

Nutritional strategies for nursery and growing-finishing pigs: mineral nutrition and feed ingredients to optimize growth performance

by

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Abstract

This thesis contains three chapters that include: 1) evaluating the effects of modified corn protein (MCP) products on growth performance and fecal dry matter (DM) of nursery pigs; 2) evaluating the effects of increasing standardized total tract digestible phosphorus (STTD P) on growth performance, bone ash, and carcass characteristics of Duroc-sired (PIC 800) pigs; and 3) evaluating the effects of added dietary iodine concentration and feeding duration on growth performance and thyroid hormone status of nursery and wean-to-finish pigs. Chapter 1 utilized 4,420 pigs in two experiments to evaluate three MCP products as replacements for specialty animal and soy protein sources. Increasing MCP inclusion resulted in a dose-dependent reduction in growth performance, particularly gain-to-feed ratio (G:F) and early post-weaning average daily gain (ADG). Despite these negative effects on growth, pigs fed MCP 1, 2, and 3 exhibited increased fecal DM, indicating that although high levels of specialty corn proteins may compromise early growth, they offer a practical benefit in formulations where increased fecal DM is desired. Chapter 2 utilized 1,040 pigs in a 136-d experiment to validate STTD P requirement estimates for Duroc-sired (PIC 800) pigs fed 82 to 110% of current PIC recommendations. Increasing STTD P linearly increased ADG (maximized at or above 103% of the recommendation) and tended to increase hot carcass weight, whereas G:F was maximized between approximately 90 and 97% of the recommendation, with no effect on bone ash or carcass quality. Chapter 3 utilized 3,700 pigs in four experiments to determine the added iodine concentration and feeding duration that optimize growth performance. Increasing added iodine improved early growth performance, with the greatest response at approximately 12 to 14 mg/kg and elevated circulating thyroxine (T₄); feeding 14.3 mg/kg continuously from weaning to approximately 110 kg improved overall G:F compared with feeding it only through the early

nursery. In summary, these experiments refine dietary nutrient concentrations to optimize performance under research and commercial conditions, providing data on the effects of modified corn protein products on nursery pig growth performance and fecal DM, the STTD P level that optimizes growth and carcass weight in Duroc-sired pigs, and the added iodine concentration and feeding duration that maximize growth and feed efficiency.

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Chapter 1 - Effects of modified corn protein-based products on growth performance and fecal dry matter of nursery pigs

Abstract

Modified corn proteins (MCP), produced through advanced wet-milling and fractionation, offer a high-protein (> 50% CP), nutrient-dense alternative to traditional specialty protein sources used in nursery pig diets. Two experiments were conducted to evaluate the effects of three different MCPs in diets for weanling pigs. In Exp. 1, 320 weanling pigs (600 × 241 DNA, initially 5.7 ± 0.02 kg) were used in a 42-d study to determine the dose-response effects of a modified corn protein (MCP 1) product. Diets were corn-soybean meal-based consisting of 0, 7.5, 10.0, and 12.5% MCP in phase 1 (d 0 to 10) and 0, 2.5, 5.0, and 7.5% MCP in phase 2 (d 10 to 21) replacing enzymatically treated soybean meal (ESBM), conventional soybean meal (SBM) and feed-grade amino acids. From d 0 to 10, average daily gain (ADG) and gain:feed ratio (G:F) decreased (quadratic, $P = 0.026$, linear, $P = 0.001$, respectively) as MCP increased. Overall (d 0 to 42), ADG, and final body weight (BW) were not affected by dietary treatment, but pigs previously fed increasing MCP 1 in phase 1 and 2 had decreased (linear, $P = 0.034$) G:F. Fecal dry matter (DM) increased then decreased (quadratic, $P = 0.016$) on d 20 as MCP 1 increased, with the greatest DM observed in pigs fed 10% MCP 1 in phase 1 and 5% MCP 1 in phase 2. In Exp. 2, 4,100 pigs (Line 42 × 337 PIC, initially 5.86 ± 0.06 kg) were used in a 42-d study to evaluate two different specialty corn protein products (MCP 2 and MCP 3). Dietary treatments were corn-SBM-based consisting of 1) High-complexity (containing fish meal and ESBM); 2) Medium-complexity (containing ESBM without fish meal); 3) MCP 2; and 4) MCP 3. The corn protein products were added at 10% in phase 1 and 5% in phase 2 and replaced fish meal and ESBM from the high-complexity diet. The level of L-Lys HCl was adjusted to

achieve a similar level of conventional SBM in the MCP 2 and 3 diets as the high complexity diet in both phases. Overall, pigs fed the medium-complexity diet had greater ($P < 0.05$) ADG compared with pigs fed MCP 3, whereas pigs fed the high-complexity diet or MCP 2 were intermediate. Gain:feed ratio was unaffected by treatment; however, pigs fed MCP 3 had greater ($P < 0.05$) fecal DM compared with the medium-complexity diet. In summary, replacing ESBM and fish meal with the MCP products tested increased fecal DM, but early nursery growth performance was negatively affected with variable results observed on overall growth performance.

Key Words: Corn protein, fecal dry matter, growth performance, nursery pigs

Introduction

Because the digestive system of the weanling pig is characterized by gut immaturity and limited enzyme secretion, the primary nutritional focus is to supply readily digestible ingredients while minimizing immune stimulation (Pluske et al., 2018; Huting et al., 2021). Conventional soybean meal (SBM) is the primary protein source utilized in swine diets; however, its use in early nursery phases is restricted due to the presence of anti-nutritional factors (ANF) such as glycinin and β -conglycinin (Wang et al., 2023). These proteins trigger a localized inflammation and oxidative stress response in the gastrointestinal tract, resulting in abnormal morphology of the small intestine and reduced absorptive capacity (Ruckman et al., 2020). To mitigate these challenges, swine nutritionists typically utilize specialty protein sources like fish meal, spray-dried blood plasma, or further-processed soybean meal ingredients like enzymatically treated soybean meal (ESBM; Ruckman et al., 2020). However, these ingredients are costly, and recent

data suggests that the impact of ESBM on growth performance of weanling pigs can be inconsistent: some studies report improved gain (Ma et al., 2019), whereas others report reduced performance at higher inclusion levels (Ruckman et al., 2020). Consequently, the evaluation of alternative specialty protein sources that support both growth performance and economic efficiency is needed.

Recently, advancements in corn co-product processing, specifically fractionation and wet-milling, have led to the development of next-generation high-protein alternatives. As is typical of corn wet milling, the starch, fiber, oil, and protein fractions are separated. The protein fraction is then further processed to increase crude protein content and combined with nutrient- and organic-acid-rich fermentation fractions. This combination creates a corn protein complex, referred to as modified corn protein (MCP), with high nutrient density and CP levels often exceeding 60% (Stas et al., 2022). Due to their high digestibility and amino acid profile, these products have the potential to serve as effective replacements for specialty animal and soy protein sources.

However, the inclusion of corn-based ingredients presents unique nutritional challenges that require evaluation. These products typically contain high concentrations of Leu, which creates an antagonism among the branched-chain amino acids (BCAA), whereby an excess of Leu increases the dietary requirement for Ile and Val (Harper et al., 1970; Cemin et al., 2019). Excess dietary Leu can interfere with the utilization of Val and Ile, potentially increasing their dietary requirement to maintain performance. Furthermore, research on similar high-protein corn products, such as dried distillers grains with solubles (HP-DDGS) has indicated that feed intake may be reduced due to palatability issues, with pigs often preferring conventional corn–soybean

meal-based diets over diets containing corn co-products or specialty protein sources (Stas et al., 2022).

Despite the potential of these next-generation MCPs, limited data exists regarding their effects on nursery pig performance. Recent preliminary work by Warner et al. (2022) indicated that an earlier version of MCP could be successfully included up to 12% in phase 1 and 6% in phase 2 diets without detrimental effects on initial growth. Building upon these initial findings, the objective of the present studies was to further refine the dose-response of MCP in early nursery diets, and to evaluate the effects of newer specialty corn protein-based products on growth performance, feed efficiency, and fecal dry matter under commercial conditions.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments (IACUC #4975 and #4943). Experiment 1 was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. There were a total of 64 pens used with 5 pigs per pen. Pens (1.22×1.52 m) were equipped with a 4-hole, dry self-feeder and nipple waterer to provide ad libitum access to feed and water. Experiment 2 was conducted at the Swine Vet Center research facility located in St. Peter, MN. The experiment utilized two identical rooms that were completely enclosed, environmentally controlled, mechanically ventilated and with totally slatted floors. There was a total of 80 pens (3.05×5.55 m) with 50 to 52 pigs per pen and each pen contained a six-hole, dry self-feeder and a pan waterer to provide ad libitum access to feed and water.

Experiment 1

The objective of Exp. 1 was to determine the dose-response effects of a modified corn protein product (MCP 1; Cargill Starches, Sweeteners, & Texturizers, Blair, Nebraska) on growth performance and fecal dry matter (DM) of nursery pigs. A total of 320 weanling pigs (DNA 600 × 241; initially 5.7 ± 0.02 kg) were used in a 42-d growth study. Pigs were weaned at approximately 18 d of age and randomly allotted to pens in light (4.9 kg) or heavy (6.6 kg) weight blocks, and then pens were allotted to one of four dietary treatments in a completely randomized block design. There were five pigs per pen and 16 pens per treatment across 2 barns. Dietary treatments consisted of 0, 7.5, 10.0, and 12.5% MCP 1 in phase 1, and 0, 2.5, 5.0, and 7.5% in phase 2 (Table 2). Modified corn protein 1 was added to the diets at the expense of enzymatically treated soybean meal (ESBM; HP 300; Hamlet Protein, Findlay, OH) and conventional SBM. Feed-grade amino acids were used to maintain consistent ratios relative to Lys across treatments. Because an established in vivo net energy (NE) value for the novel MCP 1 was unavailable at the time of formulation, experimental diets were not isoenergetic. Nutrient loading values for MCP 1 used for formulation were provided by the supplier, while values for other ingredients were derived from NRC (2012). Phase 1 diets were fed from d 0 to 10 and phase 2 from d 10 to 24, followed by a common phase 3 diet (d 24 to 42) that did not contain MCP 1 (Table 2).

All treatment diets were manufactured at the Kansas State University O.H. Kruse Feed Technology Innovation Center in Manhattan, KS. Phase 1 and 2 diets were provided in pellet form, while phase 3 was provided in meal form. Samples of complete diets were collected during manufacture and bagging of experimental diets, with a sub-sample (approximately 100 g) collected from every other bag in phase 1, every 3 bags in phase 2, and every 5 bags in phase 3.

Feed samples were pooled into one composite sample per treatment and dietary phase. A feed sample per dietary treatment and phase was submitted to University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO) and analyzed for dry matter (method 934.0, AOAC International, 2006), crude protein (method 990.03, AOAC International, 2006), crude fat (method 920.39, AOAC International, 2006), crude fiber (method 978.10, AOAC International, 2006), ash (method 942.05, AOAC International, 2006), calcium and phosphorus (method 985.01, AOAC International, 2006), starch (method 996.11, AOAC International, 2006), while Neutral detergent fiber and ADF were determined according to the procedures of Van Soest et al. (1991) using an Ankom Fiber Analyzer (Ankom Technology, Macedon, NY) with results reported in Table 3.

Individual pigs were weighed, and feed disappearance was recorded on d 0, 3, 10, 17, 24, 33, and 42 post weaning to determine average daily gain (ADG), average daily feed intake (ADFI) and gain to feed ratio (G:F). Fecal samples were collected from the same three randomly selected pigs from each pen on d 10 and 20 post weaning. After collection, fecal samples were dried at 55°C in a forced-air oven for 48 h, and the ratio of dried to wet fecal weight was used to calculate fecal DM.

Experiment 2

The objective of Exp. 2 was to determine the effect on growth performance, fecal DM, and mortality and removals of nursery pigs of two different specialty corn protein products (Cargill Starches, Sweeteners, & Texturizers, Blair, NE) compared to a high and medium complexity diet formulated similar to those used on commercial production.. A total of 4,100 weanling pigs (PIC 42 × 337, initially 5.9 ± 0.06 kg) were used in a 42-d study. At approximately 23 d of age, pigs were weaned and randomly placed in pens. Pens of pigs were

blocked by average BW and randomly allotted within block to one of four dietary treatments in a randomized complete block design. In total, there were 50 or 52 pigs per pen (equal number of barrows and gilts in each pen) and 20 replications per treatment across two rooms. Daily feed additions to each pen were accomplished using a gravimetric robotic feeding system (FeedPro; Feedlogic Corp., Wilmar, MN) able to record feed weights delivered to individual pens.

Dietary treatments were fed in three phases based on a common feed budget: phase 1 was fed at 1.8 kg/pig which was d 0 to approximately d 7 after weaning, phase 2 was fed at 5.4 kg/pig from approximately d 7 to approximately d 20, and phase 3 was a common diet fed to all pigs for the remainder of the study (Tables 4 and 5). Treatments consisted of a high-complexity diet which contained 3.5% fish meal and 7.5% ESBM in phase 1 and 5% ESBM in phase 2. The second treatment was a medium complexity diet that contained 5% ESBM and no fish meal in phase 1 and 2.5% ESBM in phase 2. This diet contained greater amounts of conventional SBM than the high complexity diet. In the final two treatments, 10% MCP 2 or 3 replaced fishmeal and ESBM in the high complexity diet in phase 1, and 5% MCP 2 or 3 was added in phase 2 replacing ESBM in the high complexity diet. All phase 1 diets contained 2% spray-dried bovine plasma and 15% whey permeate, and all phase 2 diets contained 7.5% whey permeate. The level of L-Lys HCl was adjusted to achieve a similar level of conventional SBM in the MCP diets, as the high complexity diet in both phases.

Pens of pigs were weighed on d 7 and 14 post weaning and then every 14 d thereafter until the end of the trial (d 42). While phase 2 diets were fed, fecal samples were collected on d 16 of the experiment from five randomly selected pigs from each pen to determine fecal DM. Male and female pigs used for the sampling were balanced among treatments. Fecal samples

were dried at 55°C in a forced air oven, and the ratio of dried-to-wet fecal weight determined fecal DM.

Statistical Analysis

Experiment 1

Data were analyzed using SAS OnDemand for Academics (SAS Institute Inc., Cary, NC, USA) using repeated measures employing appropriate contrast coefficients to evaluate treatment effects within phases. Dietary treatment and weight block were included as fixed effects, while barn was included as a random effect. Additionally, the overall (d 0 to 42) dataset was analyzed independently using a one-way ANOVA to assess the main treatment effects without the influence of the repeated measure's structure. For fecal DM, samples were collected from individual pigs (3 pigs per pen, balanced by sex), considering weight block, room and pen as random effects. For the analysis determining the percentage of pigs that lost weight on d 3 after weaning and mortality and removals, a generalized linear mixed model was utilized via the PROC GLIMMIX procedure in SAS, specifying a binomial distribution for the response variable. Treatment and block were included as fixed effects, while barn was modeled as a random effect. Linear and quadratic contrasts were applied to evaluate treatment effects. Least squares means were calculated for each treatment, and comparisons vs. the control group (0% MCP 1) were performed using Dunnett's multiple comparison test within each dietary phase.

Experiment 2

Analysis of growth performance data by period were analyzed using SAS OnDemand for Academics (SAS Institute Inc., Cary, NC, USA.) using repeated measures, with treatment as a fixed effect and block as a random intercept, using an unstructured covariance matrix. Additionally, the overall (d 0 to 42) dataset was analyzed independently using a one-way

ANOVA to assess treatment effects. Pen was considered the experimental unit for growth data. For fecal DM, values from the 5 individual pigs sampled per pen were analyzed independently, and the statistical model included treatment as a fixed effect, and block and pen as random intercepts to account for subsampling of multiple observations within each experimental unit (pen). Removals and mortality data were analyzed using a generalized linear mixed model via the PROC GLIMMIX procedure in SAS, specifying a binomial distribution for the response variable. Treatment was included as a fixed effect, and block was included as a random intercept. Least squares means were calculated for each treatment, and treatment differences were compared using a Tukey multiple comparison adjustment using the LSMEANS function. For both experiments, differences were considered significant at $P < 0.05$ and a tendency for significant difference considered at $0.05 < P < 0.10$.

