments. There were significant differences ($P < 0.05$) in diarrhea incidence over the experimental period, showing that the Intermediate ZnO and High ZnO treatments had lower diarrhea incidence than other treatments. These findings suggest that the response to ZnO dosage may vary depending on the production environment and disease challenge, and that the optimal ZnO concentration for maximizing growth performance may differ from that required to prevent post-weaning diarrhea.

Effects of zinc supplementation levels on fecal zinc excretion in pigs and its environmental impact

Zinc absorption and retention are tightly regulated homeostatic systems that result in similar absorption and retention levels regardless of the amount of Zn consumed in feed. When high dietary amounts of Zn are consumed above the requirement, fecal excretion increases while absorption and retention are maintained, resulting in a lower efficiency of dietary Zn utilization of about 10-20%. Hansen et al. (2023b) conducted a meta-regression analysis to investigate the relationship between zinc intake and fecal excretion in pigs. Their findings indicated that the source of zinc did not significantly affect zinc excretion in weaned pigs and proposed a regression equation to describe the relationship between dietary zinc intake and fecal zinc excretion. The Purdue swine research group conducted a meta-analysis of 7 ZnO studies to evaluate the relationship between dietary zinc intake and fecal zinc excretion (Walpole and Hong, unpublished). A study-adjusted regression analysis ($R^2 = 0.619$) indicated that apparent fecal zinc excretion rate (%) increased with increasing dietary ZnO concentration (mg/kg) after accounting for study-to-study variation. Predicted apparent fecal zinc excretion was 74.5%, 80.6%, and 86.8% at dietary ZnO concentrations of 1,000, 2,000, and 3,000 mg/kg, respectively.

Application of swine manure to agricultural land could reduce the environmental footprint of hog production by recovering and recycling nutrients back into the soil for crop production; however, it could also increase environmental risks associated with water pollution and soil ecosystems if excessive amounts of potentially toxic elements (e.g., zinc) are applied. Because manure application rates are commonly determined based on nitrogen (N), phosphorus (P), and potassium (K) contents, soils often receive Zn and Cu in excess of agronomic needs, causing a potential threat to plant and animal life, as zinc is non-degradable in the environment (Hussain et al., 2022). Hong et al. (2025) assessed the environmental impacts of ZnO use in nursery pig diets using life-cycle impact assessment modeling [ReCiPe 2016 Midpoint (H) V1.09/World (2010)H.] in Simapro LCA software (version 9.6, PRé Sustainability, Netherlands) based on data from a 6-week nursery feeding trial. During the nursery phase, the high-ZnO treatment increased freshwater and marine ecotoxicity by 59.6% and 57.9%, respectively. However, pigs fed high ZnO had greater BW at the end of the nursery period and were predicted to reach 130 kg market weight faster with less feed consumption. Consequently, high ZnO reduced several environmental burdens, including global warming potential, ozone depletion, land use, and mineral resource depletion (Figure 2).

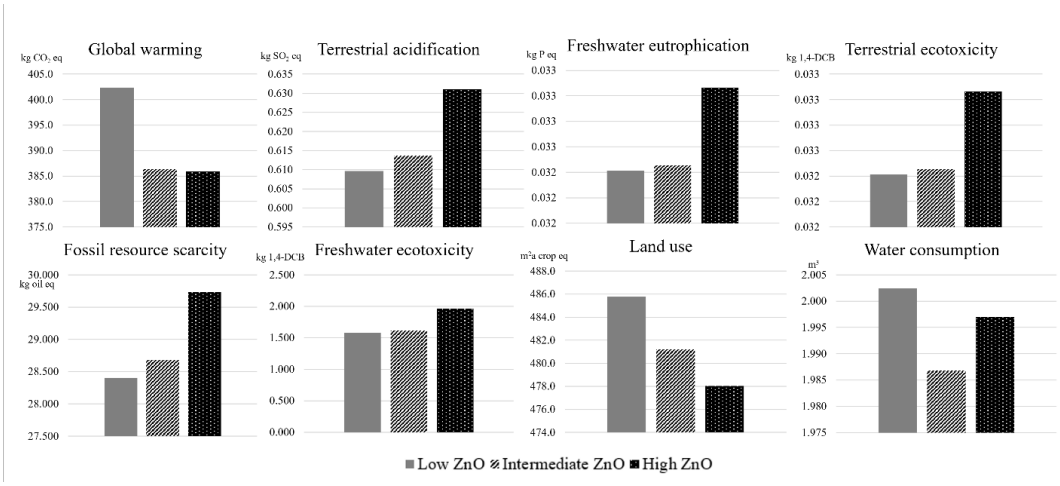

Figure 2 Life cycle impact assessment (LCIA) of dietary ZnO treatment in the wean-to-finish of the swine production system (final product: a 130kg market pig).

Effects of zinc supplementation on antimicrobial resistance

Heavy metals (e.g., Zn and Cu) can contribute to AMR through several mechanisms that alter bacterial physiology and antibiotic susceptibility, including (1) metal–antibiotic complex formation, (2) induction of multidrug efflux pumps, and (3) sublethal cellular damage. Dietary Zn supplementation at pharmacological levels in swine diets may increase the risk of AMR dissemination through co-selection and mobilization of AMR genes, facilitating their subsequent transfer to humans. High dietary Zn levels have been associated with the persistence of multidrug-resistant *Escherichia coli* (Bednorz et al., 2013; Ciesinski et al., 2018) and methicillin-resistant *Staphylococcus* spp. (Slifierz et al., 2015), as well as increased AMR in commensal *Enterococci* (Mazaheri Nezhad Fard et al., 2011), and in bacterial populations presented in pig manure (Hölzel et al., 2012). There is no definitive proof that reducing dietary Zn levels lowers the prevalence of AMR in the pig gut microbiome or manure. Addressing this knowledge gap is crucial for elucidating how Zn supplementation influences AMR dynamics, particularly through co-selection and co-regulation mechanisms within animal agricultural systems.

Muurinen et al. (2021) examined the effect of pharmacological ZnO supplementation on ARGs in

nursery pigs. Three dietary groups were compared, including a control group (corn-soy diet), an antibiotic group (AB; carbadox, 55 ppm), and a ZnCu group (ZnO: 3,000 ppm, d 0-7; 2,000 ppm, d 7-33; CuSO4: 125 ppm, d 0-33). Network analysis showed that the Control group had a simpler ARG-MGE co-occurrence network, whereas both the AB and ZnCu groups exhibited more complex networks with higher ARG mobility potential. Recently, the Purdue swine research group (Hong, Walpole, and Ju, unpublished) conducted a preliminary assessment of fecal AMR gene abundance at the end of the nursery and finisher periods using the fecal samples collected from pigs in the previously described zinc balance study. At Day 35, the continuously low-ZnO treatment showed numerically lower *tetA* detection than several step-down ZnO regimens (**Figure 3**). The overall treatment effect on tetA prevalence was not significant. However, at Day 143, tetA prevalence in the EU-regulation treatment increased to a level comparable to that of the high-ZnO treatment. Pigs fed low-ZnO diets during the nursery period may have entered the grower phase with a distinct gut microbial community and antimicrobial resistance gene profile compared with pigs previously exposed to higher ZnO concentrations. Nevertheless, there is currently insufficient scientific evidence that reducing pharmacological ZnO supplementation decreases the prevalence of AMR in feces, manure, or agricultural soils. Addressing this knowledge gap is essential for understanding the long-term implications of zinc supplementation on AMR dynamics in swine production systems.

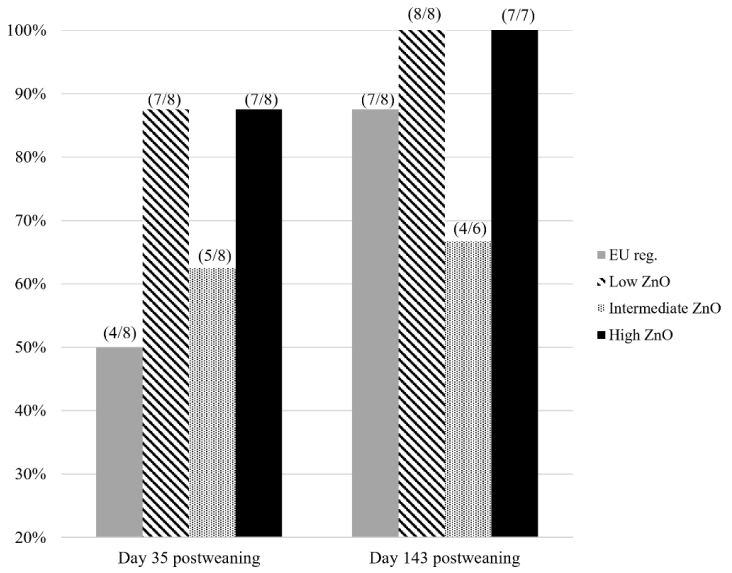

Figure 3 Prevalence of detectable tetA in pig feces on days 35 and 143 postweaning

Conclusion

To date, the optimal dietary zinc concentration and the use of pharmacological ZnO have primarily been evaluated based on growth performance and the prevention of post-weaning diarrhea. However, decisions regarding the use of pharmacological ZnO should also consider farm-specific factors, including disease history with disease challenge status, manure management practices, and antimicrobial or antibiotics practices, as these factors influence both the need for pharmacological ZnO and its potential implications for AMR. Future research should adopt a systems-level approach to identify balanced zinc supplementation strategies that optimize swine productivity and health while minimizing environmental impacts and AMR risk. Such an integrated framework could support evidence-based decision-making for sustainable and responsible zinc use in the U.S. swine production systems.

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Late-Gestation Nutrition in Prolific Sows: An Opportunity to Improve Farrowing Performance, Sow Retention, and Pig Development

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Abstract

The genetic progress in swine in the recent decade represents a remarkable opportunity for improvement in pork production efficiency and resource utilization. But, with the gains come challenges. Replacement rates and prolific sow mortality are far too high (>15%) in most commercial production systems even as significant numbers of operations (Top 10%) successfully manage to less than 6% mortality (MetaFarms, 2025). A high prevalence of anemia in prolific sows and its relationship to farrowing duration and risk of removal in commercial herds provides the industry with insight and a needed biomarker for sow health and nutrition status. Likewise, feed efficiency also provides a nutritional measure. Additionally, a health assessment to supplement condition scoring is critical. Feeding systems need flexibility to meet the sow's dynamic metabolic and nutritional needs in gestation for optimal lifetime health and productivity. Updating the nutritional strategy for prolific sows in late gestation represents a promising opportunity to maintain her health and performance, wean more high-quality pigs, and advance more efficient and sustainable production systems.

Introduction: Late Gestation in Prolific Sows is a Dynamic Opportunity to Improve Production

Many farms are realizing gains from recent progress in genetics and management. MetaFarms (2025) reports that the top 10% of farms are achieving >30 pigs weaned per sow per year. Included in the characteristics of the top 10% of farms is the ability to maintain low levels of sow mortality. However, many farms in the U.S. are not fully capitalizing on the highly productive genotypes and the potential gains in production efficiency, a tremendous opportunity cost. In an analysis of the historical trends of farms in the PigChamp database, a potential contributor to the lack of progress is a relationship between the increase in sow mortality with increasing prolificacy (Weaver, 2023). A conservative valuation of the U.S. sow herd can be approached two ways: applying a flat industry replacement value of $350 per head to the current U.S. breeding herd (5.95 million head; USDA-NASS, 2025) yields approximately $2.08 billion, while an itemized build-up of the actual cost to develop a replacement gilt through her first farrowing—genetics, feed, non-feed development costs, breeding, and gestation feed and labor—totals approximately $328 per head, yielding a closely convergent $1.95 billion. Both approaches place the conservative asset value of the U.S. breeding herd at approximately $2 billion.

As the sow is the origin of pigs born, maternal care, and nutrition in the most critical, neonatal period of life of the pig, she is the foundation of an efficient production system. Due to major genetic progress, today's prolific sow continues to increase in productivity potential with more pigs born, consistent birth weights, and increased litter weaning weights. All these measures are effective predictors of the reproductive efficiency and productivity in swine production systems. Even as the sow is an asset to the system, she may be undervalued by the industry. The parallel trend for increasing sow and pig mortality with increasing prolificacy offsets the potential gains in productivity. Improving pig livability while reducing sow removals represents one of the highest-return opportunities for the U.S. pork industry (Shull, 2020). Genetic selection for robust sows and pigs will likely be successful with a slow rate of change. Both research and the industry have made little progress in changing the mortality trend contributed by environmental factors, which have the potential for more rapid improvement. A few considerations may yield a higher return on the investment.

First, sow mortality in the U.S. and Spain is trending higher than in other countries with similar or higher levels of productivity (Johnson, 2026; Arrazola et al, 2024). The recent causes of mortality are pelvic organ prolapses,

lameness and musculoskeletal issues and sudden, non-euthanasia deaths with each contributing to 25-30% of the mortality (Kikuti et al., 2022; Rademacher et al., 2022). Very important to the etiology of sudden sow deaths is that retained pigs and ulcers have recently been identified in >40% of the sudden sow deaths around parturition (Solis et al., 2025). With less labor available for farrowing assistance and larger litters, sows may be not successfully completing the farrowing process. Longer farrowing duration in anemic sows in tropical climates poses a risk to sows (Thu et al, 2026). Higher mortality in summer months (MetaFarms, 2025) highlights the impact of heat and physiological stress as important triggering factors. These categories of mortality have exposed our limited knowledge of the metabolism and physiology of the high-producing sow in late gestation and at farrowing. In particular, the rapid rise in the incidence of prolapses, without known causes, from 2015-2024 should inspire a greater investment in our understanding of the prolific sow. While a link of prolapses to genetics in sows has been identified (Bhatia et al., 2023), evidence in humans agrees that environmental effects still account for most of the variation (Schulten et al., 2022) so nutrition should be a primary consideration.

Second, a higher level of production is being achieved in other countries with similar genetics. Historically, the productivity of prolific sows increases with advancing parity due to higher ovulation rates. Presently, prolific lines of first parity sows in the U.S. produce nearly the same number of pigs born and born alive as older parity sows. Stillborn pigs increase with advancing parities. Prolific lines in Europe continue to report increases in total pigs born and pigs born alive (Pedersen et al., 2024; Ribas et al., 2024).

With replacement rates of 50-60%, most sows are only in herds for two parities (MetaFarms, 2025; PigChamp) which is economically inefficient. Sows in the third and fourth parities have the potential to be the highest producing sows in the herd. Additionally, the progeny has the potential to be the lowest mortality, fastest gaining and highest value population of pigs in the herd.

Nutritional considerations

Feeding gestating sows has changed very little in the U.S. in the current decade despite the rapidly increasing productivity and the observed trends in mortality, prolapses and low retention rates. It is well accepted that similar to feeding other phases of production, feeding gestating sows a single diet throughout their gestation cycle leads to periods of nutrient deficiencies or excesses (Theil, 2022; Ribas et al., 2024). The late gestation SID lysine needs for sows have been determined to be 16-22 g per day, significantly higher than a typical gestation diet that delivers 12-13 grams per day as is common commercially in the U.S. (Samuel et al, 2010; Johannsen et al. 2024; Kloostra et al., 2025; Jenkins et al., 2025). Yet, one gestation diet, delivered to feed boxes/drops, delivered at a constant rate throughout gestation remains the most common feeding practice and feeding recommendation. Body condition score by visual scoring or the Knauer caliper, a device that has improved sow health and performance as much as any innovation, provides information for individual sow feeding rate adjustments to either allow for recovery of sows in thin body condition and reductions in body fat for over-conditioned sows. But a body condition score is not accurate enough to provide a determination of feed conversion, which may be the best measure of a feeding strategy.

For many reasons, nutrition has not been systematically eliminated as a contributor to prolific sow mortality: Research in sows has major challenges: 1) costly in terms of time and funding; 2) feeding systems are not designed for research or to feed more than one diet; 3) assumptions of the needed replication create very high research workloads; 4) disease risk and bio-security requirements on farms; 5) inconsistency in prolificacy and health status; and, 6) perceived risk vs benefits to farm management. An additional barrier to conducting the necessary studies is that research infrastructure and the time needed for completion of degrees or programs. These barriers can easily be overcome with the desire of the industry to invest in the research process and systematic investigations.

The criteria that determine the effectiveness of a nutritional program for prolific sows may be different than the past. The energy needs of prolific sows don't change proportionally through different phases of production with the other nutrients such as amino acids, vitamins and minerals. The requirement of the fetus for nutrients changes daily in late gestation while the need for energy increases slowly. In contrast, lactation drives daily energy need much higher as compared to lysine. Not surprisingly, by most accounts, the practice of bump feeding, increasing the feeding rate of the standard gestation diet, in late gestation research a decade ago failed to meet expectations for benefits—birth weight and litter weaning weight responses—but it may be that these responses are weakly related to the sow (Miller & Kellner, 2020; Gourley et al., 2020). The factors that must be known to feed the gestating, prolific sow from late gestation through lactation are expected feed intake, body weight, number of fetuses and nursing pigs, and the milk yield. With these, we can balance supply with needs.

Feed Efficiency in Sows

The calculation of feed conversion can be accomplished on an individual basis in sows and may be most in more rapid determinations of nutrient needs. Since feed intake of sows is fixed and routinely captured, the late gestation "gain" component is the variable requiring additional measurement. Litter birth weight and sow body weight together account for most of this gain, though the precise partition depends on litter size and the still-uncertain placental and fluid components of the conceptus. Litter birth weight is measured but the sow's body weight, placental weight and fluid need definition to ensure calculation of nutrient needs. McClellan et al. (2025) reported both total litter birth weight and total pigs born for a litter averaging 16.5 total born (Cycle I), and, for sows that continued to a second cycle on the nutrient-enriched diet, an actual litter size of 19.24 total born (Cycle II, LGPHASE)—exceeding 18 total born without extrapolation. Real gestation body weight change (day 70 to day 110) was also reported: 35.4–35.9 kg over 40 d, averaging 0.89 kg/d. Extrapolating this rate to actual farrowing (approximately 4–5 d beyond day 110) yields a total maternal weight gain, day 70 to farrowing, of approximately 39.7 kg, of which litter birth weight alone (23.06 kg, directly measured) accounts for approximately 58%.

Modeling the partitioning of gestational weight gain (Noblet et al., 1985) from litters averaging fewer than 12 total born substantially pre-dates the current level of sow prolificacy. Applying those proportions directly, even to the 16.5-born litter in the McClellan et al data (2025), may misrepresent the composition of the gain. Two important adjustments may be necessary in the more recent, litter-size-specific data. First, individual fetal and placental growth is inversely related to litter size and litter weight (Lyderik et al., 2023). Placental growth and fluids may not increase linearly with piglet count. Second, selection for prolificacy appears to have favored greater placental efficiency: high-litter-size genetic lines produce comparable fetal mass on a smaller placenta than lower-prolificacy lines, particularly at days 70 and 90 of gestation (Krombeen et al., 2019). Both findings support treating placental growth as proportionally smaller, and fetal growth as proportionally larger, than the original Noblet partition—consistent with the established finding that placental development is largely complete by mid-gestation, while fetal and mammary tissue growth accelerate sharply after day 70 (McPherson et al., 2004; Ji et al., 2005).

Table 1 partitions the day 70 to farrowing weight gain using the McClellan et al. (2025) Cycle I population (16.5 total born), using directly reported values for total gain and litter birth weight, and two independent approaches—a literature-derived placental efficiency ratio, and a direct mass-balance calculation—for the still-unmeasured placental and fluid components.

Table 1 Partition of late-gestation weight gain (day 70 to farrowing), based on McClellan et al. (2025) Cycle I population (16.5 total born). Two approaches are shown for estimating placental and fluid components

Component	Cycle I value (kg)	Basis	Status
Total weight gain, d70–farrowing	~39.7	35.65 kg (d70–110) + ~4.0 kg extrapolated to farrow	Measured + 4 day estimate
Fetal (litter birth weight)	23.06	16.5 total born, directly measured	Measured (McClellan et al., 2025)
Placental + fluid (equation method)	8.3	Placental efficiency 6.5 (Krombeen, 2019) + fluid estimate (Noblet, 1985)	Estimated
Placental + fluid (mass-balance based on weights)	1.7	Mallmann et al. (2018) equation applied to d110 BW and total born	Empirically cross-checked
Maternal tissue + fluid (equation method)	11.4	Residual: total gain − conceptus growth (lit.-ratio)	Estimated
Maternal tissue + fluid (mass-balance based on weights)	17.4	Residual: total gain − conceptus growth (mass-balance)	Estimated

The mass-balance estimate also applied Mallmann et al.'s (2018) validated post-farrowing weight equation—post-farrowing sow weight (kg) = 13.03 + (0.93 × pre-farrowing body weight, kg) – (1.23 × piglets born, n)—directly to McClellan's reported day 110 body weight (250.0 kg average) and Cycle I total born (16.5) as a cross-check calculation. This predicts a post-farrow weight of 225.3 kg, implying a total expelled mass of 24.75 kg at farrowing. Subtracting the real litter birth weight (23.06 kg) leaves approximately 1.7 kg attributable to placenta, fluid, and associated losses—notably lower than the 8.3 kg implied by the literature-based placental efficiency ratio for the same population. The mass-balance approach produces a lower estimate than extrapolation of the formulas from less productive sows, which, when applied to additional datasets, now appears to be a consistent finding rather than a one-off discrepancy. It suggests the fluid-volume component in particular, inherited from older, lower-prolificacy literature, may substantially overstate this component in modern genetics; a placenta-plus-fluid mass in the range of 2–4 kg is more physically consistent with per-fetus placental weights reported for

high-litter-size lines (Krombeen et al., 2019) than the 7–9 kg implied by generalized proportions. Because the mass-balance approach shifts less weight gain to the conceptus, it correspondingly implies a larger maternal tissue—approximately 17.4 kg, versus 11.4 kg under the literature-ratio approach—meaning more, not less, of the sow's own reserve may be drawn down during this window than the literature models would suggest. Confirming whether total maternal weight gain rises to accommodate larger litters or remains fixed while the conceptus claims a growing share of it, is an example of important subsequent cycle-specific measurement data not often provided in even single cycle studies.

This remains a specific, addressable research gap: controlled datasets measuring pre-farrowing weight, post-farrowing weight, individual piglet birth weight, and directly dissected placental and fluid weight in litters averaging more than 18 total born, tracked across consecutive cycles in the same sows will allow us to determine nutrient needs. Regardless of which fetal estimate is used, most of the the sow's own tissue and fluid reserve accretion—and therefore the majority of her vulnerability to nutrient restriction—occurs during the late gestation window in which fetal and mammary growth are accelerating most rapidly. Late-gestation nutrient supply must be sufficient to support both components in the prolific sow. The magnitude of what remains unmeasured in advanced genetics is an existing barrier to designing an evidence-based feeding program, data that is relatively inexpensive and easy to collect.

The mobilization of nutrients by the prolific sow allows for a nutritional buffer for a large litter. Pedersen et al. (2020) reported that energy associated with tissue mobilization for milk production needs correction for calculation of feed conversion. Similarly, fetal growth due to selection for heavier litter birth weights also drive weight gain in late gestation. Based on observed sow feed conversions of less than 2:1, we can go a step further and estimate that mobilization is also occurring earlier in gestation with larger litters. When nitrogen balance in late gestation is corrected for nitrogen gain by the litter, the sow is in negative nitrogen balance in late gestation (Pohlen et al, 2026 unpublished). In addition, the carryover effect of transition diet in gestation diet into lactation impacts milk production (Farmer and Johannsen, 2024). The dynamic conditions for litter growth, mammary gland development, and milk production combined with the sow's capacity for tissue catabolism mean that short-term nutritional evaluations, such as lactation studies, will likely fail to measure the impact on the sow. Neither total pigs born nor litter weaning weight, are stand-alone effective measures of the nutritional requirement of the sow herself. The sow's body weight changes must be measured.