Results

Experiment 1

The percentage of pigs that lost weight from d 0 to 3 after weaning increased (linear, $P = 0.045$; Table 6) as MCP 1 increased. Additionally, according to Dunnett's multiple comparison test, there was a tendency ($P < 0.10$) for a greater percentage of pigs that lost weight by d 3 in the 12.5% inclusion group relative to those fed 0% MCP 1. From d 0 to 10, there was a decrease (linear and quadratic, $P < 0.05$) in ADG and d 10 BW, with the greatest decrease observed as MCP 1 increased from 10 to 12.5%. Dietary treatment did not affect ADFI and consequently, G:F ratio decreased (linear, $P < 0.05$) as MCP 1 increased. According to Dunnett's multiple comparison test, from d 0 to 10, differences between treatments and the control group were observed, where pigs fed 12.5% MCP 1 had lower ($P < 0.05$) BW at d 10, ADG, and G:F compared to pigs fed the control diet.

From d 10 to 24, both ADG and ADFI exhibited a quadratic response ($P = 0.086$ and $P = 0.025$, respectively) as MCP 1 inclusion increased. This response was characterized by an initial increase in performance, with the greatest ADG and ADFI observed in pigs fed diets containing 2.5% MCP 1, followed by a decline at higher inclusions. Day 24 BW tended to decrease (linear, $P = 0.064$) as MCP 1 increased. According to Dunnett's multiple comparison test, there was a tendency ($P < 0.10$) for reduced BW on d 24 in pigs fed 2.5% MCP 1 in Phase 2 relative to pigs fed the control diet. There was no effect on G:F ratio from d 10 to 24.

From d 24 to 42, when pigs were fed a common diet, no differences in growth performance were observed ($P > 0.10$). Overall (d 0 to 42), there were no differences in ADG or ADFI, but pigs fed increasing MCP 1 had decreased (linear, $P = 0.034$) G:F. According to Dunnett's test, there was a tendency ($P < 0.10$) for decreased G:F in pigs fed the 10.0 % MCP 1 in phase 1 and 5% in Phase 2 compared to the control group.

There were no differences in fecal DM observed on d 10. However, d 20 fecal DM increased then decreased (quadratic, $P = 0.016$) as MCP 1 increased, with pigs fed 10% MCP in Phase 1 and 5% in phase 2 having the greatest fecal DM.

Experiment 2

From d 0 to 7, pigs fed high and medium complexity diets exhibited greater ($P < 0.05$; Table 7) ADG and d 7 BW compared to pigs fed diets containing either MCP 2 or 3. Pigs fed high- and medium-complexity diets had greater ($P < 0.05$) ADFI than pigs fed MCP diets. However, no differences in G:F were observed across treatments during this initial period.

Between d 7 and 14, there were no differences in ADG, ADFI or G:F. On d 14, pigs fed high or medium complexity diets maintained greater ($P < 0.001$) BW compared to those fed either MCP 2 or 3. From d 14 to 28, ADG remained unaffected by dietary treatment. Pigs fed the

medium complexity diet had greater ($P = 0.028$) ADFI compared to those fed MCP 2, while pigs fed the high complexity or MCP 3 diet were intermediate, but no differences were observed in G:F. Although numerical differences in BW persisted on d 28, they were no longer statistically significant. From d 28 to 42, when a common diet was fed, no carryover effects were observed for ADG, ADFI, G:F or BW at d 42.

Overall, pigs fed the medium complexity diets in phases 1 and 2 had greater ($P = 0.018$) ADG compared to those fed the diets with MCP 3, with pigs fed other dietary treatments intermediate. Average daily feed intake was greater ($P = 0.003$) for pigs fed the medium complexity diet compared to both MCP treatments, with pigs fed high complexity diets intermediate. No overall treatment effects were observed for G:F or final BW.

Pigs fed diets with MCP 3 had increased ($P = 0.015$) fecal DM compared to pigs fed the medium complexity diet, while pigs fed the MCP 2 and high complexity diets were intermediate. No differences were observed for mortality, removals and total mortality and removals during this study with mortality and removals being very low (less than 0.6% and 1.5%, respectively).

Discussion

The nutritional value of corn-based protein ingredients is linked to the industrial processing methods used for their production, particularly the distinction between wet and dry-milling technologies. The corn processing industry is traditionally divided into these two major streams, each generating distinct co-products (Rausch and Belyea, 2006). Wet milling is an aqueous fractionation process designed to separate the kernel into its major chemical components. This process begins with steeping in an aqueous solution, sulfur dioxide, and lactic acid, which disrupts the protein matrix through cleavage of disulfide bonds, facilitating the mechanical separation of germ, fiber, starch, and protein fractions (Jackson and Shandera, 1995).

The principal protein-rich co-product is corn gluten meal (CGM), which typically contains approximately 60% CP and is low in fiber. In contrast, dry milling, primarily used for ethanol production, involves fermentation of the whole kernel, producing distillers dried grains with solubles (DDGS), in which non-fermentable components are concentrated approximately three-fold (Stein, 2011).

The specialty corn proteins evaluated in the present studies exhibited a nutritional profile that distinguishes them from conventional wet-milling co-products. Conventional CGM contains approximately 62.9% CP but is characterized by low total Lys concentrations (1.18%; Almeida et al., 2011). In contrast, the MCP evaluated in these studies contained high CP concentrations (65.1 to 69.1%) and substantially greater SID Lys levels (2.47 to 4.56 %). Unlike corn gluten feed (CGF), which contains elevated NDF levels (30 to 48%) due to bran inclusion (Mariscal Landín et al., 2014; Lyu et al., 2018), MCP 1, 2, and 3 maintained lower NDF concentrations (5.4 to 13.6%). This limited fiber dilution suggests a higher ME value compared to CGM, as fiber negatively affects energy digestibility (Lyu et al., 2018). This assertion is further supported by Acosta et al. (2021), who observed that modern corn protein products exhibit greater standardized ileal digestibility of amino acids and metabolizable energy concentrations compared to traditional corn co-products like DDGS. These characteristics further differentiate MCP 2 and 3 from alternative high-protein technologies, such as fermented corn protein (FCP) or high – protein corn distillers dried grains with solubles (HP-DDGS), which exhibit lower protein content and substantially higher fiber (Yang et al., 2019; Stas et al., 2022). Collectively, these comparisons indicate that fractionation technology concentrates protein and reduces fiber beyond the capabilities of other processing methods. However, MCP 1, 2, and 3 retained elevated SID Leu concentrations (9.23 to 10.45%), indicating that despite improvements in Lys and fiber

content, the zein-associated amino acid antagonism remains an inherent characteristic of highly concentrated corn proteins.

Processing methods also appear to confer differences related to mineral bioavailability and functional composition. The experimental ingredients contained 0.62 to 0.66% standardized total tract digestible P (STTD P), exceeding values reported for traditional wet-milling co-products. Almeida et al. (2011) observed that CGM contains approximately 0.60% total P with limited digestibility due to phytate. The elevated STTD P in MCP 1, 2, and 3 suggests that processing may promote phytate hydrolysis, thereby enhancing P availability, similar to the effects observed during DDGS production (Stein, 2011). In addition, according to the supplier MCP 1, 2, and 3 may contain an elevated level of organic acids as well as solubilized proteins due to in-process fermentation that provide for acidification and increased peptidic fractions. Therefore, these modified corn protein products may not only contribute digestible amino acids and digestible P, but also potentially bioactive components.

Growth performance responses in Exp. 1 and Exp. 2 reflected the complex physiological limitations associated with high-protein ingredient inclusion in nursery diets. In Exp. 1, increasing MCP decreased ADG and G:F during the initial post-weaning period (phase 1), consistent with findings by Warner et al. (2022) who observed decreased G:F with increasing MCP. Similarly, Acosta et al. (2021) observed that replacing animal proteins with up to 10% corn protein resulted in reduced ADG and G:F during the initial phase after weaning, although overall nursery performance remained unaffected. In contrast, Johnson (2021) observed no adverse effects on ADG or G:F when MCP was included at 10% of the diet, although the apparent total tract digestibility (ATTD) of DM, nitrogen, and gross energy was decreased. In Exp. 2, reductions in ADG during the first week post-weaning were largely driven by decreased

feed intake in pigs fed MCP diets. This suggests that palatability or initial dietary adaptation may play a key role in early performance responses. Similar responses have been observed by Fakler et al. (2018) and Stas et al. (2022), suggesting an adaptation period to alternative protein sources.

This reduction in early performance also may be associated with a branched-chain amino acid (BCAA) antagonism. Concentrated corn proteins contain elevated concentrations of Leu, and increasing MCP substantially elevated the formulated SID Leu:Lys ratio, reaching up to 159% and 164% in the highest inclusion diets of Exp. 1 and Exp. 2, respectively, compared with approximately 112 to 117% in the control diets. In contrast, SID Val:Lys and Ile:Lys ratios were held constant across all treatments (72% and 59% in Exp. 1; 70% and 58% in Exp. 2) through diet formulation and crystalline amino acid supplementation. These ratios exceeded the NRC (2012) requirement estimates for nursery pigs (63% Val:Lys and 51% Ile:Lys), indicating that, relative to Lys and under balanced BCAA conditions, dietary Val and Ile would be considered adequate. However, NRC (2012) cautions that these requirements may not hold when dietary BCAA are unbalanced. As described by Cemin et al. (2019), the BCAA share the initial steps of their catabolic pathways, and an excess of dietary Leu can overstimulate the branched-chain α -keto acid dehydrogenase complex, increasing the catabolism of not only Leu but also Val and Ile. Because Val and Ile were held at a constant ratio to Lys while Leu:Lys increased to 159 and 164% in Exp. 1 and Exp. 2, respectively, their supply relative to Leu declined progressively as MCP increased, such that their effective availability may have become marginal under these high-Leu conditions. Such an antagonism could suppress feed intake, which may partly explain the reduced early growth performance observed in newly weaned pigs fed high MCP diets.

The mechanisms underlying these responses likely differ from those observed with fibrous corn co-products, where reduced feed efficiency is primarily driven by energy dilution

from high fiber content (Mariscal Landín et al., 2014; Yang et al., 2019). Because MCP products contain lower fiber content, the reduced early performance should not be attributed to energy dilution caused by fiber. A more plausible contributor is an overestimation of dietary energy. Because there is no established *in vivo* metabolizable energy (ME) value for these novel products, their energy content was estimated using standard prediction equations (Noblet and Perez, 1993). Although the MCP diets were formulated to contain similar ME than the control diets, if these equations overestimated the true energy value of the MCP, the pigs would experience an energy deficit, which inherently reduces ADG and G:F. A complementary factor is the amino acid balance. The elevated Leu content may have antagonized Val and Ile utilization (Harper et al., 1970; Cemin et al., 2019), inducing a secondary deficiency that suppressed feed intake. Because feed intake decreased rather than increased, this points to amino acid antagonism or reduced palatability as the primary drivers of the reduced intake. Determining the *in vivo* NE of these products and testing them in isoenergetic diets would help separate the effects of energy and amino acid balance in future studies.

Despite early growth limitations, the evaluated specialty corn proteins demonstrated favorable effects on fecal DM in Exp. 1 and compared with medium-complexity diets in Exp. 2. This response aligns with Warner et al. (2022), who observed numerically greater fecal DM in pigs fed a similar modified corn protein product. Moreover, Qiu et al. (2024) observed that fermented corn improved fecal scores and reduced the incidence of diarrhea through modulation of gut microbiota, including increased abundance of *Lactobacillus* and reduced pathogenic populations.

In summary, these data indicate that increasing MCPs in nursery diets results in a dose-dependent reduction in growth performance, particularly in early post-weaning ADG and overall

G:F. In Exp. 1, increasing MCP 1 resulted in linear decreases in early ADG and G:F, with the most severe early performance losses observed at the 12.5% inclusion level, even though overall ADG was not affected. Similar reductions in ADG and ADFI were observed in Exp. 2 when MCP 2 and 3 replaced specialty protein sources. These performance limitations may be associated with the disproportionate concentrations of amino acids in concentrated corn proteins, particularly their elevated Leu concentrations, which may increase metabolic costs and reduce N utilization efficiency. Despite these negative effects on growth performance, pigs fed MCP 1, 2, and 3 exhibited increased fecal DM. This indicates that while high levels of specialty corn proteins may compromise early growth, they offer practical benefits in dietary formulations where increasing fecal dry matter is desired.

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Table 1.1. Composition of modified corn protein (as-fed basis)¹

Nutrient, % ²	Modified corn protein 1	Modified corn protein 2	Modified corn protein 3
CP, %	65.10	65.70	69.10
Crude fat	2.10	4.00	3.00
Ash	7.90	6.50	6.00
Phosphorus	0.80	0.65	0.70
STTD P	0.62	0.62	0.66
Ca	0.01	0.02	0.04
Na	1.6	1.23	0.80
Cl	---	0.12	0.20
NDF	13.60	13.00	5.40
ADF	5.20	0.31	2.30
Dry matter	94.90	94.40	92.30
ME, kcal/kg ³	3,514	3,727	3,944
SID AA			
Arg	2.06	1.80	2.00
His	1.12	1.16	1.27
Ile	2.16	2.37	2.41
Leu	9.23	10.45	9.75
Lys	4.56	4.37	2.47
Met	1.29	1.32	1.49
Phe	3.22	---	3.85
Thr	1.60	1.98	1.97
Trp	0.26	0.29	0.28
Val	2.44	2.76	2.95

¹Modified Corn Protein, Cargill Starches, Sweeteners, & Texturizers, Blair, Nebraska. Nutrient values other than ME were provided by the supplier.

²AA, amino acids, ADF, acid detergent fiber; CP, crude protein; NDF, neutral detergent fiber; STTD P, standardized total tract digestible phosphorus.

³Metabolizable Energy was predicted from the analyzed chemical composition using the equation of Noblet and Perez (1993; NRC, 2012): $ME \text{ (kcal/kg DM)} = 4,194 - (9.2 \times \text{Ash}) + (1.0 \times \text{CP}) + (4.1 \times \text{EE}) - (3.5 \times \text{NDF})$.

Table 1.2. Composition of Exp. 1 phase 1 and 2 diets (as-fed basis)¹

Item	Modified corn protein, % ²								
	Phase 1				Phase 2				Phase 3
	0.0	7.5	10.0	12.5	0.0	2.5	5.0	7.5	7.5
Ingredient, % ³									
Corn	41.40	43.97	44.65	44.81	54.94	55.61	56.50	57.54	68.04
Soybean meal	19.99	12.49	11.83	11.80	25.26	23.34	21.26	19.02	28.12
Modified corn protein	---	7.50	10.00	12.50	---	2.50	5.00	7.50	---
Enzymatically treated SBM ⁴	7.50	5.00	2.50	---	3.75	2.50	1.25	---	---
Blood plasma	2.50	2.50	2.50	2.50	---	---	---	---	---
Whey powder	12.50	12.50	12.50	12.50	10.00	10.00	10.00	10.00	---
Whey permeate	11.25	11.25	11.25	11.25	---	---	---	---	---
Corn oil	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	---
Calcium carbonate	0.68	0.75	0.76	0.78	0.85	0.87	0.88	0.90	0.75
Monocalcium phosphate, 21% P	0.70	0.60	0.58	0.50	0.85	0.83	0.78	0.73	0.85
Sodium chloride	0.20	0.20	0.20	0.20	0.55	0.55	0.55	0.55	0.60
L-Lys-HCl	0.38	0.28	0.25	0.20	0.49	0.46	0.43	0.40	0.55
DL-Met	0.22	0.13	0.10	0.06	0.23	0.20	0.18	0.14	0.21
L-Thr	0.19	0.23	0.24	0.25	0.23	0.24	0.26	0.27	0.23
L-Trp	0.03	0.08	0.09	0.10	0.06	0.08	0.09	0.11	0.05
L-Val	0.11	0.14	0.15	0.14	0.16	0.18	0.18	0.19	0.16
L-Ile	0.02	0.07	0.08	0.08	0.03	0.05	0.06	0.07	0.07
Trace mineral premix ⁵	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix ⁶	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Phytase ⁷	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Zinc oxide ⁸	0.39	0.39	0.39	0.39	0.25	0.25	0.25	0.25	0.01
Titanium dioxide	---	---	---	---	0.40	0.40	0.40	0.40	---
Total	100	100	100	100	100	100	100	100	100
Calculated analysis									
SID AA, %									
Lys, %	1.40	1.40	1.40	1.40	1.35	1.35	1.35	1.35	1.30
Ile:Lys	59	59	59	59	59	59	59	59	53
Leu:Lys	113	141	149	159	112	122	131	140	113
Met:Lys	35	31	30	29	37	36	35	33	36
Met and Cys:Lys	58	58	58	58	58	58	58	58	57
Thr:Lys	65	65	65	65	65	65	65	65	63
Trp:Lys	21.0	21.0	21.0	21.0	21.0	21.0	21.0	21.0	19.3
Val:Lys	72	72	72	72	72	72	72	72	70

ME, kcal/kg	3,440	3,453	3,452	3,451	3,359	3,361	3,366	3,370	3,291
CP, %	21.5	21.6	21.6	21.8	20.7	20.8	20.8	20.8	20.0
Ca, %	0.67	0.65	0.64	0.62	0.72	0.72	0.70	0.69	0.62
STTD P, %	0.42	0.42	0.42	0.42	0.38	0.38	0.38	0.38	0.32
Na, %	0.40	0.52	0.56	0.60	0.35	0.38	0.42	0.46	0.28
Cl, %	0.68	0.66	0.65	0.64	0.60	0.59	0.59	0.58	0.51

¹Phase 1 diets were fed to pigs from approximately 5.4 to 7.7 kg. Phase 2 diets were fed to pigs from approximately 7.7 to 13.2 kg. Phase 3 diets were fed to pigs from approximately 13.2 to 24.5 kg.