Consequences of this widening gap between nutrient supply and needs in late gestation is becoming evident in the prevalence of anemia. Approximately 50% of gestating sows in U.S. herds are anemic (Hb <10 g/dL), with prevalence highest in late gestation (Bhattarai et al., 2018; Castevens et al., 2020). SDSU research has shown strong associations between low hemoglobin and poor outcomes: anemic sows experience more than double the farrowing duration, higher stillbirth rates, and a 43% greater risk of early removal for every 1 g/dL decline in hemoglobin (McClellan et al., 2025). These findings indicate that anemia is likely both a biomarker for health and nutrition of the sow but also a direct contributor to sow losses, increased stillborn, and reduced pig livability. Iron metabolism depends on coordinated support from trace minerals, vitamins, and antioxidant capacity (Underwood & Suttle, 1999). The importance of meeting the prolific sows' needs for iron and the lack of research data on iron is a clear example of the challenge with the research process. Research approaches to prolific sow's nutrient needs normally evaluate one nutrient and rarely account for complex nutrient interactions involving energy, protein, minerals and vitamins. The earlier challenges with sow research have left the community with a general lack of data on prolific sow micronutrient needs.

Empirical data

Decades have passed without re-assessment of specific nutrient needs in sows with very limited data in prolific sows, particularly vitamins and trace minerals, so multiple nutrients may be limiting, potentially being too many to evaluate one-by-one. So, to assess whether the plane of nutrition contributes to sow health and performance, a trial was designed to feed sows at a time of greatest fetal demand and close to industry levels of nutrients. A controlled two-cycle study was conducted with the null hypothesis that sows fed a nutrient-enriched late-gestation diet will not alter reproductive performance, hematological health, nutrient status, farrowing duration and pig development in two cycles (McClellan et al., 2025). Sows were assigned to either a control diet (CON; 11% CP, 0.52% SID lysine, 1.48× NRC trace minerals, vitamins ≥ NRC) or a late-gestation phase-fed diet (LG-Phase; 16% CP, 0.87% SID lysine, 2.48× NRC trace minerals, >2× NRC vitamins) from d 70 of gestation to farrowing. The null hypothesis was rejected for nearly all of the key variables for the sow (Table 2.) and the key benefits even extended to the piglets, which showed improved iron and vitamin D biomarkers in the suckling period. Importantly, advantages were amplified across cycles: by Cycle II, phase-fed sows produced more total born, more liveborn, and tended to wean more pigs than control sows, illustrating that improved maternal nutrient

Table 2 Effects of a late-gestation phase-feeding program on sow body weight (BW), backfat (BF), and average daily feed intake (ADFI) in cycle I

Item	Dietary treatment		SEM	*P*-value
	CON	LGPHASE		
Sows, n	35	35	-	-
Avg. sow parity, n[1]	1.6	1.6	-	-
Sow BW, kg				
day 70 gestation	213.8	214.9	4.03	0.842
day 110 gestation	249.7	250.3	4.98	0.915
day 2 lactation	242.4	239.7	5.65	0.638
day 19 lactation	239.7	242.8	5.63	0.577
Gestation BW change, kg[2]	35.9	35.4	3.33	0.874
Lactation BW change, kg[3]	-2.7	3.1	2.68	0.126
Overall BW change, kg[4]	25.9	27.9	3.74	0.603
Sow backfat, mm				
day 70 gestation	11.73	11.18	0.37	0.312
day 110 gestation	11.84	12.75	0.43	0.098
day 19 lactation	11.21	11.67	0.44	0.413
Gestation BF change, mm[2]	0.11	1.57	0.42	0.020
Lactation BF change, mm[3]	-0.63	-1.08	0.51	0.095
Overall BF change, mm[5]	-0.52	0.49	0.38	0.074
Gestation ADFI, kg/d	2.17	2.17	0.01	0.943
Lactation ADFI, kg/d	7.23	7.53	0.26	0.283

[1] Parity distribution (CON vs. LGPHASE): Parity 0 = 8 vs. 8; Parity 1 = 14 vs. 14; Parity 2 = 6 vs. 6; Parity 3 = 2 vs. 2; Parity 4 = 1 vs. 1; Parity 5 = 4 vs. 4.
[2]Differences refer to values on day 110 vs. day 70 of gestation.
[3]Differences refer to values on day 2 vs. day 19 of lactation.
[4]Differences refer to values on 70 of gestation vs. day 19 of lactation.
[5]Differences refer to values on day 110 of gestation vs. day 19 of lactation.

status enhances both immediate and subsequent performance (Tables 3 and 4).

The Impact of Late Gestation Nutrition on the Pig

Additionally, histologic evaluation of the 5th–7th rib growth plates was conducted by a board-certified pathologist blinded to treatment. Twelve 2-day of age litters (7 CON, 5 LG-Phase) and fifteen 17-day of age litters (9 CON, 6 LG-Phase) were evaluated. Lesions were scored as mild, mild-moderate, moderate, moderate-marked, or marked.

Body weights did not differ between treatments within age groups. Moderate or worse lesions were observed in 57% vs 27% of neonatal pigs and 85% vs 50% of weaned pigs (CON vs LG-Phase). The odds of moderate or greater lesions were 3.6× higher in neonatal CON pigs (95% CI 0.84–15.38) and 5.8× higher in weaned CON pigs (95% CI 1.41–23.49). The lesions progressed to weaning in the control pigs, whereas late-gestation phase-feeding reduced lesion prevalence and severity. From a herd health perspective, maternal nutritional programming may represent a practical strategy to improve structural soundness and reduce early-life skeletal risk.

These data highlight three critical points in the prolific sow: (1) late-gestation nutrition has a significant impact on the sow and her subsequent performance; (2) late-gestation nutrition impacts the sow's hematological health and pig livability; (3) single-cycle trials underestimate cumulative impacts on retention and lifetime productivity; (4) the impacts of nutrition above current industry levels extend to the pig. Much of the existing research evaluates pigs from only one parity, in a single phase of production, which may overlook how nutrient deficits affect the sow, compound over time, and miss key health outcomes such as farrowing duration. A systematic approach to evaluating the nutrient categories and their impact on the sow is a promising and efficient approach to assessing their impact on the sow's and pig's health and nutrition status.

Practical Nutrition Approaches to Livability Issues in Prolific Sows

Late gestation nutrition is a fundamental nutrition principle of balancing supply and need. It is feeding the sow to meet her needs and to feed the rapidly growing and developing pig, with the main difference today being that prolificacy requires nutritional changes in late gestation. By aligning nutrient supply with biological demand, producers have the opportunity to increase pigs weaned per sow, lower sow replacement costs, and strengthen

Table 3 Effects of late gestation phase feeding on sow reproductive performance in cycle

Item	Dietary treatment		SEM	*P*-value
	CON	LGPHASE		
Sows, n	35	35	-	-
Average parity, n	1.61	1.61	-	-
Farrowing duration, min[1]	360	290	22.24	0.028
Total born, n	16.47	16.50	0.87	0.980
Liveborn, n	14.67	15.17	0.73	0.592
Stillborn, n	1.18	0.60	0.31	0.090
Stillborn, %	6.79	3.36	1.89	0.099
Piglet birth wt., kg	1.50	1.51	0.05	0.858
Total litter birth wt., kg	23.12	23.00	0.94	0.877
Pigs weaned, n	12.31	13.39	0.49	0.062
Piglet wean wt., kg[2]	6.16	5.70	0.22	0.087
Total litter wean wt., kg[2]	74.96	72.89	2.58	0.572
Pigs weaned, %[3]	84.80	90.46	1.67	0.019
Pre weaning mortality, %	14.87	10.03	1.98	0.045
Wean age, days	19.19	18.90	0.30	0.491

[1]Farrowing duration adjusted for total born as a covariate

[2]Piglet wean weight and total litter wean weight adjusted for number of pigs weaned as a covariate

[3] Pigs weaned, % = (Live piglets post-fostering ÷ Liveborn piglets) × 100

overall system sustainability. Late gestation nutrition programs are being implemented with success by many top 10% farms but it requires an investment by management and a multi-faceted approach. Based on current evidence, here are a few recommendations that will reduce sow and pig mortality today:

1. A committed team member(s) to focus on sows in gestation and in farrowing and their nutrition is rewarded with lower mortality. An emphasis on daily evaluation of gestating sows for health reduces mortality 2.5-5% (Rademacher et al., 2022). Farrowing observations and assistance and Day One care and technologies to support the team effort are crucial. Ensure training and tools are available for testing and assessment of anemia and measure progress.
2. A nutrition strategy to increase the level of key nutrients in the gestation diet to reduce the days the sow needs to mobilize and transfer nutrients. While increasing the levels in the current single gestation diet may reduce the return on investment, the entire production system depends on healthy viable sows and pigs.
3. Updating feeding systems to phase feeding or two component feeding (Ribas et al., 2024; Gaillard et al., 2020). ESF's are already in place are amongst the most productive systems feeding prolific sows. The question seems to just be timing: implement now or later.
   - Implement a late gestation diet on d 70 (McClellan et al., 2025).
   - Utilize a transition diet on d 100 (Theil, 2015; Pedersen et al., 2020).
4. Discipline in assessing condition scores at entry to farrowing (Peppmeier et al., 2022). BCS have a d irect correlation to anemia, sow mortality, stillborns and pig liveability.
5. Top-dress supplements: A prenatal product that provides the amount of micronutrients needed by the sow is a straightforward approach if other feeding options are not practical.
6. Consider preventative and treatment options of anemic sows. Injectable iron is an option. While additional research needs to be conducted to address regulatory concerns and the impact on cull sow meat, anemic sows will benefit from injectable iron (McClellan et al., 2026; Guo et al., 2022; Park et al., 1983).

Table 4 Within-sow reproductive performance across two consecutive cycles with consistent dietary treatment[1]

Item	CON	LG-Phase	SEM	*P*-value[3]
Number of sows, n[2]	21	28	-	-
Average parity, n	2.1	2.1	-	-
Cycle I farrowing duration, min	373	286	31.18	0.006
Cycle II farrowing duration, min	353	275	32.16	0.018
SEM	22.27	23.20	-	-
***P* – value[4]**	0.443	0.695	-	-
Cycle I total born, n	16.54	16.57	1.25	0.838
Cycle II total born n	16.84	19.24	1.28	0.041
SEM	0.89	0.91	-	-
***P* – value**	0.977	0.024	-	-
Cycle I liveborn, n	14.75	15.64	1.07	0.409
Cycle II liveborn , n	15.00	17.70	1.09	0.015
SEM	0.77	0.78	-	-
***P* – value**	0.787	0.031	-	-
Cycle I stillborn, %	7.94	4.44	1.65	0.039
Cycle II stillborn, %	6.00	4.52	1.68	0.795
SEM	1.16	1.20	-	-
***P* – value**	0.258	0.534	-	-

[1] Data represent only sows that completed both cycle I and cycle II (n = 21 CON, n = 28 LG-Phase); Cycle I data in this table may differ from values in Table 3. because this analysis excludes sows that were removed or died before cycle II.

[2]Sows were re-enrolled on their assigned diet at d 70 during cycle II.

[3]*P*-values within a cycle compare treatments

[4]*P*-values across cycles evaluate differences between cycle I and cycle II within the same treatment.

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Nutritional and Environmental Enrichment Strategies to Mitigate Aggression in Late-gestation Sows

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Abstract

Aggression in group-housed gestating sows remains a persistent welfare and productivity challenge, particularly during late gestation when feeding motivation, competition for resources, and risk of injury may increase. Across a series of experiments conducted under commercial production conditions, we evaluated tryptophan supplementation, fiber supplementation, increased feed allowance, and hanging enrichment blocks made from molasses and beet pulp as practical strategies to reduce sow-to-sow aggression, improve welfare, reduce injuries, and improve productivity, litter, piglet performance, and stress-related outcomes. Under commercial production conditions, tryptophan supplementation did not meaningfully improve aggression or associated welfare outcomes, whereas fiber supplementation, increased feed allowance, and environmental enrichment reduced aspects of aggressive behavior between sows, and fiber reduced physiological stress. These results demonstrate that not all mitigation strategies identified under controlled research conditions translate consistently to commercial group-housing systems. Overall, strategies that increase satiety, alter feeder-associated competition, or provide enrichment may improve specific sow-level welfare outcomes, but these responses may not consistently translate into improved litter productivity or altered piglet stress responses.