²Modified Corn Protein, Cargill Starches, Sweeteners, & Texturizers, Blair, Nebraska.

³AA, amino acids; CP, crude protein; NE, net energy; SBM, soybean meal; SID, standardized ileal digestible; STTD P, standardized total tract digestible phosphorus.

⁴HP 300; Hamlet Protein, Findlay, OH.

⁵Provided per kg of premix: 4,409,200 IU vitamin A; 550,800 IU vitamin D3; 17,640 IU vitamin E; 1,760 mg vitamin K; 16 mg vitamin B12; 19,840 mg niacin; 11,040 mg pantothenic acid; and 3,320 mg riboflavin.

⁶Provided per kg of premix: 73.3 g Zn from zinc sulfate; 73.3 g Fe from ferrous sulfate; 22.0 g Mn from manganese oxide; 7.3 g Cu from copper sulfate; 0.22 g I from calcium iodate; and 0.20 g Se from sodium selenite.

⁷Ronozyme 2700 (DSM Nutritional Products, Parsippany, NJ) provided 1,486 FYT/kg in the final diet with an assumed 0.12% release of STTD P.

⁸Zinc oxide was included in the diet to provide 3,000 and 2,000 mg/kg of Zn in phase 1 and 2, respectively.

Table 1.3. Analyzed composition of Exp. 1 phase 1 and 2 diets (as-fed basis)¹

Nutrient, % ²	Modified corn protein 1, %							
	Phase 1				Phase 2			
	0.0	7.5	10.0	12.5	0	2.5	5.0	7.5
DM	87.65	87.21	87.72	87.45	87.14	86.98	87.71	86.76
CP	20.79	21.19	21.00	21.60	19.98	19.31	19.88	19.88
Crude fat	2.83	3.17	3.02	3.11	3.34	3.30	3.31	3.24
Crude fiber	1.86	1.59	1.37	1.40	2.19	2.01	1.57	1.43
Ash	6.09	6.22	6.23	6.25	5.81	5.98	5.68	5.65
P	0.70	0.67	0.58	0.60	0.61	0.55	0.66	0.58
Ca	0.85	0.90	0.82	0.82	0.99	0.88	0.92	0.97
NDF	4.93	4.70	4.45	3.90	6.04	5.50	5.36	4.66
ADF	2.44	2.40	2.41	2.19	3.16	2.93	2.88	2.74
Starch	31.71	35.16	32.11	33.48	28.98	26.61	30.11	28.78
Essential AA								
Arg	1.28	1.15	1.02	1.04	1.25	1.19	1.08	1.03
His	0.56	0.55	0.51	0.53	0.53	0.52	0.48	0.49
Ile	0.93	0.97	0.92	0.97	0.91	0.92	0.89	0.90
Leu	1.76	2.10	2.13	2.41	1.69	1.81	1.85	1.97
Lys	1.53	1.53	1.45	1.55	1.45	1.48	1.37	1.42
Met	0.49	0.47	0.41	0.46	0.50	0.49	0.48	0.47
Phe	1.01	1.06	1.01	1.10	0.96	0.97	0.94	0.96
Thr	1.02	1.08	1.02	1.10	0.95	1.00	0.94	0.93
Trp	0.25	0.26	0.24	0.27	0.25	0.25	0.24	0.25
Val	1.15	1.19	1.15	1.19	1.08	1.09	1.09	1.09
Non-essential AA								
Ala	1.01	1.20	1.22	1.36	0.99	1.05	1.08	1.14
Asp	2.16	1.97	1.75	1.80	2.01	1.93	1.76	1.70
Cys	0.38	0.40	0.38	0.42	0.33	0.33	0.34	0.34
Glu	3.70	3.89	3.72	4.02	3.63	3.66	3.57	3.62
Gly	0.82	0.78	0.71	0.73	0.79	0.77	0.72	0.70
Pro	1.14	1.33	1.34	1.48	1.13	1.19	1.21	1.27
Ser	0.92	0.92	0.87	0.92	0.86	0.85	0.79	0.80
Tyr	0.71	0.76	0.74	0.81	0.68	0.68	0.66	0.69

¹ Samples were analyzed for proximate analysis and complete AA profile at the University of Missouri Agricultural Experiment Station Chemical Laboratory and analyzed for Ca and P in the Kansas State University Soil Laboratory, Department of Agronomy.

²AA, amino acids.

Table 1.4. Composition of Exp. 2 phase 1 diets (as-fed basis)¹

Item	High complexity	Medium complexity	MCP 2 ²	MCP 3 ²
Ingredient. %				
Corn	47.76	46.48	48.61	48.39
Soybean meal, 47.7% CP	19.09	25.63	19.10	19.08
Modified corn protein 2	---	---	10.00	---
Modified corn protein 3	---	---	---	10.00
Enzymatically treated SBM ³	7.50	5.00	---	---
Bovine plasma	2.00	2.00	2.00	2.00
Fish meal	3.50	---	---	---
Whey permeate	15.00	15.00	15.00	15.00
Choice white grease	2.00	2.00	2.00	2.00
Calcium carbonate	0.35	0.55	0.60	0.60
Monocalcium phosphate, 21% P	0.80	1.20	1.10	1.05
Salt	0.40	0.40	0.10	0.23
L-Lys-HCl	0.32	0.37	0.22	0.46
DL-Met	0.18	0.21	0.13	0.08
L-Thr	0.18	0.20	0.19	0.19
L-Val	0.05	0.09	0.05	0.03
L-Trp	0.03	0.02	0.06	0.06
Choline chloride 60%	0.05	0.05	0.05	0.05
Vitamin premix ⁴	0.25	0.25	0.25	0.25
Trace mineral premix ⁵	0.15	0.15	0.15	0.15
Zinc oxide	0.40	0.40	0.40	0.40
Total	100	100	100	100
Calculated analysis				
SID AA, %				
Lys	1.35	1.35	1.35	1.35
Ile:Lys	58	58	58	58
Leu:Lys	117	115	164	159
Met:Lys	36	36	34	32
Met & Cys:Lys	58	58	58	58
Thr:Lys	65	65	65	65
Trp:Lys	20.0	20.0	20.0	20.0
Val:Lys	70	70	70	70
His:Lys	37	37	35	36
Total Lys, %	1.52	1.50	1.55	1.51
ME, kcal/kg	3,462	3,427	3,466	3,486
Na, %	0.40	0.40	0.40	0.40
Cl, %	0.71	0.71	0.50	0.63
CP, %	22.0	21.5	22.2	22.7

Ca, %	0.68	0.69	0.66	0.65
P, %	0.67	0.68	0.64	0.63
STTD P, %	0.57	0.57	0.57	0.57
Ca:P	1.03	1.03	1.03	1.03

¹Phase 1 diets were fed from d 0 to approximately d 7 (5.9 to 7.2 kg).

²Modified Corn Protein (MCP) 2 and 3 were provided by Cargill Starches, Sweeteners, & Texturizers, Blair, Nebraska.

³Enzymatically treated soybean meal, (HP300, Hamlet Protein, Findlay, OH).

⁴Provided per kg of premix: 4,409,200 IU vitamin A; 550,800 IU vitamin D3; 17,640 IU vitamin E; 1,760 mg vitamin K; 16 mg vitamin B12; 19,840 mg niacin; 11,040 mg pantothenic acid; and 3,320 mg riboflavin. Quantum Blue phytase (AB Vista, Plantation, FL) was included in the premix to provide 500 FTU/kg of complete diet, with an assumed release of 0.12% STTD P.

⁵Provided per kg of premix: 73.3 g Zn from zinc sulfate; 73.3 g Fe from ferrous sulfate; 22.0 g Mn from manganese oxide; 7.3 g Cu from copper sulfate; 0.22 g I from calcium iodate; and 0.20 g Se from sodium selenite.

Table 1.5. Composition of Exp. 2 phase 2 and 3 diets (as-fed basis)¹

Item	Phase 2				Phase 3
	High complexity	Medium complexity	MCP 2 ²	MCP 3 ²	Common diet
Ingredient, %					
Corn	55.03	54.22	55.33	55.20	66.18
Soybean meal, 47.7% CP	26.45	29.76	26.45	26.43	30.24
Modified corn protein 2	---	---	5.00	---	---
Modified corn protein 3	---	---	---	5.00	---
Whey permeate	7.50	7.50	7.50	7.50	---
Enzymatically treated SBM ³	5.00	2.50	---	---	---
Choice white grease	2.00	2.00	2.00	2.00	---
Calcium carbonate	0.70	0.70	0.73	0.73	0.83
Monocalcium P, 21% P	1.10	1.10	1.05	1.05	0.85
Salt	0.60	0.60	0.45	0.50	0.60
L-Lys-HCl	0.43	0.42	0.34	0.46	0.42
DL-Met	0.21	0.21	0.17	0.15	0.18
L-Thr	0.21	0.21	0.20	0.20	0.19
L-Trp	0.03	0.03	0.05	0.05	0.04
L-Val	0.09	0.10	0.08	0.07	0.08
Vitamin premix with phytase ⁴	0.25	0.25	0.25	0.25	0.25
Trace mineral premix ⁵	0.15	0.15	0.15	0.15	0.15
Zinc oxide	0.26	0.26	0.26	0.26	---
Total	100	100	100	100	100
Calculated analysis					
SID AA, %					
Lys	1.30	1.30	1.30	1.30	1.25
Ile:Lys	58	58	58	58	58
Leu:Lys	116	116	142	139	121
Met:Lys	37	37	36	35	36
Met & Cys:Lys	58	58	58	58	58
Thr:Lys	65	65	65	65	65
Trp:Lys	19.8	20.0	20.0	20.0	20.0
Val:Lys	70	70	70	70	70
His:Lys	37	37	36	37	38
Total Lys, %	1.44	1.44	1.46	1.45	1.39
ME, kcal/kg	3,397	3,388	3,407	3,417	3,284
Na, %	0.35	0.35	0.35	0.35	0.28
Cl, %	0.65	0.64	0.54	0.60	0.48
CP, %	20.9	21.0	21.4	21.6	20.6

Ca, %	0.71	0.72	0.70	0.70	0.69
P, %	0.63	0.63	0.62	0.62	0.57
STTD P, %	0.52	0.52	0.52	0.52	0.45
Ca:P	1.13	1.13	1.13	1.13	1.22

¹Phase 2 diets were fed from approximately d 7 to 20 (5.4 kg feed budget). Phase 3 was a common diet fed to all pigs for the remainder of the study.

²Modified Corn Protein (MCP) were provided by Cargill Starches, Sweeteners, & Texturizers, Blair, Nebraska.

³Enzymatically treated soybean meal, HP300, Hamlet protein, Findlay, OH.

⁴Provided per kg of premix: 4,409,200 IU vitamin A; 550,800 IU vitamin D3; 17,640 IU vitamin E; 1,760 mg vitamin K; 16 mg vitamin B12; 19,840 mg niacin; 11,040 mg pantothenic acid; and 3,320 mg riboflavin. Quantum Blue phytase (AB Vista, Plantation, FL) was included in the premix to provide 500 FTU/kg of complete diet, with an assumed release of 0.12% STTD P.

⁵Provided per kg of premix: 73.3 g Zn from zinc sulfate; 73.3 g Fe from ferrous sulfate; 22.0 g Mn from manganese oxide; 7.3 g Cu from copper sulfate; 0.22 g I from calcium iodate; and 0.20 g Se from sodium selenite.

Table 1.6. Effect of increasing modified corn protein on nursery pig performance (Exp. 1)¹

	Phase 1:	Modified corn protein 1, %				SEM	<i>P</i> =	
		0.0	7.5	10.0	12.5		Linear	Quadratic
Phase 2:		0.0	2.5	5.0	7.5			
Pigs losing weight d 3, % ²		20.3	26.8	28.1	36.6#	15.59	0.045	0.587
Initial BW, kg								
d 0		5.7	5.7	5.7	5.7	0.02	0.932	0.796
d 10		7.7	7.6	7.5	7.3*	0.11	0.001	0.039
d 24		13.2	13.2	13.2	12.6#	0.24	0.064	0.147
d 42		24.5	24.5	24.5	24.0	0.39	0.401	0.587
d 0 to 10 (Phase 1) ³								
ADG, g		203	197	189	165*	6.7	0.001	0.026
ADFI, g		215	214	216	197	8.0	0.194	0.160
G:F, g/kg		945	926	877	840*	22.0	0.001	0.128
d 10 to 24 (Phase 2)								
ADG, g		390	404	403	379	10.8	0.499	0.086
ADFI, g		532	565	553	520	14.6	0.443	0.025
G:F, g/kg		733	716	728	730	13.1	0.979	0.488
d 24 to 42 (Phase 3)								
ADG, g		632	624	629	636	12.2	0.830	0.496
ADFI, g		892	889	909	904	19.6	0.531	0.940
G:F, g/kg		711	701	692	703	6.5	0.210	0.177
d 0 to 42 (Overall) ⁴								
ADG, g		448	449	449	438	7.1	0.420	0.387
ADFI, g		609	620	626	608	12.3	0.873	0.212
G:F, g/kg		738	724	718#	721	6.0	0.034	0.271
Fecal DM, % ⁵								
d 10		18.2	18.5	18.1	17.4	0.92	0.574	0.467
d 20		17.7	18.5	20.1	17.4	0.79	0.824	0.016

Indicates that treatment differs from treatment including 0% modified corn protein for all dietary phases using a Dunnett multiple comparison test (, $P < 0.05$; #, $P < 0.10$). All Dunnett tests were performed within dietary phase or overall and not considering repeated measures analysis.

¹A total of 320 weanling pigs (DNA 241 × 600, initially 5.7 ± 0.02 kg) approximately 18 days of age were used in a 42-d experiment with 5 pigs per pen and 16 pens per treatment. Modified Corn Protein (MCP) provided by Cargill Starches, Sweeteners, & Texturizers, Blair, Nebraska.

²Percentage of pigs that had a lower BW on d 3 than on d 0.

³All phases were analyzed as a repeated measure using the appropriate contrast coefficients corresponding to each phase. An interaction between modified corn protein and phase was observed for ADG (linear, $P = 0.024$), ADFI (quadratic, $P = 0.045$), and G:F (linear, $P = 0.002$).

⁴Overall data were analyzed independently of the repeated measures as a one-way ANOVA.

⁵Feces from three pigs from each pen were weighed and dried to determine fecal DM. Treatment × day, $P = 0.386$; Treatment, $P = 0.250$; Day, $P = 0.454$.

Table 1.7. Effects of two specialty corn protein products and diet complexity on nursery pig growth performance and fecal dry matter (Exp.2)¹

Item	High complexity	Medium complexity	MCP 2 ²	MCP 3 ²	SEM	P =
Initial BW, kg						
d 0	5.9	5.9	5.9	5.9	0.06	0.475
d 7	7.3 ^a	7.4 ^a	7.0 ^b	7.0 ^b	0.13	< 0.001
d 14	9.1 ^a	9.1 ^a	8.8 ^b	8.7 ^b	0.14	< 0.001
d 28	15.4	15.4	14.9	14.9	0.23	0.115
d 42	23.6	23.7	23.2	23.2	0.31	0.402
d 0 to 7						
ADG, g	203 ^a	216 ^a	171 ^b	167 ^c	10.3	< 0.001
ADFI, g	179 ^a	184 ^a	156 ^b	156 ^b	11.0	0.001
G:F, g/kg	1,134	1,170	1,073	1,029	44.9	0.127
d 7 to 14						
ADG, g	256	241	240	239	15.0	0.743
ADFI, g	368	359	347	343	12.1	0.127
G:F, g/kg	701	685	699	708	27.5	0.942
d 14 to 28						
ADG, g	427	432	422	424	10.3	0.678
ADFI, g	604 ^{ab}	616 ^a	587 ^b	589 ^{ab}	11.6	0.028
G:F, g/kg	706	699	717	719	7.6	0.161
d 28 to 42						
ADG, g	636	644	642	636	11.8	0.884
ADFI, g	967	979	963	964	20.9	0.924
G:F, g/kg	660	659	669	663	4.7	0.322
d 0 to 42						
ADG, g	424 ^{ab}	428 ^a	416 ^{ab}	415 ^b	8.1	0.018
ADFI, g	603 ^{ab}	611 ^a	588 ^b	589 ^b	12.2	0.003
G:F, g/kg	704	701	708	704	2.9	0.140
Fecal DM, % ³	23.57 ^{ab}	22.83 ^b	24.20 ^{ab}	24.70 ^a	0.420	0.015
Mortality	0.38	0.38	0.57	0.57	0.242	0.853
Removals	1.46	1.27	1.37	0.98	0.38	0.806
Mortality and removals	1.85	1.66	1.95	1.56	0.432	0.896

^{a, b, c} Means within a row with different superscripts differ ($P < 0.05$).

¹A total of 4,100 pigs (PIC line 42 × 337; initially 5.9 ± 0.06 kg) were used with 50 to 52 pigs per pen and 20 replicates per treatment. Diets were fed in three phases based on feed budget with phase 1 provided at 1.81 kg/pig from day 0 to approximately d 7, phase 2 provided at 5.44 kg/pig from approximately d 7 to approximately d 20, and phase 3 fed for the remainder of the study. The high complexity diet contained 3.5% fish meal and 7.5% enzymatically treated SBM in phase 1 and 5% enzymatically treated SBM in phase 2. The medium complexity treatment had no fish meal and 5% enzymatically treated SBM in phase 1

and 2.5% enzymatically treated SBM in phase 2. The MCP 2 and 3 treatments had no fishmeal or enzymatically treated SBM in phases 1 or 2 and included at 10% in phase 1 and 5% in phase 2, with the level of L-Lys HCl adjusted to achieve a similar level of conventional SBM as the high complexity treatment in both phases. Phase 3 was a common diet fed to all pigs. Data for individual growth period and BW were analyzed as repeated measures, with overall data being analyzed independently of the repeated measures as a one-way analysis of variance.

² Modified Corn Protein (MCP) were provided by Cargill Starches, Sweeteners, & Texturizers, Blair, Nebraska.

³Fecal collections occurred on d 16 of the experiment while phase 2 feed was being fed for the determination of fecal DM.

Chapter 2 - Effects of dietary phosphorus on growth performance, bone ash, and carcass characteristics of Duroc-sired pigs

Abstract

Phosphorus plays a critical role in skeletal development, growth, and protein deposition in swine. While previous research has determined the standardized total tract digestible (STTD) P requirements for other genetic lines, research is needed to validate the current requirement estimates specifically for modern, Duroc-sired pigs. Therefore, a total of 1,040 pigs (PIC 800 × 1050; initially 10.2 ± 0.19 kg) were used in a 136-d study to evaluate the effects of increasing STTD P on growth performance, bone ash, and carcass characteristics. Pigs were blocked by body weight and allotted to one of five dietary treatments with 26 pigs per pen and 8 pens per treatment. Corn-soybean meal-based diets were fed across 5 phases and formulated to provide 82, 89, 96, 103, and 110% of PIC (2021) STTD P recommendations. On d 129, the two heaviest pigs per pen were harvested and the third metacarpal was collected to determine percentage bone ash. During the early grower phase (d 0 to 59), average daily gain (ADG) increased (linear, $P = 0.011$) as dietary STTD P increased. Dose-response curves modeled specifically for this period estimated a breakpoint for ADG at 103.0% of the PIC (2021) recommendations using a broken-line linear model. Dietary treatment had no impact on finisher (d 59 to market) growth performance. Overall (d 0 to 136), ADG increased (linear, $P = 0.020$) and G:F showed a marginally significant quadratic response ($P = 0.099$), with pigs fed 96% of the recommendations exhibiting the greatest overall efficiency. Body weight of pigs marketed at the final marketing event and hot carcass weight (HCW) tended to increase (linear, $P \leq 0.093$) with increasing STTD P. No differences were observed for carcass yield, backfat, loin depth, lean percentage, or bone ash. In summary, increasing dietary STTD P above current

recommendations improved ADG in early grower diets and overall, but no treatment differences were observed in the finisher phases when all pigs were exhibiting high feed intake and consuming enough STTD P to maximize performance.

Key Words: bone ash, finishing pigs, nursery pigs, phosphorus

Introduction

Phosphorus is an essential macromineral in swine nutrition, playing critical roles in skeletal development, growth performance, and protein deposition (NRC, 2012). Because P is typically the third most expensive nutrient in swine diets after energy and protein, optimizing its inclusion is a primary economic objective in diet formulation (Vier et al., 2019b). While deficient or marginal P levels can restrict growth and compromise bone mineralization, excess dietary P leads to increased P excretion (Lautrou et al., 2020).

To accurately address these biological and environmental needs, current nutritional systems, such as the NRC (2012), utilize the standardized total tract digestible (STTD) P system as the standard method to estimate requirements. This system is preferred because it corrects for basal endogenous phosphorus losses, ensuring that the digestible phosphorus values of individual feed ingredients can be added together when formulating diets. However, these requirement estimates require ongoing validation as production systems and genetic lines evolve. While previous empirical dose-response studies have determined the STTD P requirements for other commercial lines (Vier et al., 2019b), continuous advancements in genetic selection for lean growth and the industry shift toward heavier market weights necessitates the ongoing re-evaluation of nutrient recommendations. Modern Duroc-sired terminal lines, such as PIC 800,

possess increased growth potential and average daily feed intake (ADFI) compared to conventional lines (Camp et al., 2024). Because daily nutrient requirements expressed as a dietary percentage are biologically driven by the amount of feed consumed, these specific intake and rapid growth trajectories may alter daily quantitative P needs.

A consistent challenge in defining P requirements is the physiological divergence between the dietary levels needed to maximize growth performance and those required to optimize skeletal integrity. Empirical data demonstrate that maximizing average daily gain (ADG) and feed efficiency requires lower STTD P concentrations compared to maximizing bone mineralization criteria, such as bone ash (Adeola et al., 2015). Under conditions of marginal P deficiency, pigs exhibit adaptive physiological responses, prioritizing soft tissue (muscle) accretion over bone mineralization (Lautrou et al., 2024). The objective of this study was to determine the STTD P requirement of Duroc-sired pigs from 10 to 133 kg under commercial conditions using growth performance, bone mineralization, and carcass characteristics as response criteria. It was hypothesized that the high lean growth rate of this modern line may drive an absolute daily P demand (g/d) that may exceed its feed intake capacity during early growth phases, and consequently, that the dietary STTD P concentration (%) needed to maximize overall performance would be greater than the current PIC (2021) recommendations.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment (IACUC #4975). The experiment was conducted at a commercial research barn located in south-central Minnesota. The barn had slatted concrete flooring, deep pits for manure storage, and was naturally ventilated. There was a total of 40 pens

used with 26 pigs per pen. Each pen (4.0×4.3 m) contained a three-hole stainless steel dry self-feeder (Thorp Equipment, Thorp, WI) to provide ad libitum access to feed and water. Daily feed additions to each pen were accomplished using a gravimetric robotic feeding system (FeedPro; Feedlogic Corp., Wilmar, MN) able to record feed weights delivered to individual pens.

Animal and treatment structure

A total of 1,040 pigs (800×1050 , PIC, Hendersonville, TN, initially 10.2 ± 0.19 kg) were used in a 136-d study. Pigs were housed in mixed-sex pens containing equal numbers of barrows and gilts (13 barrows and 13 gilts; 26 pigs per pen), and pens were allotted to one of five dietary treatments in a randomized complete block design with initial weight as a blocking factor to achieve 8 pens per treatment.

Treatment diets were corn-soybean meal-based. Three treatment diets were manufactured (low, intermediate, and high STTD P) and blended to reach the STTD P levels of 82, 89, 96, 103, and 110% of PIC (2021) recommendations (Table 1). Because the PIC (2021) recommendations are expressed as a STTD P to net energy ratio (g STTD P/Mcal NE), the 100% reference concentration for each phase was derived from that ratio and the diet's NE content. Diets were fed in five phases based on average body weight: phase 1 was fed from 10 to 23 kg, phase 2 was fed from 23 to 45 kg, phase 3 was fed from 45 to 73 kg, phase 4 was fed from 73 to 100 kg and phase 5 was fed from 100 to 130 kg. No phytase was included in any of the diets. To achieve the targeted increases in STTD P levels, the inclusion rate of monocalcium phosphate was progressively increased. To maintain a constant total calcium to phosphorus (Ca:P) ratio across all treatments within a given phase, limestone inclusion was proportionally increased with monocalcium phosphate. Ingredient net energy (NE) values were based on the NRC (2012). Diets were formulated to be isocaloric within each phase, with NE targets gradually increasing as

the pigs matured. Because the addition of inorganic minerals dilutes the energy of the diet, the proportion of corn was increased relative to soybean meal to maintain these constant NE levels without using added fat. As a result of these ingredient shifts, feed-grade amino acids were adjusted to ensure standardized ileal digestible (SID) amino acid profiles remained constant across all STTD P treatments within each phase.

Pen weights and feeder measurements were recorded on d 0 (allotment), 11, 18, 31, 45, 59, 70, 83, 95, 112, and 136 to determine ADG, ADFI, gain:feed ratio (G:F), and grams of STTD P intake per day. Pigs were marketed in four separate events. On d 115 and 122 (first and second marketing events, respectively), the 2 to 4 heaviest pigs per pen were visually selected, individually weighed, tattooed, and marketed, ensuring that the number of marketed pigs was balanced across treatments. On d 129 (third marketing event), to accommodate bone collection procedures, the heaviest remaining barrow and the heaviest remaining gilt per pen were visually selected, individually weighed, tattooed with a pen identification number, and marketed. On d 136 (final marketing event), all remaining pigs were marketed. Overall carcass data represent a weighted average of the four marketing events.

All pigs were tattooed and transported to a commercial packing plant in southwestern Minnesota (JBS Swift and Company, Worthington, MN) for processing and carcass data collection. Carcass measurements included hot carcass weight (HCW), loin depth, backfat depth, and percentage lean. Fat depth and loin depth were measured with an optical probe inserted between the third and fourth last rib (counting from the ham end of the carcass) at approximately 7 cm from the dorsal midline. Percentage carcass yield was calculated by dividing the individual HCW collected at the plant by the individual final live weight recorded at the farm prior to each marketing event.

At the abattoir, the left front foot from the specific gilt and barrow marketed during the third marketing event (d 129) was removed at the junction of the carpal bones and the radius. These feet were further dissected to isolate the third metacarpal. Bones were transferred on dry ice to the Kansas State University Swine Laboratory and stored at -20°C until analysis of bone mineral content.

Bone Ash Analysis

For the bone ash analysis, the third metacarpals were wrapped in cheesecloth to maintain their tag identification and placed in Soxhlet extractors containing petroleum ether for 7 d as a means of removing water and fat. Defatted metacarpals were then placed in a 105°C drying oven for 7 d. Bones were subsequently ashed in a muffle furnace at 600°C for 24 h to determine percentage ash. The percentage of bone ash was calculated as the proportion of the dry, defatted, pre-ashed bone multiplied by 100.

Chemical Analysis

Representative diet samples were obtained from 6 feeders of each treatment approximately 3 d after the beginning and 3 d before the end of the phase and stored at -20°C until analysis. Samples of the diets were combined within dietary treatment, and a composite sample from each treatment was analyzed for Ca and P (Midwest Laboratories, Omaha, NE; Table 2; AOAC 985.01, 2006).

Statistical Analysis

Data were analyzed as a randomized complete block design. The lmer function was used from the lme4 package in RStudio [Version 4.0.2 (2020-06-22), R Core Team, R Foundation for Statistical Computing, Vienna, Austria] with pen serving as the experimental unit. The model utilized treatment as a fixed effect and BW block as a random effect. Linear and quadratic

polynomial contrasts were constructed to evaluate the overall effects of increasing dietary STTD P concentrations for each response variable. Hot carcass weight was used as a covariate for backfat depth, loin depth, and percentage lean. Dose response curves were evaluated using the GLIMMIX procedure of SAS evaluating linear (LM), and broken-line linear (BLL) models. The best fitting model was selected using the Bayesian Information Criterion (BIC) with improved model fit accepted when BIC decreased by at least 2.0. Results were considered significant with $P \leq 0.05$ and marginally significant with $P \leq 0.10$.

Results

Chemical analysis

The average values of analyzed total P across dietary phases were approximately 13%, 17%, 13%, 14%, and 12% greater than formulated values for the treatments representing 82%, 89%, 96%, 103%, and 110% of PIC (2021) recommendations, respectively (Table 3). While analyzed total P varied among treatments within phases, proportional increases were maintained, with values at the highest treatment consistently greater than at the lowest. Deviations from formulated values were of similar magnitude across all treatments. Similarly, the average values of analyzed Ca across phases were approximately 34%, 36%, 37%, 33%, and 40% greater than formulated values for the same treatments, respectively. Consequently, the analyzed Ca:P ratio was wider than formulated, averaging from 1.52:1 to 1.63:1 among treatments compared with a formulated range of 1.27:1 to 1.33:1.

Growth performance

From day 0 to 59, increasing STTD P increased ADG (linear, $P = 0.011$; Table 4), STTD P intake per day (linear, $P < 0.001$), and body weight on d 59 (linear, $P = 0.017$). During this

period, feed intake (ADFI) and gain:feed ratio (G:F) were not affected by dietary treatment. From d 59 to 136, increasing STTD P increased the STTD P intake per day (linear, $P < 0.001$); however, no differences in ADG, ADFI, or G:F were observed.

Overall, from d 0 to 136, increasing STTD P increased ADG (linear, $P = 0.020$) and STTD P intake per day (linear, $P < 0.001$). Gain:feed ratio tended to be affected by dietary treatment (quadratic, $P = 0.099$), with the greatest overall G:F occurring at 96% of the PIC (2021) recommendation. Overall ADFI was not affected by STTD P level. While a marginal increase was observed for body weight at the final marketing event on d 136 (linear, $P = 0.087$), the overall average market weight across all marketing events was not affected by STTD P level.

For grower ADG, dose-response models (linear and broken-line linear) showed similar fits, with differences in the Bayesian Information Criterion (BIC) below two units (Figure 1). Specifically, the broken-line linear (BLL) model estimated a breakpoint at 103.0% (95% CI: [81.7, 124.3%]; BIC = 365.3) of the PIC (2021) recommendation. The linear model predicted maximum ADG above the upper range of 110% of PIC recommendations evaluated (BIC = 364.5).

Bone and carcass characteristics

For percentage bone ash, there was no evidence of a difference between dietary treatments.

For carcass characteristics, hot carcass weight marginally increased (linear, $P = 0.093$) as STTD P increased. However, there were no differences observed for carcass yield, back fat depth, loin depth, or lean percentage.

Discussion

The precise formulation of dietary P is a critical objective in modern swine nutrition to maximize performance while minimizing P excretion in manure. Although the STTD P requirements of growing-finishing pigs have been described previously, few studies have characterized them in a contemporary, high lean-growth terminal line evaluated across the entire late-nursery-to-finish period under commercial conditions. The present study addressed this gap. Two aspects of the response merit closer interpretation: the growth response to STTD P was concentrated in the early period and largely absent later, and bone ash did not respond across the range tested, a pattern that appears to depart from the requirement hierarchy that is conventionally reported.

Overall, ADG was maximized when STTD P was fed at 103% of the PIC (2021) recommendations. This overall effect was primarily driven by the early growth period (d 0 to 59; approximately 10 to 58 kg), where dose-response modeling estimated that maximum ADG was reached at or above 103% of the recommendations, while G:F was not impacted by treatment. In contrast, during the finishing phase (d 59 to 136; approximately 58 to 133 kg), ADG, ADFI, and G:F did not differ among treatments. Physiologically, this reflects the dynamic relationship between the rapid rate of lean tissue deposition and the intake capacity of younger pigs; because their high growth potential necessitated a higher dietary nutrient concentration to satisfy their absolute daily demands. A comparable pattern was reported by Vier et al. (2019a), who observed a similar trend in 11- to 23-kg nursery pigs, noting that maximizing ADG required higher dietary STTD P concentrations than those recommended by the NRC (2012).