Introduction

The transition from individual stall housing to group gestation systems has been driven by animal welfare concerns, legislative changes, and increasing consumer and retailer pressure to provide sows with greater behavioral freedom (Verdon et al., 2015). Although group housing allows greater movement and social interaction, it also introduces management challenges related to aggression, particularly when unfamiliar animals are mixed and dominance relationships are established (Velarde, 2007; Stevens et al., 2015; Greenwood et al., 2016). Sow aggression is a persistent welfare and production concern because it can increase body lesions, vulva injuries, stress responses, and management difficulty, while also influencing producer-facing decisions related to mixing strategies, space allowance, feeding system design, worker safety, and long-term genetic selection for social behavior and adaptability (Verdon et al., 2016). As a result, identifying practical strategies to reduce aggression in group-housed gestating sows remains a priority for improving sow welfare while maintaining productivity in commercial production systems.

Most research evaluating aggression in group-housed sows has focused on the immediate post-mixing period, when agonistic interactions are typically greatest as sows establish social hierarchies (Stevens et al., 2015; Greenwood et al., 2016; Verdon et al., 2016). While this period is important to consider, late-gestation aggression represents an additional and less-studied welfare concern. Late-gestation is commonly characterized as the period beginning around gestation d 90, coinciding with increased mammary development and preparation for farrowing (Sorensen et al., 2002). However, anecdotal observations from commercial systems suggest that aggression may increase during the final days before sows are moved to the farrowing room. This likely reflects the combined effects of late-gestation physical discomfort, increased feeding motivation, and social disruption as sows are removed for farrowing (Rizvi et al., 2000;

Stevens et al., 2015). Therefore, strategies implemented during the final week of gestation may be especially valuable for reducing injury risk immediately before farrowing, when vulva trauma, lesions, and stress may create welfare concerns and potentially complicate farrowing and early lactation management.

Although limited research has specifically evaluated mitigation of late-gestation aggression under commercial conditions, several practical nutritional and environmental strategies may have potential. Increased dietary tryptophan, increased feed allowance, and soluble fiber supplementation may reduce aggression by influencing serotonergic signaling, satiety, feeding motivation, and competition for resources (Poletto et al., 2014; Zang, 2014; Huang et al., 2020). Environmental enrichment may also redirect exploratory and oral behaviors toward manipulable substrates rather than pen mates (Marchant et al., 2023), although its effectiveness likely depends on sustained interest, accessibility, durability, and whether enrichment itself becomes a competitive resource. Importantly, these approaches must be evaluated during the late-gestation period rather than assuming responses observed at initial mixing will translate to the pre-farrowing period. In addition, because maternal stress can negatively influence offspring welfare and development (Otten et al., 2015), reducing sow aggression immediately before farrowing may benefit not only the sow but also subsequent litter outcomes and piglet stress responses. Therefore, the overall objective of these studies was to evaluate practical intervention strategies designed to mitigate aggression and welfare concerns and improve reproductive performance during the final week of gestation in commercially group-housed sows.

Materials and Methods

Animals and housing

Five experiments were conducted at the Carthage Innovative Swine Solutions High Power Pork, LLC multiplier farm (La Prairie, IL, USA) to evaluate practical strategies for reducing aggression in group-housed sows during late gestation. Across experiments, nulliparous and multiparous sows were enrolled in late gestation and allotted to group pens based on breed date and parity. Each experiment used a similar design, with pens assigned to either a control or treatment group representing one of five possible late-gestation aggression mitigation strategies: tryptophan supplementation, soluble fiber supplementation, increased feed allowance, or environmental enrichment using three hanging blocks per pen made of molasses and beet pulp. Trial-specific information including sow numbers, pens per treatment, parity, gestation days treatments started and ended, and treatment details are reported in Table 1.

Sows were housed in group pens and managed according to standard farm procedures. Diets were formulated as primarily corn and soybean meal with DDGS to meet or exceed nutritional requirements for gestating sows (Table 2; NRC, 2012), and sows were fed using an automated individual sow feeding system (GESTAL 3G electronic sow feeding system; Jyga Technologies, Saint-Lambert-de-Lauzon, QC, Canada). Control pens and environmental enrichment pens received the standard gestation diet and feeding program used by the farm (Table 2). Treatment pens received the assigned intervention during late gestation until sows were moved to farrowing (Table 2).

Sow body weights were collected before treatment initiation and again as sows entered farrowing to calculate average daily gain (ADG). Feed intake was recorded using records from an automated individual sow feeder and pen means were calculated. Sow removals and mortality were recorded throughout each experiment. Vulva scores were collected before treatment, during the treatment period, and at movement to farrowing using a previously described scoring system (AssureWel, 2020). The AssureWel protocol visually assesses the vulva region using a 0 to 2 scale, where 0 = no damage, 1 = mild recent damage including fresh or scabbed bite wounds, and 2 = severe damage including swelling, open wounds, or bleeding.

Table 1 Trial-specific sow characteristics and treatment details for four late-gestation aggression studies

	Tryptophan[1]		Fiber[2]		Feed Allowance[3]		Enrichment[4]	
Parameter	CON	TRT	CON	TRT	CON	TRT	CON	TRT
Treatment level details								
Pens, *n*	9	9	9	9	9	10	9	9
Sows/pen, sows ± SD	52.3 ± 1.6	53.6 ± 1.5	52.9 ± 2.57	52.6 ± 1.24	52.9 ± 2.57	53.0 ± 2.16	53.2 ± 2.2	53.4 ± 1.1
Experiment level details								
Parity, mean ± SD	2.7 ± 1.2		3.4 ± 2.0		2.9 ± 1.9		3.4 ± 0.6	
Allotment, gestation d ± SD	102.0 ± 2.6		101.5 ± 1.5		100.9 ± 1.9		102.0 ± 1.1	
Treatment start, gestation d ± SD	103.0 ± 1.7		102.5 ± 1.5		101.9 ± 1.9		103.0 ± 1.1	
Treatment end, gestation d ± SD	111.4 ± 1.1		111.7 ± 1.2		111.7 ± 1.1		110.7 ± 1.1	

[1]A control (CON) corn-soybean meal–DDGS based diet with 0.11% SID Trp or the CON diet supplemented with an additional 0.24% SID Trp (TRT)

[2]A control (CON) corn-soybean meal–DDGS based diet or the CON diet with 1.21 kg/d of soybean hulls to provide 100 g/d of soluble fiber (TRT)

[3]A corn-soybean meal–DDGS based diet fed at 2.5 kg/d (CON) or 3.6 kg/d (TRT)

[4]Pens provided with no hanging enrichment blocks (CON) or three evenly spaced hanging enrichment blocks (TRT; AllBite™; Alltech; Nicholasville, KY)

Four focal sows were selected within each pen to represent the parity distribution of the pen. These focal sows were used for body lesion scoring, tear stain scoring, and biological sample collection. Body lesion scores were collected pre-treatment, during the treatment period
(d 3 and 5), and at movement to farrowing following the treatment period using methods adapted from the Welfare Quality® Assessment protocol for pigs (Welfare Quality®, 2009). Tear staining was evaluated before treatment and at movement to farrowing following the treatment period using previously described methods (Telkanranta et al., 2015). Saliva samples were collected from the primary focal sow in each pen on d 3 and 5 of the treatment period for cortisol analyses.

Pens were video recorded during the treatment period to evaluate sow behavior. Video was collected on d 3 and 5 post-treatment administration in 6, two-hour periods per day. Aggressive interactions were defined based on three criteria all resulting in retreat of the other pen mate involved in the altercation: (1) forcefully knocking or pushing pen mate using head (non-belly nosing), (2) sow mounts pen mate (back two feet remain on the floor), (3) sow forcefully bites ears, face, body, or vulva of pen mate. Aggression was summarized as the average number of aggressive interactions per hour within each pen. Videos were analyzed by trained observers who maintained an interobserver agreement of at least 90%.

Table 2 Diet composition (as-fed basis)

Item	Control	Fiber	Tryptophan
Ingredient, %			
Corn	62.59	42.15	62.35
Soybean meal, 47.7 % CP	4.75	3.20	4.75
Corn DDGS	29.00	19.55	29.00
Soybean hulls	---	32.50	---
Calcium carbonate	1.89	1.28	1.89
Monocalcium phosphate, 21% P	0.22	0.15	0.22
Salt	0.47	0.32	0.47
L-Lys-HCl	0.28	0.19	0.275
L-Thr	0.05	0.03	0.05
L-Trp	0.02	0.01	0.26
Choline chloride, 60%	0.12	0.08	0.12
Vitamin and trace mineral with phytase[1]	0.25	0.17	0.25
Engage M[2]	0.05	0.05	0.05
Sal-curb[3]	0.33	0.33	0.33
Total	100.00	100.00	100.00
Calculated composition			
SID Lys	0.58	0.52	0.58
SID Ile:Lys	0.76	0.76	0.76
SID Leu:Lys	2.46	2.19	2.46
SID Met & Cys:Lys	0.78	0.72	0.78
SID Thr:Lys	0.76	0.73	0.76
SID Trp:Lys	0.20	0.19	0.60
SID Val:Lys	0.95	0.91	0.95
SID His:Lys	0.58	0.44	0.58
NE, kcal/kg	2,457	1,978	2,468
CP, %	15.42	13.82	15.41
Crude Fiber, %	3.5	14.0	3.5
NDF, %	13.90	27.47	13.88
ADF, %	5.35	16.32	5.35
Ca, %	0.84	0.74	0.84
STTD P, %	0.40	0.29	0.40

[1] Quantum Blue (AB Vista, Plantation, FL), provided an assumed release of 0.14% STTD P with 750 FTU/Kg in the control diet, and assumed release of 0.09% STTD P with 505 FTU/Kg.
[2] Mycotoxin binder, United Animal Health, Sheridan, IN.
[3] Liquid antimicrobial, Kemin Industries, Des Moines, IA.

Farrowing and lactation phase

At farrowing, litter data were collected from all enrolled sows, including the number of liveborn, stillborn, mummified, and weaned pigs. Return-to-estrus interval was recorded after weaning. Litter weaning weight was collected from the primary focal sow litters. From each primary focal sow litter, one barrow and one gilt representing the average litter body weight were selected as sentinel piglets for a standardized stress test conducted 1 d prior to weaning. Piglets were held on their back for 3 min. Immediately after the stress event, blood samples were collected for plasma cortisol analysis, and the time required to collect blood was recorded for use in the statistical analysis. Hair samples were collected from each sentinel piglet and stored for later cortisol analysis.

Cortisol analyses

Sow saliva, piglet plasma, and piglet hair samples were analyzed for cortisol concentrations as indicators of short and chronic stress responses. Cortisol was measured using commercially available enzyme-linked immunosorbent assay kits according to manufacturer instructions. Intra-assay coefficients of variation for piglet hair cortisol, sow salivary cortisol, and piglet plasma cortisol were 4.2, 4.9, and 4.7%, respectively.

Statistical analysis

Pen was considered the experimental unit. The fiber supplementation and increased feed allowance treatments were analyzed together because both treatments were designed primarily to improve sow satiety during late gestation. The tryptophan supplementation and environmental enrichment trials were analyzed independently. Treatment was the primary fixed effect for sow performance, litter characteristics, piglet performance, and piglet stress-response outcomes. For repeated measures, including sow injuries, tear staining, salivary cortisol, and aggressive behavior, models included treatment, day, time when appropriate, and their interactions. For sow injury and tear staining outcomes, statistical models failed to converge; therefore, these data were excluded from statistical analyses and were presented descriptively. Pen and block were included as random effects when appropriate. Blood collection duration was included as a covariate for piglet plasma cortisol analysis. Statistical significance was defined as $P \leq 0.05$, and tendencies were considered when $0.05 < P \leq 0.10$.