This concept becomes clearer when looking at the absolute daily intake (g/d) of STTD P (Figure 2). During the grower phase, ADG improved as STTD P intake increased until the level

of STTD P matched the requirement estimate established by NRC (2012), after which no further improvement in ADG occurred. During the finishing phase however, the lack of response could be explained by the high daily STTD P intake for all treatments. Because voluntary feed intake naturally increases with body weight, even the restricted 82% diet provided 6.2 g/d of STTD P. This value already exceeds the 5.95 to 6.11 g/d requirement estimated by the NRC (2012) for the 75 to 135 kg finishing range. Because their basic biological needs were already satisfied at the lowest inclusion level, adding more STTD P to the diet offered no further growth benefit.

Traditionally, a well-established hierarchy exists where the STTD P concentration required to maximize bone mineralization is greater than that required for maximum ADG, which in turn is greater than that needed to optimize G:F (Adeola et al., 2015; Vier et al., 2019b). However, bone ash percentage evaluated at market weight remained statistically unaffected across the entire 82% to 110% STTD P range. During the finishing phase, the high voluntary feed intake of the pigs resulted in an absolute P consumption that satisfied the biological requirements for bone mineralization even at the lowest dietary treatment (82%). Consequently, any transient bone demineralization that may have occurred during the early grower phase, may have been reversed via compensatory mineralization during the prolonged finishing phase feeding period. The lack of bone response should also be considered alongside the sampling criteria. Bone samples were collected from the heaviest pig in each pen, representing about 7% of the total population. Given their higher feed consumption, these fast-growing pigs had an elevated absolute P intake that further protected them from a STTD P deficit that might impact bone strength.

Feed intake, and the resulting absolute STTD P intake, most likely explains the lack of a bone ash response in the current study. Camp et al. (2024) demonstrated in commercial

evaluations that Duroc-sired pigs can consume approximately 150 g/d more feed than other terminal-sired lines. Although absolute STTD P intake in the lowest treatment of the present study (4.3 g/d) was identical to that of the lowest treatment of Vier et al. (2019b) during the grower phase, the two diverged markedly during the finishing phase where pigs in the current study consumed 6.2 g/d of STTD P, compared with 5.0 g/d in Vier et al. (2019b). In that study, bone ash increased linearly and did not plateau until 131% of NRC (2012) estimates, corresponding to an STTD P intake of approximately 7.4 to 8.3 g/d. This indicates that their lower-intake pigs remained below the threshold for maximal mineralization throughout the trial. By contrast, the elevated voluntary feed intake of the pigs in the current study sustained absolute STTD P consumption above the level associated with demineralization during the finishing period, which likely explains why bone ash remained unaffected across the range evaluated.

Regarding carcass characteristics, hot carcass weight (HCW) of the final pigs marketed tended to increase linearly with STTD P concentration, aligning closely with patterns observed for ADG. However, no significant differences were observed in carcass yield, backfat, or lean percentage. This aligns with Williams et al. (2023) who demonstrated that proportional carcass traits, specifically those expressed as a percentage of HCW, such as yield and lean percentage, remain consistent when STTD P is adequate to support basic growth. Consequently, the current data indicate that dietary P primarily drives the absolute mass of tissue deposition rather than altering the proportional composition of the final carcass.

Diets were formulated to maintain a constant Ca:P ratio; however, analyzed total Ca exceeded formulated values more than analyzed P compared to formulated P, resulting in analyzed Ca:P ratios of 1.52:1 to 1.63:1. A wide Ca:P ratio can impair performance, particularly when dietary P is marginal (Reinhart and Mahan, 1986; González-Vega et al., 2016; Merriman et

al., 2017). However, ratios up to 1.6:1 can be fed without reducing growth (Wu et al., 2018). Because ratios of this experiment fell near this upper limit, any effect on growth was likely modest and part of the response in the grower phase with the low STTD P treatments may reflect the pigs overcoming a calcium imbalance rather than just a P deficiency. This limitation is shared with Vier et al. (2019b), whose analyzed Ca:P ratios ranged from 1.40:1 to 1.74:1. Furthermore, because analyzed total P exceeded formulated values by approximately 14%, the absolute STTD P intakes (g/d) reported herein from formulated values likely underestimates actual intake. Unlike Vier et al. (2019b), where analyzed P fell below target in the lowest treatments, the higher effective P concentrations here reinforce that pigs fed the lowest treatment consumed enough absolute P to maintain bone mineralization.

Ultimately, apparent differences in percentage-based requirements between studies are largely reflective of voluntary feed intake. For commercial nutritionists, the present study emphasizes that percentage-based formulation targets must be dynamically adjusted to the actual feed intake curves of specific genetic lines across different phases to ensure absolute physiological thresholds (g/d) are met. This study demonstrates that early grower pigs require diets formulated at or above 103% of current STTD P recommendations to maximize growth. During the finishing phase, levels at 82% of current recommendations were sufficient to maintain maximum growth and feed efficiency. At these late-stages, the high feed intake of Duroc-sired pigs ensures that the absolute P intake (g/d) remains sufficient to maintain skeletal mineralization prior to market and this data would suggest that additional research should be conducted in late finishing phases with lower levels of STTD P to determine the level needed to maximize growth and bone strength.

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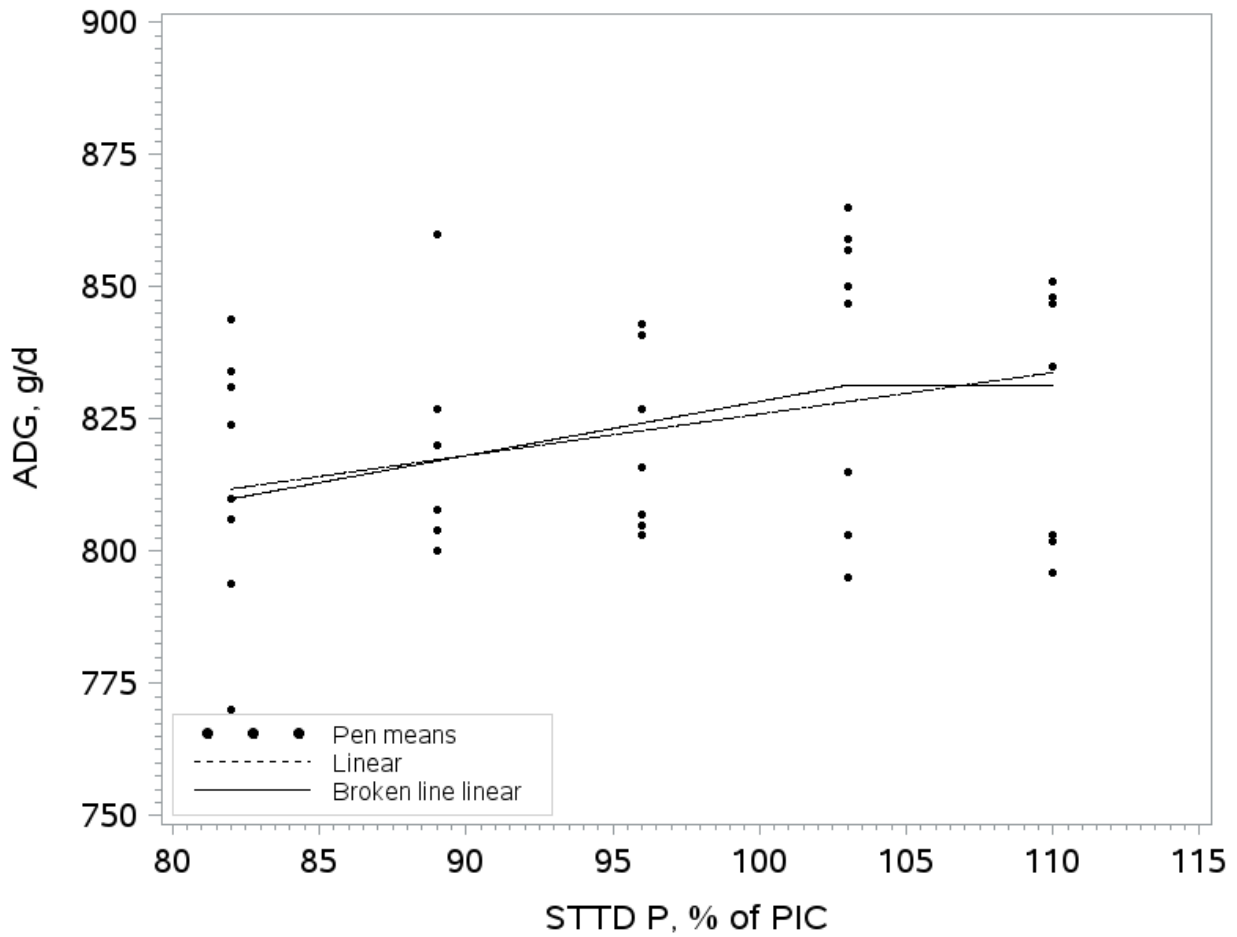


Figure 2.1. Fitted regression models for grower phase average daily gain (ADG, d 0 to 59) as a function of increasing percentage of PIC recommendation for standardized total tract digestible phosphorus (STTD P) for Duroc-sired pigs. Linear, and broken line linear (BLL) models were fit resulting in comparable Bayesian Information Criterion values (< 2 unit difference). The BLL model estimated a breakpoint at 103.0% (95% CI: [81.7, 124.3%]; BIC = 365.3), and the linear model predicted maximum ADG above the upper range of 110% of PIC recommendations evaluated (BIC = 364.5).

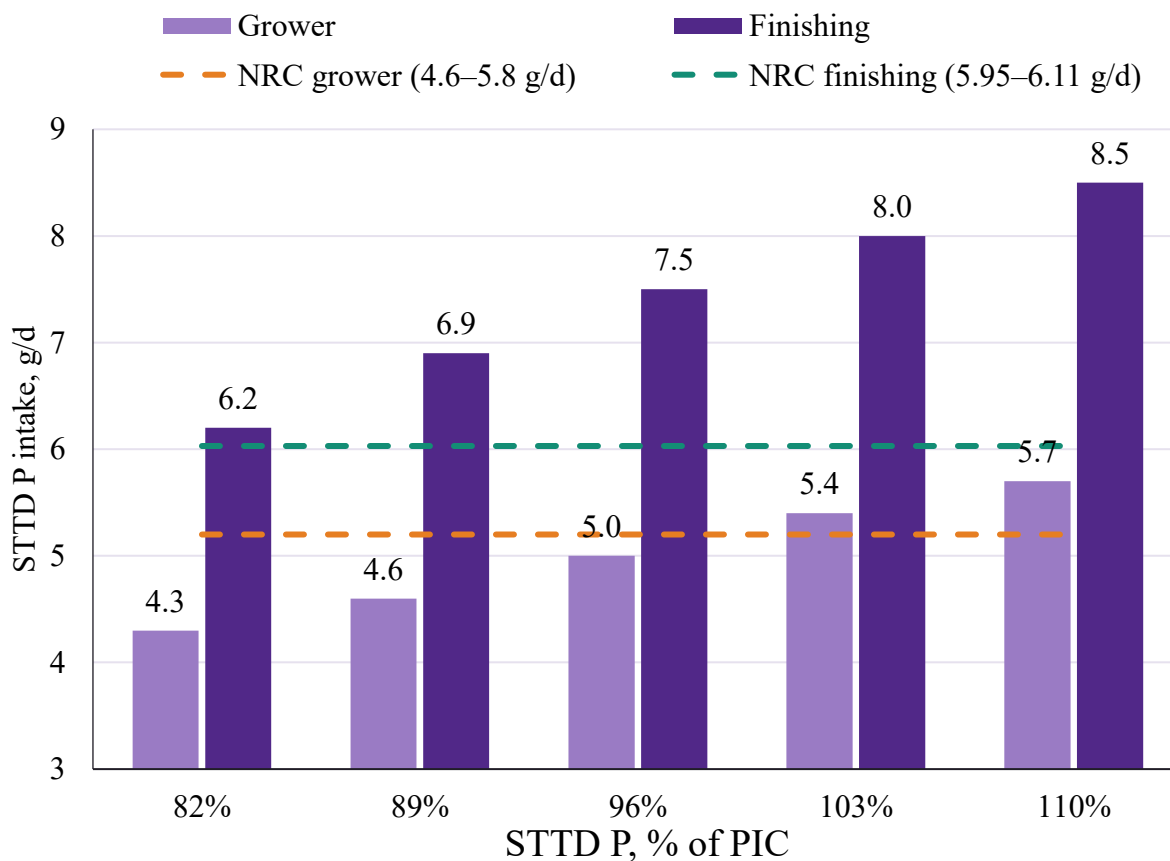


Figure 2.2. Daily standardized total tract digestible phosphorus (STTD P) intake (g/d) during the grower (d 0 to 59; 10 to 58 kg) and finishing (d 59 to 136; 58 to 133 kg) phases as a function of dietary STTD P level (expressed as a percentage of PIC 2021 recommendations) for Duroc-sired pigs. Horizontal dashed lines represent the estimated daily STTD P requirement ranges recommended by the NRC (2012) for grower (4.6 to 5.8 g/d) and finishing (5.95 to 6.11 g/d) pigs.

Table 2.1. Diets composition (as-fed basis)¹

Item	STTD P, % of PIC ² :	Phase 1			Phase 2			Phase 3		
		82	96	110	82	96	110	82	96	110
Ingredient, %										
Corn		58.11	59.57	61.04	65.09	66.51	67.84	73.63	74.78	75.93
Soybean meal, 47.7% CP		38.12	36.03	33.95	31.45	29.45	27.57	23.24	21.61	19.97
Limestone		1.20	1.33	1.46	1.19	1.32	1.45	1.11	1.21	1.32
Monocalcium P, 20.8% P		0.98	1.31	1.64	0.87	1.18	1.47	0.75	1.00	1.26
Salt		0.60	0.60	0.60	0.53	0.53	0.53	0.54	0.55	0.55
L-Thr		0.26	0.28	0.31	0.21	0.24	0.26	0.16	0.18	0.20
DL- Met		0.22	0.24	0.26	0.17	0.19	0.20	0.11	0.12	0.14
L-Lys		0.21	0.27	0.34	0.18	0.25	0.31	0.16	0.22	0.27
Vitamin and trace mineral premix ³		0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Copper sulfate		0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
L-Trp		0.05	0.06	0.07	0.05	0.06	0.06	0.05	0.05	0.06
L-Val		0.01	0.05	0.08	---	0.03	0.06	---	0.03	0.06
Calculated analysis										
SID ⁴ AA %										
Lys		1.28	1.28	1.28	1.10	1.10	1.10	0.88	0.88	0.88
Met & Cys:Lys		58	58	58	58	58	58	58	58	58
Thr:Lys		65	65	65	65	65	65	65	65	65
Trp:Lys		18	18	18	18	18	18	18	18	18
Val:Lys		68	68	68	69	68	68	71	71	71
Total Lys, %		1.44	1.44	1.43	1.24	1.23	1.23	1.00	0.99	0.99
Net energy, kcal/kg		2,320	2,320	2,320	2,356	2,356	2,356	2,400	2,400	2,400
SID Lys:net energy, g/Mcal		5.52	5.52	5.52	4.67	4.67	4.67	3.67	3.67	3.67
Ca, %		0.71	0.78	0.86	0.66	0.74	0.81	0.59	0.65	0.71
P, %		0.56	0.61	0.67	0.51	0.56	0.61	0.45	0.50	0.54

Ca:P ratio	1.27	1.27	1.27	1.31	1.31	1.31	1.30	1.30	1.30
STTD P, % ⁵	0.33	0.39	0.44	0.30	0.35	0.39	0.26	0.30	0.34

¹Phase 1 diets were fed from approximately 11 to 23 kg, phase 2 from approximately 23 to 45 kg, and phase 3 from approximately 45 to 73 kg.

²Standardized total tract digestible phosphorus (STTD P), expressed as a percentage of the PIC (2021) recommendations. The PIC (2021) nutrient specifications express the STTD P requirement as a ratio to net energy (g STTD P/Mcal NE), and the 100% treatment represents that recommended ratio applied to the dietary energy density. The 89 and 103% STTD P treatment diets were achieved by proportionally blending the 82 and 96% diets, and the 96 and 110% diets, respectively.

³Provided per kg of premix: 5,544,000 IU vitamin A; 1,108,750 IU vitamin D; 36,960 IU vitamin E; 2,465 mg vitamin K; 20.8 mg vitamin B12; 24,639.9 mg niacin; 18,188 mg pantothenic acid; and 5,545 mg riboflavin; 62.5 g Zn from Zn oxide; 50 g Fe from ferrous sulfate; 25 g Mn from manganese sulfate; 7.5 g Cu from copper sulfate; 0.175 g I from calcium iodate; and 0.075 g Se from sodium selenite.

⁴Standardized ileal digestible.

⁶Standardized total tract digestible phosphorus.

Table 2.2. Diets composition (as-fed basis, continued)¹

Item	STTD P, % of PIC ² :	Phase 4			Phase 5		
		82	96	110	82	96	110
Ingredient, %							
Corn		79.21	80.26	81.24	79.36	80.30	81.34
Soybean meal, 47.7 % CP		17.93	16.45	15.05	18.29	17.01	15.60
Limestone		1.06	1.16	1.25	0.98	1.06	1.15
Monocalcium P, 20.8% P		0.60	0.83	1.05	0.46	0.65	0.86
Salt		0.55	0.55	0.56	0.55	0.55	0.56
L-Thr		0.13	0.14	0.16	0.06	0.07	0.09
DL- Met		0.07	0.08	0.09	0.01	0.02	0.03
L-Lys		0.15	0.20	0.24	0.01	0.05	0.10
Vitamin and trace mineral premix ³		0.20	0.20	0.20	0.20	0.20	0.20
Copper sulfate		0.05	0.05	0.05	0.05	0.05	0.05
L-Trp		0.04	0.05	0.06	0.03	0.03	0.04
L-Val		---	0.03	0.05	---	---	---
Calculated analysis							
SID AA ⁴ %							
Lys		0.73	0.73	0.73	0.63	0.63	0.63
Met & Cys:Lys		58	58	58	58	58	58
Thr:Lys		65	65	65	65	65	65
Trp:Lys		18	18	18	18	18	18
Val:Lys		73	73	73	86	82	79
Total Lys, %		0.84	0.84	0.83	0.74	0.74	0.74
Net energy, kcal/kg		2,430	2,430	2,430	2,431	2,431	2,431
SID Lys:net energy, g/Mcal		3.00	3.00	3.00	2.59	2.59	2.59
Ca, %		0.53	0.58	0.64	0.49	0.53	0.58
P, %		0.40	0.44	0.48	0.37	0.40	0.44
Ca:P ratio		1.30	1.30	1.30	1.30	1.30	1.30
STTD P, % ⁵		0.22	0.26	0.29	0.19	0.23	0.26

¹Phase 4 diets were fed from approximately 73 to 100 kg. Phase 5 diets were fed from approximately 100 to 130 kg. The 89% and 103% of PIC recommendations for STTD P treatment diets were achieved by proportionally blending the 82% and 96% diets, and the 96% and 110% diets, respectively.

²Standardized total tract digestible phosphorus (STTD P), expressed as a percentage of the PIC (2021) recommendations. The PIC (2021) nutrient specifications express the STTD P requirement as a ratio to net energy (g STTD P/Mcal NE), and the 100% treatment represents that recommended ratio applied to the dietary energy density. The 89 and 103% STTD P treatment diets were achieved by proportionally blending the 82 and 96% diets, and the 96 and 110% diets, respectively.

³Provided per kg of premix: 5,544,000 IU vitamin A; 1,108,750 IU vitamin D; 36,960 IU vitamin E; 2,465 mg vitamin K; 20.8 mg vitamin B12; 24,639.9 mg niacin; 18,188 mg pantothenic acid; and 5,545 mg riboflavin; 62.5 g Zn from Zn oxide; 50 g Fe from ferrous sulfate; 25 g Mn from manganese sulfate; 7.5 g Cu from copper sulfate; 0.175 g I from calcium iodate; and 0.075 g Se from sodium selenite.

⁴Standardized ileal digestible.

⁵Standardized total tract digestible phosphorus.

Table 2.3. Chemical analysis of experimental diets (as-fed-basis)¹

Item	STTD P, % of PIC recommendation				
	82	89	96	103	110
Total P, %					
Phase 1	0.66 (0.56)	0.78 (0.58)	0.74 (0.61)	0.72 (0.64)	0.78 (0.67)
Phase 2	0.58 (0.51)	0.68 (0.54)	0.60 (0.56)	0.65 (0.58)	0.77 (0.61)
Phase 3	0.49 (0.45)	0.52 (0.47)	0.56 (0.49)	0.57 (0.52)	0.51 (0.54)
Phase 4	0.46 (0.40)	0.45 (0.42)	0.53 (0.44)	0.53 (0.46)	0.56 (0.48)
Phase 5	0.40 (0.37)	0.42 (0.39)	0.43 (0.41)	0.51 (0.42)	0.48 (0.44)
Total Ca, %					
Phase 1	1.10 (0.71)	1.08 (0.74)	1.07 (0.78)	1.07 (0.82)	1.07 (0.86)
Phase 2	1.02 (0.66)	1.03 (0.70)	0.94 (0.73)	1.07 (0.77)	1.22 (0.81)
Phase 3	0.77 (0.58)	0.92 (0.61)	0.92 (0.65)	0.89 (0.68)	0.88 (0.70)
Phase 4	0.62 (0.53)	0.71 (0.55)	0.88 (0.58)	0.80 (0.61)	0.94 (0.64)
Phase 5	0.54 (0.49)	0.57 (0.51)	0.68 (0.53)	0.74 (0.55)	0.86 (0.58)

¹Values are analyzed, with calculated values in parentheses. Standardized total tract digestible phosphorus (STTD P) is expressed as a percentage of the PIC (2021) recommendations. Representative samples of treatment diets were taken from 6 feeders per dietary treatment 3 d after the beginning and 3 d before the end of each phase and stored at -20°C . After blending, subsamples were submitted to Ward Laboratories, Inc. (Kearney, NE) for analysis. The 89 and 103% treatments were obtained by blending the 82, 96, and 110% diets; their calculated values derive from the corresponding blend proportions.

Table 2.4. Effect of standardized total tract digestible phosphorus (STTD P) level on growth performance of late nursery and finishing pigs¹

Item	STTD P, % of PIC recommendation					SEM	<i>P</i> =	
	82	89	96	103	110		Linear	Quadratic
BW, kg								
d 0	10.2	10.2	10.2	10.2	10.2	0.19	0.987	0.879
d 59	58.4	58.3	58.8	59.6	59.4	0.66	0.017	0.918
First marketing, d 115 ²	133.9	131.5	135.8	133.5	135.7	1.74	0.306	0.686
Second marketing, d 122 ²	133.0	131.3	132.5	134.3	134.0	1.39	0.290	0.579
Third marketing, d 129 ²	138.5	139.2	134.6	137.7	137.3	1.57	0.442	0.366
Final marketing, d 136	132.3	134.0	133.9	135.1	134.2	1.18	0.087	0.227
Average market weight ²	133.2	133.8	133.9	134.9	134.4	0.73	0.116	0.590
Period 1 (d 0 to 59)								
ADG, g	816	812	821	835	830	8.2	0.011	0.164
ADFI, g	1,474	1,461	1,465	1,506	1,483	14.1	0.129	0.747
G:F g/kg	552	556	562	556	559	2.5	0.180	0.244
STTD P intake, g/d	4.3 ^e	4.6 ^d	5.0 ^c	5.4 ^b	5.7 ^a	0.07	< 0.001	0.829
Period 2 (d 59 to 136)								
ADG, g	1,043	1,048	1,052	1,052	1,048	7.71	0.200	0.241
ADFI, g	2,975	2,975	2,984	3,012	3,003	24.9	0.199	0.988
G:F g/kg	351	352	353	351	350	1.73	0.723	0.175
STTD P intake, g/d	6.2 ^e	6.9 ^d	7.5 ^c	8.0 ^b	8.5 ^a	0.06	< 0.001	0.049
Overall (d 0 to 136)								
ADG, g	939	940	950	957	950	6.5	0.020	0.361
ADFI, g	2,292	2,282	2,294	2,324	2,313	20.9	0.123	0.804
G:F, g/kg	410	412	414	412	411	1.7	0.664	0.099
STTD P intake, g/d	5.4 ^e	5.9 ^d	6.4 ^c	6.9 ^b	7.2 ^a	0.06	< 0.001	0.160
Bone characteristics ³								
Abattoir bones, n	15	16	12	13	16	---	---	---
Ash content, %	59.2	60.7	59.9	60.7	60.6	0.16	0.888	0.464
Carcass characteristics ⁴								
Count, n	182	187	195	194	191	---	---	---
HCW, kg	97.9	98.6	98.6	99.2	99.2	0.73	0.093	0.664
Yield, %	73.7	73.9	73.6	73.8	73.9	0.15	0.422	0.781
Back fat depth, mm	16.5	16.8	16.0	16.5	16.5	0.23	0.936	0.316
Loin depth, mm	67.6	66.8	67.3	68.1	67.3	0.51	0.879	0.802
Lean, %	57.0	56.7	57.2	57.1	56.8	0.16	0.888	0.464

¹A total of 1,040 (PIC 800 × 1050; initially 10.2 ± 0.19 kg) pigs were used in a late nursery and finishing experiment to determine the impact of STTD P levels, based on the PIC (2021) phosphorus recommendations, on growth performance. Treatments were assigned in a randomized complete block design with 26 pigs per pen and 8 pens per treatment.

Chapter 3 - Effects of dietary iodine concentration and feeding duration on growth performance of nursery and wean-to-finish pigs

Abstract

Four experiments were conducted to evaluate the effects of added dietary iodine concentration and feeding duration on growth performance and thyroid hormone status of pigs from 6 to approximately 110 kg. In Exp. 1, 180 weaned pigs (Camborough $\times$ 337; initially 5.8 ± 0.05 kg) were used in a 35-d study to evaluate 5 concentrations of added I as potassium iodide (0, 0.14, 1.4, 14, and 140 mg/kg). Overall, body weight (BW), average daily gain (ADG), and average daily feed intake (ADFI) increased (linear, $P < 0.008$) with added I, with the greatest performance observed at 14 mg/kg. On d 35, plasma thyroxine (T4) and the T4:triiodothyronine (T3) ratio increased (linear, $P = 0.001$). In Exp. 2, 720 barrows (DNA 200 $\times$ 400; initially 6.3 ± 0.01 kg) were used in a 46-d study to evaluate increasing concentrations of added iodine as calcium iodate (0.3, 6.2, 12.2, 18.1, 24, and 30 mg/kg). During the 39-d experimental period, ADG and ADFI increased, decreased, and then increased (cubic, $P \leq 0.023$) and G:F increased (linear, $P < 0.018$ and quadratic, $P < 0.058$) as added iodine increased, with performance improving as iodine increased from 0.3 to 12.2 mg/kg. Broken-line linear models predicted no further improvement beyond 12.2 and 9.3 mg/kg of added iodine for ADG and G:F, respectively. In Exp. 3, 720 barrows (DNA 200 $\times$ 400; initially 6.2 ± 0.04 kg) were used in a 38-d study to determine the optimal feeding duration of 12.2 mg/kg added iodine in the nursery. Overall (d 0 to 38), no differences in ADG, ADFI, or G:F were observed among feeding durations. In Exp. 4, 2,080 mixed-sex pigs (PIC 337 $\times$ 1050; initially 5.7 ± 0.004 kg) were used in a 126-d study to evaluate the feeding duration of 14.3 mg/kg added iodine (d 0 to 20, d 0 to 42, or d 0 to 126)

from weaning to approximately 110 kg. Overall (d 0 to 126), pigs fed 14.3 mg/kg added iodine for the entire trial had increased ($P < 0.05$) G:F compared with those fed 14.3 mg/kg only in the early nursery phase (5.7 to 12.9 kg), with other durations intermediate. Collectively, pigs fed diets with approximately 12 to 14 mg/kg of added iodine had increased early growth performance and elevated circulating T4, while continuous supplementation from weaning to approximately 110 kg optimized overall G:F.

Key Words: dose-response, feed efficiency, iodine, thyroid hormone, swine.

Introduction

For decades, the dietary energy and amino acid requirement estimates of swine have been established based on the concentration needed to maximize growth and feed efficiency. In contrast, requirement estimates for vitamins and trace minerals have historically been derived from the minimum concentrations required to prevent clinical deficiency signs and sustain basic metabolic function (NRC, 2012). Iodine is a trace element of particular interest in this context because it is the obligatory structural substrate for the thyroid hormones thyroxine (T4) and triiodothyronine (T3; Köhrle, 2023). Through this endocrine axis, dietary iodine supply is linked to the metabolic processes related to lean tissue accretion and growth (Mullur et al., 2014). In nursery and growing pigs, subclinical iodine deficiency reduces circulating thyroid hormone concentrations, resulting in lethargy, unthriftiness, decreased growth rate, and goiter (Cromwell et al., 1975; Rosol and Gröne, 2016). Based on the dietary concentrations required to mitigate these physiological challenges and normalize both thyroid size and growth rate, the NRC (2012)

established a baseline iodine requirement estimate of 0.14 mg/kg for all body weights of nursery and growing pigs.

This historical baseline contrasts markedly with modern commercial diet formulation. A recent survey representing 72% of the U.S. sow inventory documented that nutritionists routinely supplement iodine well above the historical requirement estimate across all production, averaging between 3.1 and 3.9 times the NRC (2012) estimate during the nursery period, and 2.0 to 2.7 times above the requirement estimate throughout the finishing phases (Faccin et al., 2023). While the minimum requirement estimate of 0.14 mg/kg has successfully prevented clinical deficiency signs across the industry, this shift toward higher commercial baselines underscores that long-standing estimates warrant contemporary re-evaluation. Specifically, the dietary iodine concentration that maximizes growth performance has not been clearly defined, and the dose-response relationship between elevated iodine concentrations and nursery pig performance remains formally uncharacterized.

Although elevated iodine shows promise as a metabolic modifier in swine, two practical questions remain unresolved. First, the dietary concentration that maximizes performance has not been established through formal dose-response modeling. Second, the ideal duration of supplementation is unknown, as it remains unclear whether the benefits of feeding higher concentrations of iodine are confined to the early nursery phase, a critical window of heightened thyroidal responsiveness and intestinal maturation (Hernandez and Stohn, 2018), or if they persist when supplementation extends into the grow-finish period. Therefore, the objectives of these four experiments were to characterize the growth and thyroid hormone response of nursery pigs to a wide range of added dietary iodine concentrations (Exp. 1), to determine the dose-response relationship between added dietary iodine and nursery pig growth performance using

formal modeling (Exp. 2), to evaluate the optimal duration of elevated iodine feeding within the nursery period (Exp. 3), and to evaluate the effects of elevated iodine concentration and feeding duration on wean-to-finish growth performance under commercial conditions (Exp. 4). It was hypothesized that elevated added dietary iodine would improve growth performance and elevate circulating thyroid hormone concentrations, and that the metabolic benefits on overall growth and feed efficiency would be optimized by continuous supplementation through the growing-finishing period.

Materials and Methods

All animal procedures were approved by the Institutional Animal Care and Use Committees of the respective institutions (University of Georgia for Exp. 1, AUP# A2019 08-038-R1; Kansas State University for Exp. 2 and 3, IACUC-4943, and Exp. 4, IACUC-4975). Experiment 1 was conducted in an environmentally controlled nursery at the University of Georgia, Athens, GA. Each pen (0.97×2.08 m) was equipped with a dry self-feeder and a waterer to provide ad libitum access to feed and water, allowing approximately 0.35 m^2 of floor space per pig.

Experiments 2 and 3 were conducted at the Kansas State University Segregated Early Weaning facility in Manhattan, KS, which has two identical, totally enclosed, environmentally controlled, and mechanically ventilated barns. Each pen (1.2×1.2 m) was equipped with a 4-hole dry self-feeder and a cup waterer to provide ad libitum access to feed and water, allowing approximately 0.25 m^2 per pig. Experiment 4 was conducted at a commercial wean-to-finish research facility in south-central Minnesota. The barn was naturally ventilated with slatted concrete flooring over deep pits. Each pen provided approximately 0.67 m^2 per pig and was

equipped with a 3-hole stainless steel dry self-feeder (Thorp Equipment, Thorp, WI) and a cup waterer for ad libitum access to feed and water.

Diet preparation and chemical analysis

All diets across the four experiments were corn-soybean meal-based. In Exp. 1, the five target concentrations of iodine (0, 0.14, 1.4, 14, and 140 mg/kg) were achieved by adding potassium iodide (99% iodine, Thermo Fisher Scientific, Fair Lawn, NJ) directly to the trace mineral premix, which was included at 1% of the diet. In Exp. 2, 3, and 4, the basal concentration of 0.3 mg/kg of added iodine was supplied by ethylenediamine dihydriodide (EDDI) in the standard trace mineral premix, and experimental concentrations were achieved using a custom iodine premix prepared by diluting calcium iodate (63.5% iodine; Phibro Animal Health Corporation, Teaneck, NJ) with ground corn at a 1:100 ratio, yielding a premix containing 0.635% iodine; this custom premix ensured homogeneous distribution of iodine in the final diet. For Exp. 2 to 4, representative feed samples were collected from the feeders and feed mill, pooled, and analyzed in duplicate for total iodine concentration at the Michigan State University Veterinary Diagnostic Laboratory (East Lansing, MI).