Results and Discussion

Tryptophan

Results have been previously reported by Hopkins et al. (2026a), and relevant data are presented in Table 3. Dietary supplementation with an additional 0.24% SID tryptophan during late gestation did not reduce aggressive interactions or improve sow performance under commercial group-housing conditions. Sow body weight, ADG, ADFI, and return to estrus interval were not affected by treatment, indicating that increasing dietary tryptophan during this late-gestation window did not alter short-term maternal growth or feed intake responses. Similarly, lesion score, vulva score, and tear staining score did not differ between treatments (data not presented). Tryptophan supplementation also did not improve litter characteristics, including total born, live born, stillborn, mummies, number weaned, or litter weaning weight. These results suggest that, under the conditions of this study, 0.24% added tryptophan was not sufficient to produce measurable improvements in sow productivity, welfare-related scores, or subsequent litter performance.

Tryptophan supplementation also did not affect sow salivary cortisol or piglet plasma and hair cortisol concentrations, suggesting that the treatment did not measurably alter sow physiological stress or offspring stress-related outcomes at weaning. Although tryptophan has been proposed as a nutritional strategy to influence serotonergic pathways associated with behavior and aggression, the lack of treatment effects on aggression, cortisol responses, welfare-related scores, and production outcomes suggests that this strategy may have limited efficacy when applied during the final week of gestation in large commercial groups. Independent of treatment, aggressive interactions were reduced ($P < 0.01$) from d 3 to d 5 post-treatment administration, with sows averaging 25.1 ± 1.2 versus 20.2 ± 1.2 aggressive interactions/h, respectively (data not presented), suggesting that aggression declined over time as sows acclimated to the feeding period, pen environment, or social dynamics. Therefore, the overall lack of treatment response may reflect both the short supplementation period and the complexity of aggression in commercial group-housed systems, where behavior is influenced by group size, resource competition, social hierarchy, and feeder access. Overall, late-gestation tryptophan supplementation at this inclusion level and duration did not appear to be an effective standalone strategy for reducing aggression or improving sow, litter, welfare-related, or piglet stress-related outcomes.

Added fiber and increased feed allowance

Results have been previously reported by McAuley et al. (2026), and relevant data are available in Table 4 and Figures 1, 2, and 3. Increasing feed allowance and added soluble fiber during late gestation increased ADFI and ADG under commercial group-housing conditions. Initial sow body weight did not differ among treatments, indicating that treatment groups were similar at the start of the study. However, farrow entry body weight was greater ($P = 0.04$) for sows fed added fiber compared with control sows, while sows receiving increased feed allowance were intermediate. Average daily gain was increased ($P < 0.01$) for sows receiving increased feed allowance or added fiber compared with control sows, corresponding to approximately 63 and 73% greater ADG, respectively. Average daily feed intake was increased ($P < 0.01$) by both feed allowance and added fiber versus control sows, with the greatest ADFI observed in sows receiving increased feed allowance and intermediate intake observed in added fiber-fed sows. The increase in intake was expected for both treatment groups as daily feed allotment was increased by 1.13 and 1.21 kg/d for feed allowance and fiber sows, respectively. Despite increased ADFI and improved ADG, litter performance was not improved by either treatment, likely indicating that the limited duration of late-gestation dietary intervention was not associated with measurable improvements in reproductive success.

Table 3 Effects of supplemental dietary tryptophan during late gestation on sow performance, litter characteristics, cortisol responses, and aggression in commercially group-housed sows

Characteristic	CON	TRP	SEM	*P*-value
Sow performance				
Initial BW, kg	256.85	252.33	2.53	0.22
Final BW, kg	268.22	264.41	2.77	0.35
ADG, kg/d	1.10	1.17	0.04	0.23
ADFI, kg/d	2.44	2.40	0.07	0.43
Return to estrus interval, d	5.02	4.74	0.20	0.30
Litter characteristics				
Total born, n	17.04	17.34	0.19	0.30
Live born, n	15.17	15.31	0.19	0.60
Stillborn, n	1.45	1.50	0.10	0.70
Mummies, n	0.39	0.45	0.04	0.20
Number weaned, n	13.14	13.10	0.18	0.90
Weaning BW, kg	74.55	76.71	3.01	0.62
Cortisol				
Sow salivary cortisol, ng/mL	6.94	7.22	0.79	0.80
Piglet plasma cortisol, ng/mL	43.39	40.25	6.82	0.75
Piglet hair cortisol, pg/mg	5.65	7.81	1.46	0.16
Aggression				
Total aggression, interactions/h	22.60	22.60	1.40	0.71

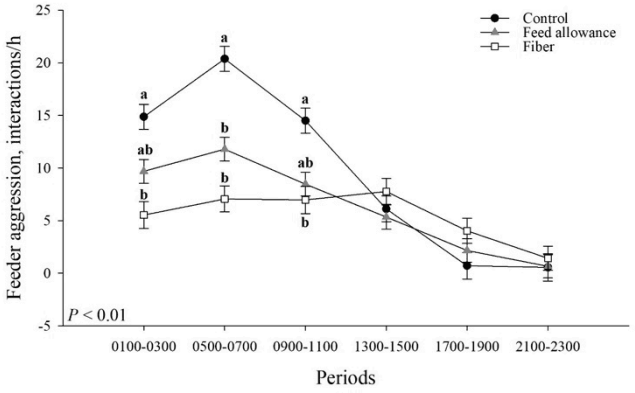

Figure 1 Effect of late-gestation control, feed allowance, and added fiber diet treatments on feeder-associated aggressive interactions across time periods. Within each time period, different superscripts (a,b) differ ($P < 0.01$), whereas means sharing a superscript do not differ

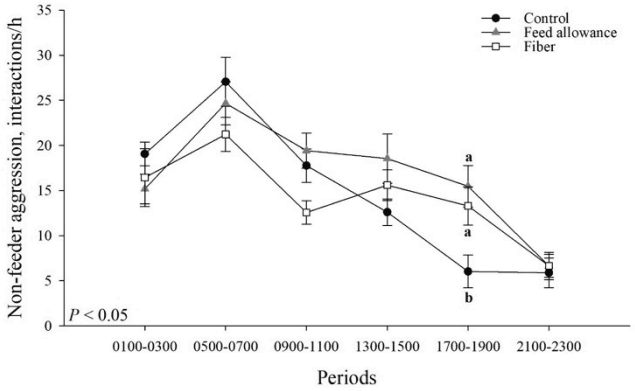

Figure 2 Effect of late-gestation control, feed allowance, and added fiber diet treatments on feeder-associated aggressive interactions across time periods. Within each time period, different superscripts (a,b) differ ($P < 0.05$), whereas means sharing a superscript do not differ

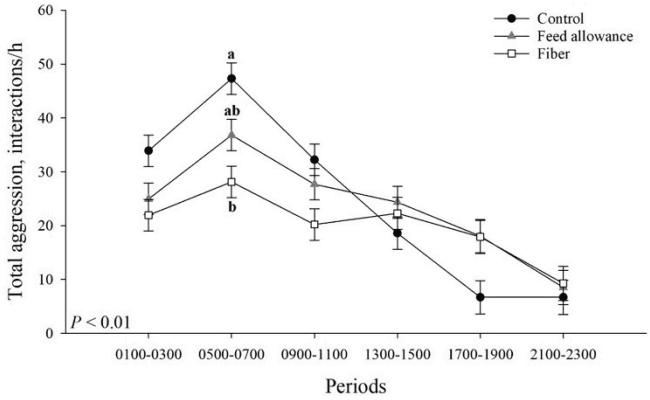

Figure 3 Effect of late-gestation control, feed allowance, and added fiber diet treatments on total aggressive interactions across time periods. Within each time period, different superscripts (a,b) differ ($P < 0.01$), whereas means sharing a superscript do not differ

Furthermore, lesion score, vulva score, and tear staining scores did not differ between treatments (data not presented).

Dietary treatment also influenced sow physiological stress responses. Sow salivary cortisol was reduced ($P < 0.01$) in added fiber sows compared with sows receiving increased feed allowance and control sows were intermediate. However, piglet plasma cortisol did not differ among treatments ($P = 0.40$) and although piglet hair cortisol tended to differ among treatments ($P = 0.07$), mean separation did not indicate differences among treatment groups. These responses suggest that added soluble fiber may have reduced physiological stress in sows, but treatment effects were not reflected in piglet cortisol measures.

The temporal distribution of aggressive behavior also differed among treatments. Across the entire observation period feeder-associated aggression was reduced ($P < 0.01$) in increased feed allowance and added fiber sows when compared with control pens, but no overall dietary treatment differences ($P > 0.10$) in total aggressive interactions and non-feeder aggression were observed. Feeder-associated aggression differences by treatment were most apparent during the early observation periods. From 0100 to 0300 h, feeder aggression was lower in added fiber pens than control pens, with increased feed allowance pens being intermediate. From 0500 to 0700 h, both increased feed allowance and fiber-fed pens had lower feeder aggression than control pens. A similar pattern was observed from 0900 to 1100 h, where fiber-fed pens had lower feeder aggression than control pens and increased feed allowance pens were intermediate. In contrast, non-feeder aggression followed a different pattern across the day with greater non-feeder aggression observed from 1700 to 1900 h in increased feed allowance and added fiber pens compared with control pens. Finally, total aggression was reduced ($P < 0.01$) in added fiber sows from 0500 to 0700, sows when compared to control sows while feed allowance sows were intermediate. These data indicate that feed-based interventions did not uniformly reduce all forms of aggression but instead altered when and where aggression occurred. Specifically, increased feed allowance and soluble fiber inclusion reduced feeder-associated aggression during the early part of the day, coinciding with the start of the automated feeder system's 24-h feeding cycle, whereas non-feeder aggression was transiently greater later in the day.

Taken together, these data indicate that late-gestation feed-based interventions improved sow feed intake and weight gain while altering the daily pattern of aggressive behavior. Soluble fiber appeared to provide the more favorable overall response because it reduced sow salivary cortisol relative to increased feed allowance and reduced feeder-associated aggression compared with

control pens. In contrast, increased feed allowance improved sow performance and reduced feeder-associated aggression but did not provide the same physiological stress benefit. Therefore, added soluble fiber may be a more promising nutritional strategy for improving sow welfare during late gestation under commercial group-housing conditions, although neither intervention improved litter performance.

Table 4 Effects of increased feed allowance or soluble fiber inclusion during late gestation on sow performance, litter characteristics, cortisol responses, and aggression in commercially group-housed sows

Characteristic	CON	Feed allowance	Fiber	SEM	*P*-value
Sow performance					
Initial BW, kg	264.31	262.63	265.67	2.58	0.71
Final BW, kg	276.37[a]	282.41[ab]	285.81[b]	2.39	0.04
ADG, kg/d	1.03[a]	1.68[b]	1.78[b]	0.02	< 0.01
ADFI, kg/d	2.42[a]	3.48[c]	3.15[b]	0.03	< 0.01
Litter characteristics					
Total born, n	17.23	17.02	16.93	0.20	0.53
Live born, n	15.23	14.91	14.92	0.19	0.37
Stillborn, n	1.53	1.62	1.59	0.09	0.70
Mummies, n	0.42	0.42	0.39	0.04	0.69
Number weaned, n	12.48	12.61	12.48	0.19	0.84
Sow fallout, %	7.0	8.4	8.1	1.3	0.71
Cortisol					
Sow salivary cortisol, ng/mL	6.85[ab]	7.87[a]	4.19[b]	0.98	< 0.01
Piglet plasma cortisol, ng/mL	49.80	46.00	36.09	17.13	0.40
Piglet hair cortisol, pg/mg	5.27	7.07	6.31	0.83	0.07
Aggression					
Non-feeder aggression, interactions/h	14.73	16.65	14.29	3.19	0.32
Feeder aggression, interactions/h	9.51[a]	6.34[b]	5.46[b]	0.72	<0.01
Total aggression, interactions/h	24.22	23.39	19.94	1.73	0.18

Environmental enrichment

Results have been previously reported by Hopkins et al. (2026b), and relevant data are available in Table 5. Provision of molasses and beet pulp-based enrichment blocks during late gestation reduced total aggressive interactions in commercially group-housed sows ($P = 0.02$). Feeder-based aggression also tended to be reduced in sows provided enrichment blocks ($P = 0.09$), whereas non-feeder aggression was not affected ($P > 0.10$). Although the magnitude of the reduction in aggression was modest, these data suggest that enrichment blocks may have provided an alternative outlet for exploratory or oral behavior, thereby redirecting some sow activity away from pen-mate aggression, particularly around feeder areas. This response is relevant under commercial conditions where large group size, competition for resources, and late-gestation social instability can contribute to increased aggression and injury risk. Independent of treatment, feeder-based, non-feeder-based, and total aggressive interactions were greater ($P < 0.01$) on d 3 compared with d 5 by 13.7, 6.2, and 17.1%, respectively, and aggressive interactions declined ($P < 0.01$) by 85.7% from 0100–0300 h to 2100–2300 h. These temporal responses indicate that aggressive behavior was greatest earlier in the treatment period and during earlier observation windows, but decreased as sows acclimated to the enrichment objects, pen environment, or social conditions.

In addition to reducing aggression, enrichment increased sow average daily feed intake ($P = 0.05$), although sow average daily gain and body weight were not affected ($P > 0.10$). Moreover, lesion score, vulva score, and tear staining score did not differ between treatments (data not presented). Enrichment did not affect total born, live born, stillborn, or mummies ($P > 0.10$), but number weaned tended to be greater for sows provided enrichment blocks ($P = 0.10$). Similarly, sow salivary cortisol and piglet hair cortisol were not affected by enrichment ($P > 0.10$), whereas piglet plasma cortisol tended to be reduced in piglets from sows provided enrichment blocks ($P = 0.10$). These responses suggest that enrichment blocks may have modestly improved sow behavioral outcomes and may have contributed to small improvements in feed intake, piglet stress responsiveness, and weaning output; however, the effects were not broad enough to substantially alter most sow performance, litter characteristics, or physiological stress biomarkers under these commercial conditions.

Overall, these results indicate that molasses and beet pulp-based enrichment blocks may be a practical strategy to modestly reduce late-gestation aggression in commercially group-housed sows, particularly feeder-associated aggression. The tendency for reduced piglet plasma cortisol and increased number weaned suggests

Table 5 Effects of environmental enrichment during late gestation on sow performance, litter characteristics, cortisol responses, and aggression in commercially group-housed sows

Characteristic	CON	BLOCK	SEM	*P*-value
Sow performance				
Initial BW, kg	262.70	263.50	1.83	0.70
Final BW, kg	272.36	273.51	1.73	0.50
ADG, kg/d	0.93	0.99	0.03	0.18
ADFI, kg/d	2.21	2.26	0.02	0.05
Litter characteristics				
Total born, n	17.47	17.53	0.19	0.84
Live born, n	15.07	15.26	0.19	0.49
Stillborn, n	1.89	1.72	0.13	0.34
Mummies, n	0.44	0.46	0.04	0.71
Number weaned, n	12.10	12.49	0.17	0.10
Cortisol				
Sow salivary cortisol, ng/mL	7.85	7.06	1.34	0.58
Piglet plasma cortisol, ng/mL	49.43	37.40	5.19	0.10
Piglet hair cortisol, pg/mg	7.11	7.30	0.98	0.87
Aggression				
Non-feeder aggression, interactions/h	2.22	2.09	0.47	0.25
Feeder aggression, interactions/h	5.21	4.34	2.39	0.09
Total aggression, interactions/h	15.02	12.46	2.49	0.02

the potential for downstream benefits, but these responses should be interpreted cautiously because they did not reach the threshold for statistical significance. Additional refinements in enrichment type, quantity, placement, timing, or duration may be needed to determine whether behavioral improvements can be translated into more consistent physiological or litter productivity responses.

Conclusions

Overall, these studies demonstrate that late-gestation nutritional and environmental strategies produced variable sow-level responses under commercial group-housing conditions, but these responses did not consistently translate into improved production outcomes or altered piglet stress physiology. Supplemental tryptophan did not reduce aggression or improve sow or litter performance. Increasing feed allowance or adding soluble fiber improved sow feed intake and weight gain, and soluble fiber reduced sow salivary cortisol concentrations, suggesting a potential benefit for sow physiological stress; however, neither treatment improved litter characteristics nor piglet survival through weaning. Environmental enrichment blocks produced the clearest reduction in aggressive interactions, but this behavioral improvement was not accompanied by measurable changes in sow cortisol, piglet cortisol, or litter productivity. Across studies, piglet plasma and hair cortisol responses were largely unaffected d by treatment, indicating that sow-level behavioral or physiological responses were not consistently reflected in offspring stress measures at weaning. Collectively, these results suggest that late-gestation aggression in commercially housed sows is difficult to modify through a single intervention and is likely influenced by complex interactions among feeding motivation, resource access, satiety, enrichment opportunity, and pen-level social dynamics.

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Impacts of Evaluation of *Bacillus subtilis* Combined with Plant Extracts as a Feed Additive for Weaned Pigs

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Abstract

Newly weaned pigs often experience reduced feed intake, diarrhea, inflammation, and impaired intestinal function as they adjust to a new diet and environment. This study evaluated whether a commercial blend of Bacillus subtilis, a beneficial spore-forming bacterium, and plant extracts could help pigs manage this transition. A total of 240 pigs were fed one of four diets for 28 days: an unsupplemented control diet, the control diet supplemented with the blend at 500 or 1,000 mg/kg, or the control diet supplemented with carbadox as an antibiotic comparison. Overall growth performance was similar among treatments, but pigs receiving the blend experienced less frequent and less severe diarrhea. The blend also reduced early signs of inflammation, helped regulate antioxidant defenses, reduced signs of intestinal inflammation by day 28, and was associated with intestinal changes consistent with improved adaptation after weaning. Gut bacterial communities changed mainly as the pigs aged rather than in response to the diets, suggesting that these benefits occurred without broadly disrupting normal microbiome development. Overall, the blend improved post-weaning resilience and may provide a practical non-antibiotic strategy for supporting nursery pig health.

Introduction

Weaning is a major challenge for young pigs because their digestive, immune, and microbial systems are still developing. Separation from the sow, mixing, and the transition to dry feed can reduce feed intake and increase intestinal inflammation, oxidative stress, and diarrhea, resulting in greater treatment needs and less predictable nursery performance (Moeser et al., 2017; Upadhaya and Kim, 2021; Tang et al., 2022).

As antibiotic use becomes more restricted, interest has increased in nutritional strategies that support pigs during this transition. *Bacillus subtilis* is a stable, spore-forming beneficial bacterium that may support digestion, intestinal function, immunity, and microbial balance. Plant-derived compounds such as cinnamaldehyde and thymol also have antimicrobial, antioxidant, and anti-inflammatory properties. Combining *Bacillus subtilis* with plant extracts may therefore provide complementary benefits during the post-weaning period (Deng et al., 2020; Li et al., 2012; Zhao et al., 2023).

This study evaluated the effects of *Bacillus subtilis* combined with plant extracts on growth performance, diarrhea, immune and oxidative responses, intestinal health, and fecal microbiome development in weaned pigs. We hypothesized that supplementation would reduce diarrhea and inflammatory stress while maintaining growth and supporting intestinal adaptation.

Experimental Approach

The experiment was conducted at the Michigan State University Swine Teaching and Research Center. A total of 240 pigs weaned at 21 ± 1 d of age, with equal numbers of barrows and gilts, were blocked by initial body weight (BW) and litter and assigned to four dietary treatments in a randomized complete block design. Each treatment included 10 pens with six pigs per pen, and the pen was the experimental unit for growth performance and clinical observations. The 28-d nursery period was divided into phase 1 (d 0 to 14) and phase 2 (d 14 to 28).

The treatments were: 1) a basal nursery diet without additive supplementation (CON); 2) CON plus 500 mg/kg of *Bacillus subtilis* combined with plant extracts (BPS); 3) CON plus 1,000 mg/kg of the same combination (BPD); and 4) CON plus 50 mg/kg carbadox (CBX). The commercial *Bacillus subtilis* and plant-extract product was TruPhyte Pro (JH Biotech, Inc., Ventura, CA, USA), and carbadox was purchased from Phibro Animal Health Corporation (Teaneck, NJ, USA). Diets were fed in mash form and formulated to meet or exceed nutrient requirements (NRC, 2012). The diets did not contain

spray-dried plasma or pharmacological concentrations of zinc oxide. Basal diet ingredient composition is presented in Table 1.

Table 1 Ingredient compositions of experimental diets[1]

Ingredient, %	Control Phase1	Control Phase2
Corn	44.41	57.27
Dried whey	15.00	10.00
Soybean meal	18.00	22.00
Fish meal	10.00	7.00
Lactose	6.00	-
Soy protein concentrate	3.00	-
Soybean oil	2.00	2.00
Limestone	0.56	0.70
L-Lysine·HCl	0.21	0.23
DL-Methionine	0.08	0.05
L-Threonine	0.04	0.05
Salt	0.40	0.40
Vit-mineral, Sow 6[2]	0.30	0.30
Total	100.00	100.00

[1]In each phase, three additional diets will be formulated by adding 500 or 1000 mg/kg of *Bacillus subtilis* combined with plant extracts, or 50 mg/kg or carbadox to the control diet, respectively.

Pig BW and feed disappearance were recorded on d 0, 7, 14, 21, and 28 to calculate average daily gain (ADG), average daily feed intake (ADFI), and gain-to-feed ratio (G:F). Diarrhea was scored twice daily on a 1-to-5 scale, where 1 represented normal feces and 5 represented watery diarrhea. Frequency was calculated as the percentage of pen-days with a score of at least 3 or at least 4. Blood was collected from six pigs per treatment on d 0, 7, 14, 21, and 28 to measure acute-phase, inflammatory, and oxidative-status biomarkers. Six pigs per treatment were euthanized on d 14 and d 28 for intestinal morphology and mucosal gene-expression analyses. Fecal samples collected on d 0, 14, and 28 were analyzed using shotgun metagenomic sequencing.

Data were analyzed as a randomized complete block design. Statistical significance was declared at $P < 0.05$, and responses from $0.05 \leq P < 0.10$ were interpreted cautiously as tendencies. The protocol was approved by the Michigan State University Institutional Animal Care and Use Committee (PROTO202300333).

Results and Discussion

Growth performance and feed utilization

During phase 1, ADFI differed among treatments ($P < 0.01$; Table 2). Despite these differences in intake, phase 1 ADG and G:F were not affected. From d 15 to 21, CON pigs consumed more feed than pigs in all supplemented groups, while a pairwise comparison indicated better G:F for CBX than CON. Across the complete 28-d period, overall ADG, ADFI, and G:F did not differ in the overall treatment tests. Final BW was numerically 0.42 to 0.51 kg greater in BPS, BPD, and CBX pigs than in CON pigs.

The growth response is best interpreted as maintenance of performance rather than a classic feed-intake or growth-promoting effect. BPS pigs-maintained BW gain during the early nursery period despite lower feed intake. This pattern is consistent with, but does not prove, improved nutrient use, a lower inflammatory cost, or more efficient intestinal adaptation. Digestibility was not measured, so the present data cannot identify the specific cause. Previous studies have reported improved digestive activity or feed efficiency with *Bacillus subtilis*, plant extracts, or their combination, but the magnitude and timing of the response depend on the strain, extract composition, diet, and health challenge (Deng et al., 2020; Tan et al., 2020; Zhao et al., 2023).