Experiment 1

A total of 180 mixed-sex pigs (Camborough × 337, PIC) were used in a 35-d study. At weaning (d 21), pigs were blocked by initial body weight (5.81 ± 0.05 kg) and randomly assigned to one of five dietary treatments in a randomized complete block design. There were four pigs per pen (two barrows and two gilts) and nine pens per treatment. Diets were fed in three dietary phases (phase 1 from d 0 to 10, phase 2 from d 10 to 21, and phase 3 from d 21 to 35). The five dietary treatments were achieved by incorporating custom trace mineral premixes formulated to provide 0, 0.14, 1.4, 14, or 140 mg/kg of added iodine. The trace mineral premixes

were included at 1% of the basal diet and were formulated to meet or exceed NRC (2012) requirement estimates for all other trace minerals. Pigs were housed in an environmentally controlled nursery and provided ad libitum access to feed and water. Feed intake and body weight (BW) were recorded weekly and on d 0, 7, 10, 14, 21, 28, and 35 to determine average daily gain (ADG), average daily feed intake (ADFI), and gain:feed ratio (G:F).

Blood samples were collected on d 21 and 35 in heparinized blood collection tubes (BD Vacutainer, Franklin Lakes, NJ) via the orbital sinus (Dove and Alworth, 2015) from all pigs. Blood was centrifuged ($2,000 \times g$, 20 min, 4°C) and plasma was collected, aliquoted, and stored at -20°C, before sending to the USDA Meat Animal Research Center (USDA, Clay Center, NE) for T3 and T4 analysis using MP Biomedical kits (MP Biomedicals, Solon, OH). To determine the intraassay CV, a pool of serum from finishing barrows was included in each assay and averaged 4.7% and 7.6% for T4 and T3, respectively.

Experiment 2

A total of 720 barrows (DNA 200 $\times$ 400; initially 6.3 ± 0.01 kg BW) were used in a 39-d study. At weaning (d 21), pigs were randomly assigned within six BW blocks to one of six dietary treatments in a generalized randomized block design. There were five pigs per pen and 24 pens per treatment. Diets were fed for the first 39 d (phase 1 from d 0 to 10, phase 2 from d 10 to 24 and phase 3 from d 24 to 39), and then all pigs were fed a common diet for the last week of the study (d 39 to 46). To create the dietary treatments, two extreme diets were manufactured for each phase: a low-iodine control diet (0.3 mg/kg of added iodine) and a high-iodine diet formulated to contain 30 mg/kg of added iodine. The four intermediate dietary treatments (6.2, 12.2, 18.1, and 24 mg/kg of added iodine) were then produced by proportionally blending the low- and high-iodine diets. Treatment diets were manufactured at the Kansas State University

O.H. Kruse Feed Technology Innovation Center (Manhattan, KS). Pig BW and feed disappearance were measured on d 0, 10, 15, 24, 31, 39, and 46 to determine ADG, ADFI, and G:F.

Experiment 3

A total of 720 barrows (DNA 200 × 400; initially 6.2 ± 0.04 kg BW) were used in a 38-d growth trial. At weaning (approximately d 20), pigs were randomly assigned within three BW blocks (light, medium, and heavy) to one of four dietary treatments in a generalized randomized block design. There were five pigs per pen and 36 pens per treatment (six pens per treatment within each block). Experimental diets were fed in 3 phases (phase 1, pellets, from d 0 to 10; phase 2, mash, from d 10 to 24; and phase 3, mash, from d 24 to 38). The control diet contained 0.3 mg/kg added iodine throughout the 3 phases. Experimental treatments included 12.2 mg/kg added iodine during phase 1 and 0.3 mg/kg added iodine during phases 2 and 3; 12.2 mg/kg added iodine during phases 1 and 2, and 0.3 mg/kg added iodine during phase 3; and 12.2 mg/kg added iodine throughout all 3 phases. Treatment diets were manufactured at the Kansas State University O.H. Kruse Feed Technology Innovation Center (Manhattan, KS). Pig BW and feed disappearance were measured on d 0, 10, and then weekly thereafter until d 38 to determine ADG, ADFI, and G:F.

Experiment 4

A total of 2,080 mixed-sex pigs (PIC 337 × 1050; initially 5.7 ± 0.004 kg) were used in a 126-d study. At placement, pigs were sorted by sex, and pens were stocked with 26 pigs per pen (13 barrows and 13 gilts). Pens were blocked by average BW into 20 blocks and assigned to one of four dietary treatments (20 pens per treatment) in a randomized complete block design. Six dietary phases were provided on a time basis, formulated for sequential BW ranges (5.5 to 6.8,

6.8 to 11.3, 11.3 to 22.7, 22.7 to 45.4, 45.4 to 72.6, and 72.6 to 110 kg) and fed from d 0 to 7, 7 to 20, 20 to 42, 42 to 70, 70 to 98, and 98 to 126, respectively. Phases 1 and 2 were manufactured in pellet form (CFS, Truman, MN) and the remaining phases were manufactured in meal form at the United FCS Klossner feed mill (Klossner, MN). For each feeding phase, two diets were manufactured: a control (0.3 mg/kg of added iodine) and a high iodine diet (14.3 mg/kg of added iodine). Dietary treatments were based on the duration of feeding the 14.3 mg/kg diet relative to control. Treatments included: control (0.3 mg/kg of added iodine from d 0 to 126); 2) early nursery (14.3 mg/kg of added iodine from d 0 to 20, followed by 0.3 mg/kg thereafter); 3) entire nursery (14.3 mg/kg of added iodine from d 0 to 42, followed by 0.3 mg/kg from d 42 to 126); and 4) weaning to-finish (14.3 mg/kg of added iodine fed continuously from d 0 to 126). Pig BW and feed disappearance were measured bi-weekly to determine ADG, ADFI, and G:F.

Statistical Analysis

In all experiments, pen served as the experimental unit, and results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

Growth performance and thyroid hormone data from Exp. 1 were analyzed as a randomized complete block design using PROC GLM in SAS (SAS Enterprise; SAS Inst. Inc., Cary, NC), with pigs blocked by BW and sex. Initial BW (d 0) served as a covariate for all growth performance criteria. Linear and quadratic effects of dietary iodine were evaluated using orthogonal contrast coefficients generated via the IML procedure of SAS to account for the logarithmic spacing of the dietary treatments.

Data from Exp. 2 were analyzed as a generalized randomized block design in a one-way ANOVA using the lmer function of the lme4 package in RStudio (Version 4.5.3; R Core Team,

Vienna, Austria), with dietary treatment and weight block as fixed effects and barn as a random effect. Linear, quadratic, and cubic contrasts were tested across increasing concentrations of dietary iodine. In addition, linear, quadratic, cubic, broken-line linear (BLL), and broken-line quadratic (BLQ) dose-response models were fit to estimate the iodine concentrations that optimized ADG and G:F. Models were compared using the Bayesian Information Criterion (BIC), where the model exhibiting the lowest BIC value was considered best-fitting, and a reduction in BIC greater than 2 units was deemed meaningful evidence of model superiority.

Data from Exp. 3 were analyzed as a generalized randomized block design using the `lm` function in RStudio (Version 4.5.3; R Core Team, Vienna, Austria), with dietary treatment, group, and the interaction between group and weight block as fixed effects.

Data from Exp. 4 were analyzed as a randomized complete block design using the `lmer` function of the `lme4` package in RStudio (Version 4.5.3; R Core Team, Vienna, Austria), with treatment as a fixed effect and BW block as a random effect. The proportion of dead or removed pigs relative to the number of pigs placed per pen was used as the response variable for mortality and removals using a binomial distribution and logit link function.

Results

Experiment 1

From d 0 to 10, ADG and ADFI increased (linear, $P \leq 0.028$) as dietary iodine increased, resulting in an increase (linear, $P = 0.016$) in d 10 BW (Table 8). Despite the linear response, there was little improvement in response criteria above 14 mg/kg of added iodine. There were no differences observed in G:F.

From d 10 to 21, no differences in ADG, ADFI, or G:F were observed due to added iodine. However, d 21 BW increased (linear, $P = 0.034$) as added dietary iodine increased, again with little increase beyond 14 mg/kg of added iodine.

From d 21 to 35, ADG increased (linear, $P = 0.028$) as dietary iodine increased, with little increase beyond 14 mg/kg of added iodine. Additionally, ADFI increased (linear, $P = 0.036$) as added dietary iodine increased; specifically, pigs fed any supplemental level of iodine had greater intake compared with the unsupplemented control group.

Overall from d 0 to 35, increasing dietary iodine increased ADG (linear, $P = 0.008$). Like previous timepoints, despite the linear response, there was little increase in ADG observed beyond 14 mg/kg added iodine. Furthermore, ADFI increased (linear, $P = 0.006$) as added dietary iodine increased. Consequently, d 35 BW increased (linear, $P = 0.006$) as dietary iodine increased, also maximizing at 14 mg/kg of added iodine.

On d 21, circulating thyroxine (T4) concentrations increased (linear, $P = 0.021$) as dietary iodine increased (Table 9). The greatest T4 concentration was observed in pigs fed 14 mg/kg of added iodine. Neither triiodothyronine (T3) concentrations nor the T4:T3 ratio were affected by increasing concentrations of dietary iodine on d 21.

On d 35, plasma T4 concentrations increased (linear, $P < 0.001$ and quadratic, $P = 0.026$) as added dietary iodine increased. This quadratic response was characterized by a plateau in T4 concentrations starting at 1.4 mg/kg of added dietary iodine, with little increase observed thereafter. Similarly, the T4:T3 ratio increased (linear, $P < 0.001$ and quadratic, $P = 0.025$) with increasing dietary iodine, maximizing in pigs fed 14 mg/kg of added iodine. There were no differences in circulating T3 concentrations among dietary treatments at the conclusion of the study.

Experiment 2

From d 0 to 10, a tendency (cubic, $P \leq 0.072$) was observed for ADG, G:F, and d 10 BW, with performance improving as added iodine increased from 0.3 to 12.2 mg/kg, decreasing at 24 mg/kg, and increasing again at 30 mg/kg (Table 10). From d 10 to 24, increasing added iodine increased ADG (linear, $P = 0.009$), with a tendency for a cubic response ($P = 0.062$) and d 24 BW followed the same cubic pattern (cubic, $P = 0.008$). Average daily feed intake during this period showed a cubic response ($P = 0.034$), and a marginal quadratic response was observed for G:F ($P = 0.086$), which improved with added iodine up to 24 mg/kg and then worsened at 30 mg/kg. From d 24 to 39, ADG and ADFI showed a marginal cubic response (cubic, $P \leq 0.056$), and BW on 39 followed a cubic response (cubic, $P \leq 0.014$), all reflecting the same pattern of improvement to 12.2 mg/kg, decline at 24 mg/kg, and recovery at 30 mg/kg.

For the overall experimental period (d 0 to 39), ADG and ADFI showed a cubic response ($P \leq 0.023$) in which performance improved as added iodine increased from 0.3 to 12.2 mg/kg, decreased at 24 mg/kg, and increased again at 30 mg/kg, whereas G:F increased (linear, $P = 0.018$ and quadratic, $P < 0.058$) as dietary iodine increased. Body weight at d 39 followed the same cubic pattern ($P = 0.014$) as ADG.

For the experimental-period (d 0 to 39) dose-response analysis, linear, quadratic, cubic, and broken-line linear (BLL) models were evaluated, with model selection based on the lowest BIC. For ADG (Figure 1), the BLL and cubic models provided the best fit where the BLL model predicted no further improvement beyond a breakpoint of 12.2 mg/kg of added iodine. The cubic model predicted 95 and 100% of maximum ADG at added iodine greater than 5.2 and 10.2 mg/kg, respectively. For G:F (Figure 2), the BLL and quadratic polynomial (QP) models provided the best fit where the BLL model predicted no further improvement beyond a

breakpoint of 9.3 mg/kg, whereas the QP model predicted 95 and 100% of maximum G:F at greater than 16.0 and 20.4 mg/kg of added iodine, respectively.

Experiment 3

The duration of feeding an elevated concentration of added iodine (12.2 mg/kg) did not affect ADG, ADFI, or G:F during any of the three feeding phases (Table 11). Consequently, for the overall nursery period (d 0 to 38), final BW, ADG, ADFI, and G:F did not differ among treatments, regardless of whether 12.2 mg/kg added iodine was fed for 0, 10, 24, or 38 d.

Experiment 4

There were no differences in BW among treatment groups at any time point during the experiment (Table 12). From d 0 to 20, G:F was affected by dietary treatment ($P = 0.029$), where pigs assigned to the wean-to-finish treatment had increased G:F compared with those fed the 0.3 mg/kg control diet, with pigs assigned to the early and entire nursery treatments being intermediate. Additionally, a tendency ($P = 0.097$) for a treatment difference was observed for ADFI, whereas no difference was observed for ADG.

From d 20 to 42, pigs fed 14.3 mg/kg of added iodine continuously had increased ($P = 0.006$) G:F compared with the control and early nursery treatments, with pigs fed increased I the entire nursery phase intermediate.

No treatment differences in performance were observed from d 42 to 126. Overall (d 0 to 126), G:F was affected by dietary treatment ($P = 0.022$), where pigs assigned to the wean-to-finish treatment had increased G:F compared with those on the early nursery treatment, with the control and entire nursery treatments being intermediate. No differences in overall ADG, ADFI, mortality, removals, or total removals and mortality were observed.

Discussion

Iodine is an essential trace mineral required for the synthesis of the thyroid hormones T4 and T3 (Flachowsky, 2007). Thyroxine is the predominant hormone secreted by the thyroid gland and functions largely as a circulating reservoir, whereas T3 is the biologically active form that binds nuclear receptors to regulate energy metabolism, protein synthesis, cellular differentiation, and thermoregulation (Bloise et al., 2018; Stepien and Huttner, 2019). Because most circulating T4 is converted to T3 in peripheral tissues by deiodinases, the balance between the two hormones, expressed as the T4:T3 ratio, reflects whether changes in thyroid status arise from altered glandular output or from altered peripheral conversion. In young pigs, these physiological processes operate at high rates during the rapid post-weaning growth phase (Paulikova et al., 2011). Despite this critical metabolic role, the iodine requirement estimate for swine was established primarily to prevent clinical goiter and normalize thyroid weight rather than to optimize growth performance where early evaluations concluded that 0.14 to 0.15 mg/kg was sufficient to prevent goiter (Sihombing et al., 1974; Cromwell et al., 1975), and this deficiency-prevention threshold became the basis of the current NRC (2012) requirement estimate of 0.14 mg/kg. A key limitation of that framework is that those foundational studies evaluated a maximum of only 0.4 mg/kg added iodine, so the possibility of a performance optimum well above the deficiency threshold was never tested, and commercial practice has since mirrored this conservative baseline, averaging only 0.44 to 0.55 mg/kg added iodine in U.S. nursery diets (Faccin et al., 2023).

The four experiments herein collectively evaluated and characterized the endocrine and growth responses of pigs to elevated dietary iodine across both research and commercial environments. Supplemental iodine well above the current requirement estimate, on the order of

10 to 100 times the NRC (2012) estimate, improved growth performance and, where thyroid hormones were measured, increased circulating T4 and the T4:T3 ratio without altering plasma T3, indicating that the response was driven by greater thyroid hormone output rather than by increased peripheral conversion. The specific expression of this benefit varied with developmental stage, manifesting primarily as feed-intake-driven gain in early nursery pigs and transitioning to improved feed efficiency across the wean-to-finish period. Additionally, the magnitude of the response depended on baseline performance, given that pigs already growing at high rates showed little further improvement (Exp. 3). Together, these experiments indicate that iodine may act as a conditional metabolic modifier whose benefit is greatest when growth is compromised. In this respect, iodine parallels other trace minerals such as Zn, Cu, and more recently Mn (Hill et al., 2000; Shelton et al., 2011; Edmunds et al., 2022), for which increased concentrations are used to optimize performance rather than merely to prevent clinical deficiency.