Table 2 Growth performance of weaned pigs fed diets supplemented with *Bacillus subtilis* combined with plant extracts

Item[1]	CON[2]	BPS[3]	BPD[4]	CBX[5]	SEM	*P*-value		
						Diet	*Lin*	*Quad*
BW, kg								
day 0	6.11	6.14	6.12	6.12	0.17	0.91	0.80	0.52
day 7	6.44	6.46	6.48	6.45	0.17	0.97	0.70	0.95
day 14	7.46	7.44	7.39	7.46	0.22	0.93	0.47	0.86
day 21	9.32^{b}	9.56^{ab}	9.60^{ab}	9.75^{a}	0.20	0.16	0.17	0.54
day 28	12.77	13.28	13.19	13.26	0.27	0.26	0.17	0.22
ADG, g/d								
day 0 to 7	63	51	58	56	6.23	0.62	0.59	0.23
day 7 to 14	167	164	152	168	14.39	0.67	0.25	0.98
Phase 1[6]	106	99	98	103	8.04	0.81	0.29	0.71
day 15 to 21	365	372	369	403	14.41	0.20	0.85	0.80
day 21 to 28	577	604	593	585	21.83	0.79	0.55	0.40
Phase 2[7]	435	455	446	456	12.77	0.57	0.53	0.32
Overall[8]	248	265	261	265	7.53	0.29	0.21	0.23
ADFI, g/d								
day 0 to 7	107^{a}	96^{b}	107^{a}	106^{a}	4.57	<0.01	0.81	<0.01
day 7 to 14	205^{b}	198^{c}	219^{a}	199^{bc}	5.74	<0.01	<0.01	<0.01
Phase 1	154^{b}	147^{c}	161^{a}	153^{b}	4.07	<0.01	<0.01	<0.01
day 15 to 21	470^{a}	437^{b}	441^{b}	443^{b}	10.30	<0.01	0.01	0.03
day 21 to 28	836	830	823	818	24.09	0.67	0.25	0.93
Phase 2	597	589	587	589	15.77	0.70	0.21	0.69
Overall	354	349	355	351	7.59	0.63	0.92	0.18
Gain:Feed								
day 0 to 7	0.58	0.50	0.54	0.53	0.06	0.809	0.60	0.41
day 7 to 14	0.81	0.83	0.71	0.83	0.06	0.273	0.11	0.50
Phase 1	0.68	0.67	0.63	0.67	0.05	0.715	0.22	0.81
day 15 to 21	0.79^{b}	0.85^{ab}	0.84^{ab}	0.91^{a}	0.03	0.064	0.28	0.39
day 21 to 28	0.70	0.73	0.72	0.71	0.03	0.733	0.49	0.36
Phase 2	0.73	0.77	0.75	0.77	0.02	0.407	0.50	0.24
Overall	0.70	0.76	0.73	0.75	0.02	0.236	0.37	0.11

[a,b]Within a row, means without a common superscript differ ($P < 0.05$).
[1]BW = body weight, ADG = average daily gain, ADFI = average daily feed intake, and G:F = gain:feed.
[2]CON = the complex nursery basal diet; Control
[3]BPS = CON + 500 mg/kg *Bacillus subtilis* combined with plant extracts
[4]BPD = CON + 1000 mg/kg *Bacillus subtilis* combined with plant extracts
[5]CBX = CON + 50 mg/kg carbadox
[6]Phase 1= weaning day (day 0) to day 14 of experiment
[7]Phase 2= day 14 to 28 of experiment
[8]Overall= weaning day (day 0) to day 28 of experiment

Diarrhea control

The reduction in diarrhea was the clearest and most practically relevant response. The complete 28-d period, the frequency of diarrhea scores of at least 3 was 28.09% in CON, 17.59% in BPS, 20.68% in BPD, and 21.91% in CBX pigs (P = 0.01). The frequency of severe diarrhea scores of at least 4 was 6.17%, 2.78%, 2.78%, and 2.16%, respectively (P = 0.02; Table 3). Thus, both inclusion levels reduced overall diarrhea and severe diarrhea, but BPS produced the most consistent respons e across phases and individual observation days.

Table 3 Frequency of diarrhea of weaned pigs fed diets supplemented with *Bacillus subtilis* combined with plant extracts

Item	CON[2]	BPS[3]	BPD[4]	CBX[5]	*P*-value
Frequency of diarrhea ≥ 3					
Phase 1[6]	30.13[a]	17.95[b]	23.08[ab]	23.08[ab]	0.09
Phase 2[7]	26.19[a]	17.26[b]	18.45[ab]	23.21[ab]	0.16
Overall[8]	28.09[a]	17.59[b]	20.68[b]	21.91[ab]	0.01
Frequency of diarrhea, ≥ 4					
Phase 1	7.69[a]	5.13[ab]	3.21[ab]	2.56[b]	0.13
Phase 2	2.98	0.60	2.38	1.79	0.43
Overall	6.17[a]	2.78[b]	2.78[b]	2.16[b]	0.02

[a,b]Within a row, means without a common superscript differ (P < 0.05).
[1]Frequency = number of pen days with fecal score ≥ 3 or ≥ 4
[2]CON = the complex nursery basal diet; Control
[3]BPS = CON + 500 mg/kg *Bacillus subtilis* combined with plant extracts
[4]BPD = CON + 1000 mg/kg *Bacillus subtilis* combined with plant extracts
[5]CBX = CON + 50 mg/kg carbadox
[6]Phase 1= weaning day (day 0) to day 14 of experiment
[7]Phase 2= day 14 to 28 of experiment
[8]Overall= weaning day (day 0) to day 28 of experiment

The lack of a simple linear dose response is important for practical application. Doubling the inclusion from 500 to 1,000 mg/kg did not consistently improve fecal outcomes. Post-weaning diarrhea is multifactorial and can reflect limited digestive capacity, epithelial disruption, inflammation, oxidative stress, and microbial instability (Han et al., 2024). *Bacillus subtilis* and plant bioactives may address several of these factors through enzyme and antimicrobial production, support of epithelial function, and modulation of inflammatory and oxidative pathways. Previous work with essential oils alone or combined with a *Bacillus*-based direct fed microbials also reduced diarrhea in weaned pigs (Li et al., 2012; Tan et al., 2020). The current study did not isolate a single mechanism, and the response is more likely the result of coordinated host and microbial effects.

Systemic immune and oxidative responses

On d 7, serum C-reactive protein (CRP) was lower in BPS, BPD, and CBX pigs than in CON pigs (P = 0.01; Table 4). Glutathione peroxidase (GPx) activity on d 7 was greater in BPS pigs than in CON and CBX pigs (P = 0.04;). These responses indicate attenuation of the early acute-phase response and selective support of antioxidant defense during the first week after weaning. Similar antioxidant and anti-inflammatory responses have been reported with cinnamaldehyde- and thymol-containing plant extracts (Li et al., 2012; Niu et al., 2024).

Later biomarker responses were less uniform. Serum amyloid A (SAA) was greater in BPS pigs on d 21 than in CON and CBX pigs, while d 28 GPx and thiobarbituric acid reactive substances (TBARS) differed among treatments in different directions. BPS and CBX had lower TBARS than BPD on d 28, whereas CON was intermediate. These findings caution against describing the additive as producing a uniform increase in every antioxidant or immune marker. The strongest systemic evidence was the lower early CRP response, which aligned with the reduction in diarrhea, while the later biomarker pattern reflected dynamic adaptation rather than a single-direction response.

Table 4 Selected serum immune and oxidative-status biomarkers

Item	CON[1]	BPS[2]	BPD[3]	CBX[4]	SEM	*P*-value
day 7 PW[11]						
TNF-α, pg/mL	157.41[a]	122.86[ab]	115.22[b]	126.72[ab]	14.17	0.18
CRP, ng/mL	252.77[a]	86.71[b]	144.94[b]	60.75[b]	43.80	0.01
Haptoglobin, ng/mL	45.69	50.75	75.74	50.54	23.74	0.71
GPx (nmol/min/ml)	223.39[b]	276.93[a]	244.53[ab]	196.11[b]	17.60	0.04
TBARS (μM MDA)	1.22	1.84	2.15	1.48	0.42	0.53
SAA (μg/ml)	147.30	127.50	153.25	112.60	14.66	0.32
day 14 PW						
TNF-α, pg/mL	139.55	110.97	107.88	122.55	14.56	0.44
CRP, ng/mL	174.67	91.44	63.06	50.64	37.11	0.13
Haptoglobin, ng/mL	41.46	77.10	82.79	69.29	25.84	0.69
GPx (nmol/min/ml)	296.49	254.2	250.01	235.72	34.43	0.60
TBARS (μM MDA)	1.65	1.60	1.41	1.25	0.24	0.68
SAA (μg/ml)	212.58	155.90	198.29	176.50	32.20	0.64
day 21 PW						
TNF-α, pg/mL	104.38	98.55	115.74	115.18	15.69	0.54
CRP, ng/mL	255.81	293.85	115.95	161.21	79.05	0.39
Haptoglobin, ng/mL	142.92[ab]	152.93[a]	68.39[b]	119.35[ab]	25.55	0.16
GPx (nmol/min/ml)	220.08[ab]	168.59[b]	233.93[a]	225.56[a]	27.69	0.10
TBARS (μM MDA)	1.93	1.34	1.78	1.94	0.27	0.35
SAA (μg/ml)	132.87[b]	267.82[a]	169.67[ab]	184.10[b]	31.77	0.01
day 28 PW						
TNF-α, pg/mL	125.95	101.54	120.95	101.79	15.69	0.54
CRP, ng/mL	148.20	101.51	116.36	75.62	36.22	0.57
Haptoglobin, ng/mL	138.32	149.99	83.30	141.04	24.28	0.17
GPx (nmol/min/ml)	151.23[bc]	124.37[c]	206.61[ab]	214.42[a]	19.70	0.02
TBARS (μM MDA)	1.60[ab]	1.06[bc]	1.64[a]	0.72[c]	0.17	0.01
SAA (μg/ml)	114.33	123.88	132.75	109.40	9.38	0.39

CRP = C-reactive protein (ng/mL); GPx = glutathione peroxidase (nmol/min/mL); SAA = serum amyloid A (μg/mL); TBARS = thiobarbituric acid reactive substances (μM MDA); MDA = malondialdehyde. [a-c]Within a row, means without a common superscript differ (P < 0.05).

Intestinal inflammatory regulation and morphology

Intestinal gene-expression responses changed with time. On d 14, BPD reduced occludin (OCLN) expression relative to CON, while CBX increased tumor necrosis factor-α (TNF-α) and mucin 2 expression relative to selected supplemented groups (Table 5). By d 28, the pattern had shifted: OCLN expression was greatest in BPD pigs, and interleukin-1β (IL-1β) and TNF-α expression were lower in BPS, BPD, and CBX pigs than in CON pigs. The later reduction in mucosal pro-inflammatory signaling is consistent with studies in which cinnamaldehyde-, thymol-, and carvacrol-containing blends reduced intestinal cytokine responses and supported barrier function (Shao et al., 2023; Zhao et al., 2023). The transient d 14 responses also show that the timing of sample collection is important when interpreting feed-additive effects.

Intestinal morphology on d 28 showed favorable, although not statistically conclusive, patterns in supplemented pigs. The jejunal villus-height-to-crypt-depth ratio (VH:CD) was numerically greatest in BPD pigs, compared with CON pigs. Similarly, the VH:CD was greatest in BPS pigs, compared with CON pigs, with BPD and CBX intermediate. Because the overall treatment effects for these ratios were not significant, these findings should be interpreted as supportive trends rather than direct evidence of improved nutrient absorption. Nevertheless, when considered alongside reduced diarrhea and lower intestinal IL-1β and TNF-α expression on d 28, the results suggest improved intestinal adaptation and epithelial stability after weaning (Deng et al., 2020; Zhao et al., 2023).

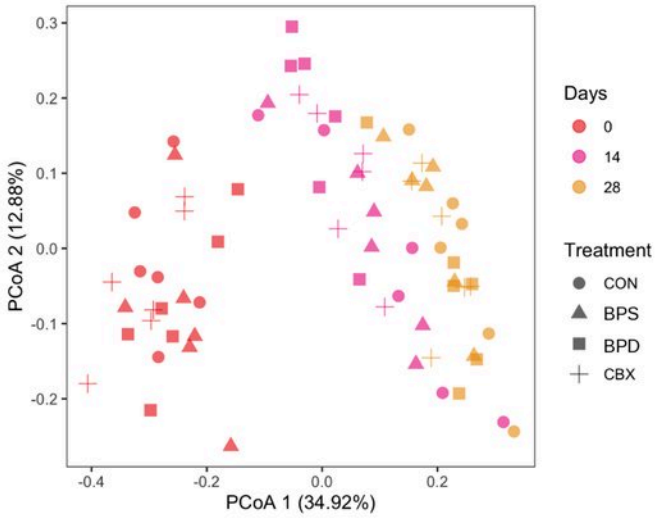

Figure 1 Principal coordinates analysis of fecal microbial beta diversity. Each point represents one pig sample; color denotes sampling day and symbol denotes dietary treatment. Samples separated primarily by day post-weaning, whereas substantial overlap occurred among treatments within each day.

Table 5. Selected intestinal gene-expression and morphology responses

Item	CON[2]	BPS[3]	BPD[4]	CBX[5]	*P*-value
OCLN, d 14	1.00^{a}	0.79^{ab}	0.60^{b}	0.80^{ab}	0.09
TNFα, d 14	1.00^{b}	1.10^{b}	1.19^{b}	1.58^{a}	0.18
MUC2, d 14	1.00^{ab}	0.88^{bc}	0.52^{c}	1.32^{a}	0.20
OCLN, d 28	1.00^{c}	1.33^{bc}	1.67^{a}	1.37^{ab}	0.12
IL1β, d 28	1.00^{a}	0.72^{b}	0.59^{b}	0.60^{b}	0.12
TNFα, d 28	1.00^{a}	0.68^{b}	0.61^{b}	0.68^{b}	0.08
Jejunal VH:CD, d 28	1.12^{b}	1.20^{ab}	1.36^{a}	1.22^{ab}	0.07
Ileal VH:CD, d 28	1.17^{b}	1.46^{a}	1.41^{ab}	1.38^{ab}	0.11

Gene-expression data are presented relative to CON, which was set to 1.00. OCLN = occludin; TNFα = tumor necrosis factor-α; MUC2 = mucin 2; IL1β = interleukin-1β. $^{a-c}$Within a row, means without a common superscript differ ($P < 0.05$).

Fecal microbiome development

Principal coordinates analysis showed that samples clustered primarily by sampling day rather than dietary treatment (Figure 1). Day 0 samples were clearly separated from d 14 and d 28 samples, whereas treatment groups overlapped substantially within each sampling day. Canonical analyses likewise identified age and time after weaning as the primary drivers of microbial community structure.

Selected minor taxa differed among treatments, including a greater abundance of Cytophagia in supplemented pigs on d 28, but there was no broad restructuring of the dominant fecal community. This result is biologically plausible because the pig fecal microbiome changes rapidly with age and the transition from milk to a plant-based nursery diet (Frese et al., 2015). The additive therefore improved diarrhea and several host-response measures without disrupting normal community succession. The benefits may have been mediated more strongly through host inflammatory, oxidative, or epithelial responses, or through localized microbial changes not fully represented in feces. Similar work with plant-extract blends has shown intestinal benefits with relatively limited changes in overall fecal microbiota (Shao et al., 2023).

Expected benefits and implementation limits

The response should be framed as improved resilience and diarrhea control rather than guaranteed growth promotion. The additive may be most valuable during the first 28 d after weaning, when pigs are adapting to lower feed intake, a new diet, and a rapidly changing intestinal environment. It should be used as one component of a nursery program that also addresses temperature, water availability, sanitation, diet digestibility, feeder access, and pathogen control. No feed additive can compensate for major deficiencies in these areas.

The results apply to the specific *Bacillus subtilis* and plant-extract formulation tested. Strain identity, spore concentration, extract composition, coating, and manufacturing quality can affect performance, so the response should not be generalized to all probiotic or phytogenic products. The study used clinically normal pigs, did not include an experimental pathogen challenge, and did not measure nutrient digestibility or economic return. Responses may differ in higher-challenge commercial systems or with diets containing spray-dried plasma, pharmacological zinc oxide, or other gut-health additives. Farm-level validation should focus on diarrhea frequency, treatment rate, mortality, removal rate, final BW, and cost per pig placed rather than on growth rate alone.

Conclusions

Supplementing nursery pig diets with *Bacillus subtilis* and plant extracts reduced the frequency and severity of diarrhea while maintaining growth after weaning. These benefits were accompanied by signs of lower early inflammation, better regulation of antioxidant defenses, reduced intestinal inflammation later in the nursery period, and intestinal changes consistent with improved adaptation. The gut microbial community changed mainly as the pigs aged, with little evidence that supplementation broadly disrupted normal microbiome development. Overall, this combination may be a useful non-antibiotic strategy to support gut health and resilience in newly weaned pigs when used as part of a well-managed nursery program.

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The True Cost of Mortality: Quantifying Economic Losses and Management Opportunities in Swine Production

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Introduction

In recent years mortality has become one of the largest challenges facing the U.S. swine industry. Johnson (2026a, b) reviewed individual producer production information and concluded that sow mortality and growing pig mortality increased from 2015-2023. Recent years have seen subtle improvements in mortality, but issues still linger, particularly those associated with disease pressure from endemic pathogens like PRRS and PEDv. Mortality reduces profitability by lowering revenue, increasing variable production costs and by increasing fixed costs over lower output. In 2025, pork exports represented almost 30% of total production in the U.S. (USMEF, 2026). The modern U.S. swine industry is highly efficient and has built a reputation as a global supplier of affordable, wholesome pork protein to the world by leveraging competitive advantages in feed and labor costs compared to other pork exporting entities. Brazil continues to emerge as one of the strongest competitors to the U.S. pork industry. Recent results collected through InterPIG (2025) have illustrated the improved competitiveness in cost of production from 2020-2024 compared to the United States. To remain relevant on the global stage as a pork exporter it will require continued improvement in pig livability. The objective of this presentation is to quantify the economic impact of mortality across breeding and growing pig production systems and discuss management strategies to promote pig survivability.

Economic examples quantifying mortality impacts

Sow farm productivity is largely impacted by sow mortality, stillborn rate, and pre-wean mortality. Sow mortality itself can increase non-productive days, reduce litters per sow per year, increase gilt replacement costs and lower pigs weaned per sow per year. All can have detrimental impacts on revenue generation and costs of production. Euken and Schulz developed a mortality calculator spreadsheet tool to help further quantify economic impact of sow and pre-wean mortality on farm profitability. Using the default cost inputs and updating market values to 5-year avg numbers (Table 1.), the calculator would show that the improvement in value from a 1% reduction in sow mortality was worth $13.66/inventoried sow or for a 2,500-sow farm, an increase in income over total costs of $34,158. The authors specify that this base model does not incorporate the impact of higher sow mortality on parity distribution, and it assumes stagnant sow inventory. Increased sow mortality can accelerate herd turnover, altering parity distribution. Sanz-Fernandez (2024) observed parity distribution impacts on reproductive performance including pre-wean mortality and pigs weaned per sow per year. This presentation will expand to evaluate the impact of mortality on parity distribution and its associated change in herd performance. Additionally, the discussion will cover the impact of variable cost reduction from lowering sow herd inventory to maintain target wean pig throughput.

For wean-to-finish operations, mortality can worsen feed efficiency, lower facility utilization, increase variable labor demand, and lower manure production all of which contribute to reduced profitability. Because feed usage accumulates throughout the production period, the later mortality occurs the greater economic impact it can have. Euken and Schulz (2021) created a decision-making tool focused on the impact of mortality on wean-to-finish economics. After updating the decision tool to 5-year average market hog carcass price and current feed costs (Table 2.), the savings from improving mortality by 1% from 7 to 6, when mortality occurs at an average weight of 80 lb, are $1.19/pig placed or $2,863 per 2,400 pigs placed. Alternatively, if the mortality occurring is reduced by 1% and average weight at mortality is 160 lb, then net income increases to $1.38/pig placed or $3,317 per 2,400 pigs placed.

Table 1 Breed-to-wean decision tool inputs

Mortality inputs	**Current**	
Total sow mortality (%)	14.0%	
Sow mortalities that occur from farrowing to breed (%)	7.0%	
Pre-wean pig mortality	15.0%	
Production inputs		
Litters per mated female per year	2.200	
Pigs born alive per litter	13.50	
Pigs per mated sow per year w/o pre-wean mortality	29.70	
Pigs per mated sow per year with pre-wean mortality	25.25	29.07
Number of sows	2,500	head
Sow cull rate	45.0%	
Sow replacement rate	59%	
Cull sow weight	450	lbs.
Price inputs		
Weaned pig price[1]	$49.90	per head
Cull sow price[2]	$58.81	per cwt.
Cost of developed replacement gilt ready to breed	$300.00	per head
Additional inputs for complete budget		
Other income		
Manure credit	$13.00	per sow per year
Variable inputs and costs		
Feed cost	$0.10	per lb.
Feed processing and delivery cost	$18.00	per ton
Pounds of feed	2,350	lbs.
Labor cost	$16.50	per hour
Labor hours	7.00	per sow per year
Veterinary and health cost	$40.00	per sow per year
Semen cost, genetic fee	$30.00	per sow per year
Marketing and professional fees	$4.00	per sow per year
Utilities and fuel cost	$25.00	per sow per year
Machinery, facility and equipment repairs	$22.00	per sow per year
Other variable costs	$10.00	per sow per year
Fixed costs		
Machinery, facilities, and general overhead	$170.00	per sow per year
Taxes and insurance	$10.00	per sow per year
Legal and accounting	$11.00	per sow per year

[1] Mean of Weighted Early-Wean pig price, Aug 1 2021-Jul 31 2026. AMS_2810, USDA AMS
[2] Mean of weighted price 400-449 lb sows, Aug 1 2021-Jul 31 2026. LM_HG234, USDA AMS

Conclusion

Mortality should not be viewed solely as a biological outcome but as a primary driver of production efficiency and profitability. Incremental improvements create meaningful gains in resource efficiency and cost reduction. Quantifying these economic impacts will help producers prioritize efforts towards improvement. Ultimately, improving survivability represents one of the biggest opportunities to enhance competitiveness of the U.S. swine industry.

Table 2 Wean-to-finish decision tool inputs

	Current	
Wean-to-finish mortality (%)	7.0%	
Average weight of dead pigs (lbs.)	80	lbs.
Est. feed use based on average weight of pigs at death	14%	
Wean-to-finish feed efficiency	2.70	lbs.
Weight in live (lbs.)	12	lbs.
Weight out live (lbs.)	290	lbs.
Size of operation or group		
Number of pigs in	2,400	head
Number of pigs marketed	2,232	head
Income		
Market hog carcass price per cwt.[1]	$84.51	per cwt.
Manure value per head	$2.30	per head
Variable costs		
Weaned pig price per head	$40.00	per head
Feed price per lb. wean-to-finish	$0.09	per lb.
Feed processing and delivery per ton	$18.00	per ton
Labor cost per hour	$16.50	per hour
Labor hours per head	0.6	Hours per head
Bedding cost per head		per head
Utilities cost per head	$2.13	per head
Machinery, facility/equipment repairs cost per head	$2.00	per head
Veterinary and health cost per head	$4.50	per head
Marketing cost per head	$1.00	per head
Interest rate on operating loan	4%	
Fixed costs		
Facilities, equipment ownership	$20.00	per head
Taxes and insurance	$1.70	per head
Legal and accounting	$0.59	per head

[1]Mean of Weighted Early-Wean pig price, Aug 1 2021-Jul 31 2026. LM_HG217, USDA AMS

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