Experiment 1 provided the initial evidence for a supplementation range by evaluating a broad spectrum of added dietary iodine concentrations, 0 to 140 mg/kg. Growth performance (ADG, ADFI, and BW) was greatest when fed at 14 mg/kg, with no further benefit at the highest concentration reported. This performance optimum was accompanied by an endocrine response by d 35, with both plasma T4 and the T4:T3 ratio increasing with dietary iodine, whereas plasma T3 remained unchanged. Furthermore, no reductions in performance or signs of toxicity were observed at 140 mg/kg, which is consistent with the established swine toxic threshold of 400 to 800 mg/kg (Newton and Clawson, 1974). Because iodine is the substrate for hormone synthesis (Leung and Braverman, 2014), the rise in T4 without a corresponding change in T3 indicates that supplemental iodine expanded the circulating prohormone pool rather than inappropriately

forcing systemic increases in T3. This suggests peripheral tissues can locally convert this increased T4 into active T3 to regulate cellular metabolism independently of blood T3 levels (Salvatore et al., 2014; Bianco et al., 2019). Building on this finding, Exp. 2 was designed to more closely define the response to maximize growth performance using dose-response modeling. Both ADG and ADFI exhibited a cubic response, improving as added iodine increased to 12.2 mg/kg, decreasing at 24 mg/kg, and increasing again at 30 mg/kg, while G:F increased linearly. Broken-line linear models identified breakpoints of 12.2 and 9.5 mg/kg to maximize ADG and G:F, respectively, indicating that the primary performance benefits were captured at or below 12 mg/kg.

The cubic response observed in Exp. 2 was caused by a reduction in performance at 24 mg/kg of added iodine, followed by a full recovery at 30 mg/kg. A closer examination of the data reveals that this drop in gain was driven primarily by a localized decrease in feed intake. Because feed efficiency remained stable for this treatment, the pigs did not appear to suffer any metabolic difficulty. Diet analysis confirmed the expected iodine concentrations, ruling out a feed-mixing error. Additionally, true iodine toxicity is unlikely because performance fully recovered at the highest dose, and these inclusion rates are far below the established toxic threshold of 400 to 800 mg/kg (Newton and Clawson, 1974). Although the exact mechanism causing this feed intake depression at 24 mg/kg of added iodine remains unclear, it does not represent a physiological limit to iodine utilization. Ultimately, because performance recovered at 30 mg/kg with no further benefit beyond the initial plateau, the broken-line linear model provides the most logical interpretation of the dose-response relationship, estimating maximum ADG near 12.2 mg/kg.

A notable feature of this dataset is how the response to added iodine appeared to shift depending on the animal's specific physiological and environmental context. Improvements in

nursery growth performance in Exp. 1 were driven by feed intake and daily gain, whereas Exp. 4 showed wean-to-finish improvements almost entirely in feed efficiency, and Exp. 2 captured elements of both. This variance may reflect the changing physical constraints of the animal as it matures. In young nursery pigs, physical gut capacity often limits maximum feed intake (Nyachoti et al., 2004; NRC, 2012); therefore, elevated thyroid activity may manifest primarily as an intake-driven boost in early gain. Conversely, as pigs enter the grow-finish period and feed intake becomes regulated more by metabolic energy demand than by physical gut volume, the physiological benefit of supplemental iodine may transition toward improved net feed efficiency.

This context-dependent responsiveness may also provide an explanation for the lack of response observed in Exp. 3. Although Exp. 3 utilized the same genetic line, initial body weight, and research facility as Exp. 2, the unsupplemented control pigs achieved a baseline performance of 449 g/d ADG and 730 g/kg G:F that were greater than the peak performance of the best iodine-supplemented group in Exp. 2 (440 g/d and 714 g/kg). Because metabolic modifiers often elicit their greatest measurable benefits when animals face subclinical, environmental, or nutritional challenges (Cromwell, 2001), the baseline health and growth rate of the Exp. 3 cohort may have left little physiological margin for supplemental iodine to elicit further improvement. While the exact cause of this inconsistency remains undetermined, these observations suggest that the magnitude and expression of the iodine response are not absolute, but rather potentially modulated by the baseline performance and challenge status of the specific group of pigs.

The responsiveness of nursery pigs observed in the current experiments aligns directly with recent large-scale commercial data reported by Hart et al. (2026). In a study utilizing over 2,400 weaned pigs, they observed that increasing supplemental iodine up to 50 mg/kg yielded linear improvements in both daily gain and feed efficiency during the late nursery phase. The

consistency of this early-life response across different research and commercial environments points to a critical biological window during the post-weaning transition. As a piglet shifts from milk to solid feed, its gastrointestinal tract undergoes rapid structural remodeling. This intestinal maturation is governed by the localized generation of active triiodothyronine (T3); during the transition to dry feed, the gut mucosa upregulates iodothyronine deiodinase enzymes to locally convert systemic T4 into the active T3 required to drive crypt cell proliferation, enterocyte differentiation, and the assembly of adult nutrient transporters (Hernandez and Stohn, 2018). Simultaneously, other actively growing peripheral tissues, such as skeletal muscle, utilize this expanded systemic pool of T4 to drive the intracellular protein synthesis and nutrient utilization required for faster physical growth (Bloise et al., 2018; Stepien and Huttner, 2019). Because these young animals operate at a high rate of thyroid turnover (Paulikova et al., 2011), the typical post-weaning reduction in feed intake may restrict the basal supply of iodine right when physiological demand peaks. Providing elevated dietary iodine during this window overcomes the substrate limitation, ensuring a steady systemic pool of T4 to drive intestinal remodeling.

This developmental mechanism may also explain why the growth response to supplemental iodine appears to diminish over time. When Li et al. (2012) fed up to 10 mg/kg of added iodine to finishing pigs, they observed no benefits in growth or carcass traits. This is biologically logical: a mature pig has already completed gastrointestinal maturation. With lower relative thyroid hormone turnover and a fully developed intestinal mucosa, the older animal actively downregulates its thyroidal transporters to prevent excessive hormone synthesis (Li et al., 2013). This age-dependent trajectory was demonstrated in Exp. 4, where the advantage in feed efficiency from continuous iodine supplementation accumulated almost entirely during the

first 42 d post-weaning, maintaining that fixed advantage through the grow-finish phases rather than expanding it.

Experiment 4 represents one of the first evaluations of elevated iodine fed continuously from weaning to approximately 110 kg. Under commercial conditions daily gain and final weight were not altered. Continuous feeding of 14.3 mg/kg of added iodine improved overall wean-to-finish feed efficiency compared with supplementation only during the early nursery, while both the unsupplemented control and the entire nursery supplementation treatments were intermediate. Because feed accounts for 60 to 70% of total swine production costs, efficiency improvements of this magnitude yield meaningful feed savings at the commercial scale. Combined with the low inclusion cost of calcium iodate and its wide safety margin, continuous supplementation offers a favorable return on investment for commercial formulation strategies.

In summary, these experiments indicate that adding dietary iodine well above the current NRC (2012) requirement estimate improved nursery pig growth performance in three of the four studies, with broken-line models identifying breakpoints between 9.5 and 12.2 mg/kg maximizing performance. Furthermore, feeding 14.3 mg/kg of added iodine continuously from weaning to market optimized overall feed efficiency without altering weight gain or viability. While the variability observed across trials suggests that the response to elevated levels of added iodine may be modulated by the herd's basal growth rate or environmental conditions, overall, the present data support a dietary iodine requirement estimate near 12 to 14 mg/kg to maximize feed efficiency across both research and commercial conditions

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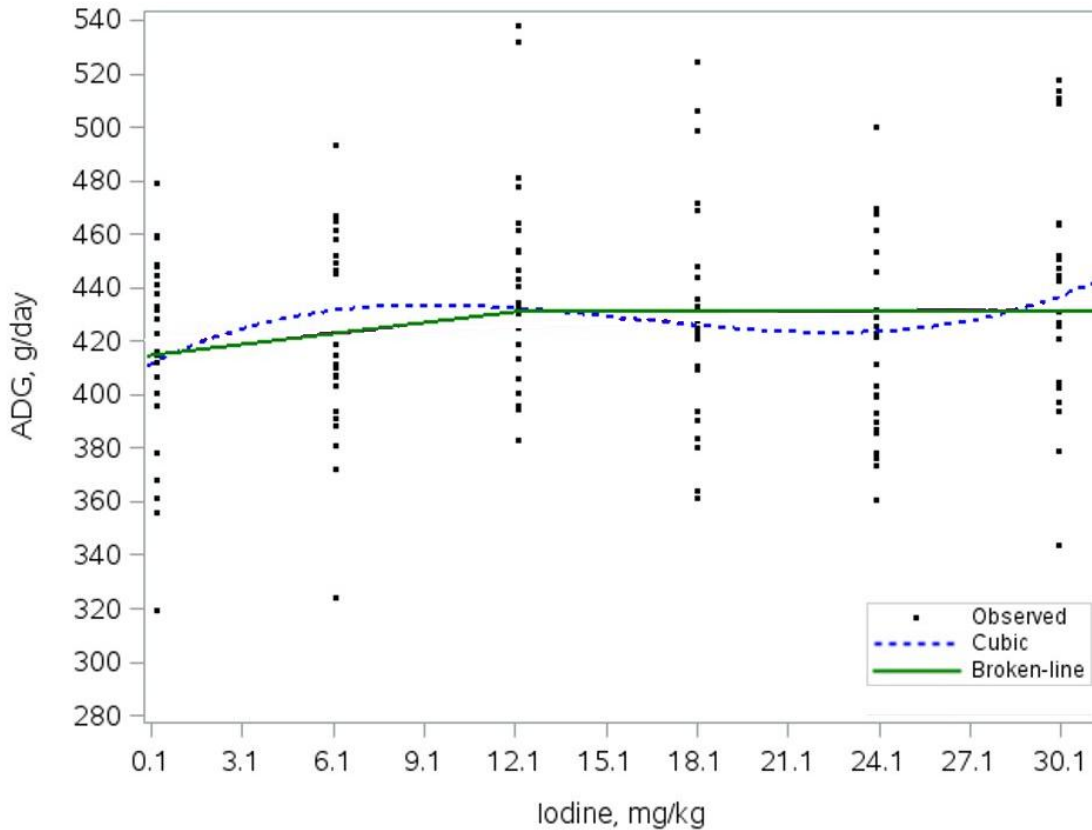


Figure 3.1. Estimation of added iodine concentration to maximize ADG for 6.3 to 23.0 kg DNA 200 × 400 pigs, Exp. 2. A total of 720 barrows (DNA 200 × 400; initially 6.3 ± 0.1 kg) were used in a 46-d trial. Cubic, broken-line linear (BLL), and broken-line quadratic (BLQ) models were fitted to estimate the added iodine concentration required to maximize ADG during the 39-d experimental period. The cubic and BLL models resulted in the best fit based on Bayesian Information Criterion (BIC), with a lower number indicative of a better fit (BIC = 1401.4 vs. 1402.8, cubic vs. BLL, respectively). The BLL model predicted no further improvement beyond 12.2 mg/kg added iodine. The cubic model predicted 95 and 100% of maximum ADG at greater than 5.2 and 10.15 mg/kg added iodine, respectively. The cubic model equation for ADG was: $\text{ADG, g/day} = 0.0088 \times (\text{Added Iodine, mg/kg})^3 - 0.423 \times (\text{Added Iodine, mg/kg})^2 + 5.569 \times (\text{Added Iodine, mg/kg}) + 411.00$.

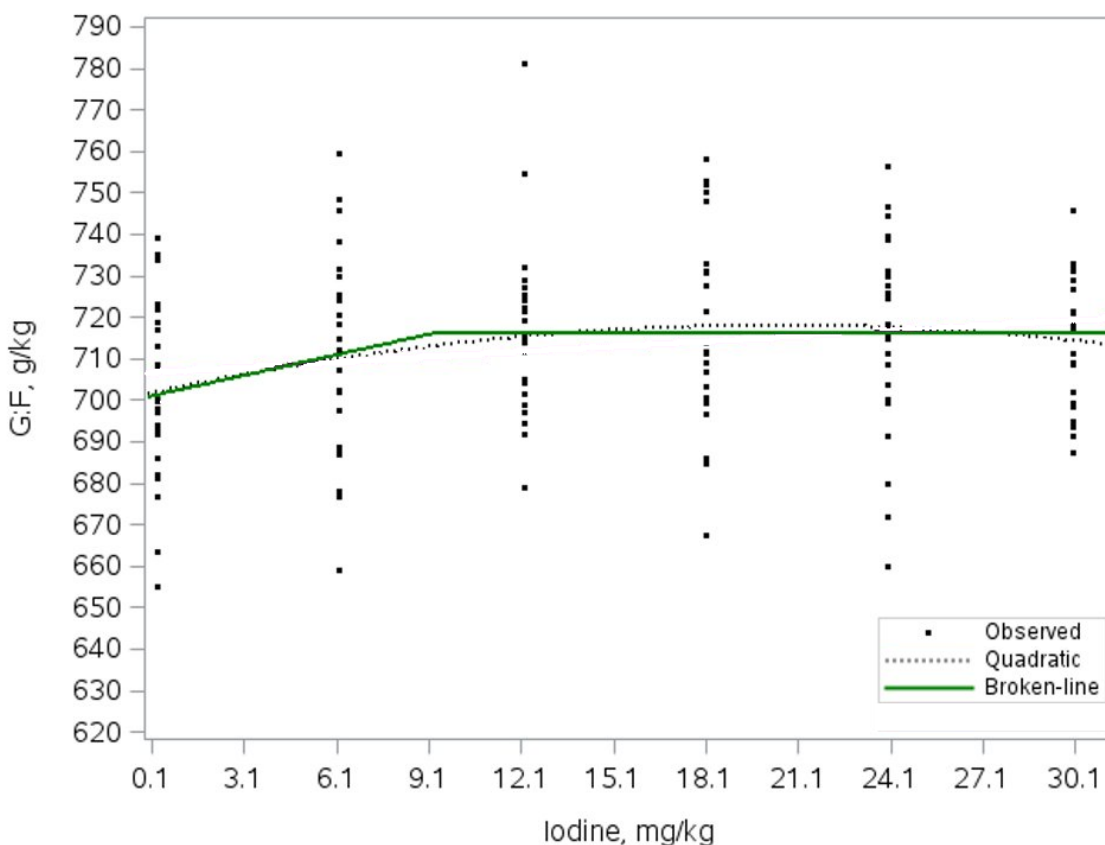


Figure 3.2. Estimation of added iodine requirements to minimize G:F for 6.3 to 23.0 kg DNA 200 × 400 pigs, Exp. 2. A total of 720 barrows (DNA 200 × 400; initially 6.3 ± 0.1 kg) were used in a 46-d trial. Quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models were fitted to estimate the added iodine concentration required to maximize G:F during the 39-d experimental period. The BLL and QP models resulted in the best fit based on Bayesian Information Criterion (BIC), with a lower number indicative of a better fit (BIC = 1297.3 vs. 1297.4, BLL vs. QP, respectively). The BLL model predicted no further improvement beyond 9.3 mg/kg added iodine. The QP model predicted 95 and 100% of maximum G:F at greater than 16.0 and 20.4 mg/kg added iodine, respectively. The QP model equation for G:F was: $G:F, \text{ g/kg} = -0.0395 \times (\text{Added Iodine, mg/kg})^2 + 1.614 \times (\text{Added Iodine, mg/kg}) + 701.49$.

Table 3.1. Composition of Exp. 1 diets (as-fed basis)¹

Item	Phase 1 ¹	Phase 2	Phase 3
Ingredient, %			
Corn	24.14	43.33	61.82
Soybean meal, 47% CP	18.64	27.01	32.34
Ground oats	10.00	5.00	---
Hydrolyzed soy protein ²	10.00	5.00	---
Whey	15.00	5.00	---
Lactose	10.00	5.00	---
Fish meal	5.00	3.00	---
Soybean Oil	3.35	2.90	1.33
Limestone	0.74	0.85	0.84
Dicalcium phosphate	0.64	0.91	1.55
Salt	0.20	0.25	0.35
L-Lysine HCl	0.40	0.30	0.35
DL-Methionine	0.16	0.11	0.12
L-Threonine	0.11	0.06	0.05
Vitamin premix ³	0.25	0.25	0.25
Mineral premix ⁴	1.00	1.00	1.00
Zinc oxide	0.37	---	---
Calculated analysis			
SID ⁵ AA, %			
Lys, %	1.50	1.35	1.20
Met&Cys:Lys	55	55	57
Thr:Lys	59	59	61
Trp:Lys	17	18	19
Net energy, kcal/kg	2,478	2,478	2,445
SID Lys:net energy, g/Mcal	6.05	5.45	4.91
CP, %	23.19	23.06	21.36
Ca, %	0.85	0.80	0.80
STTD P ⁶ , %	0.45	0.40	0.40

¹ Phase 1 was fed from d 1 to 10 (5.8 to 7.3 kg). Phase 2 was fed days from d 10 to 21 (7.3 to 12 kg), and Phase 3 was fed days from d 21 to 35 (12 to 20.2 kg).

²Hamlet Protein 300, Findlay, OH.

³Provided per kg of premix: 1,653,600 IU vitamin A; 661,200 IU vitamin D; 26,400 IU vitamin E; 1,320 mg vitamin K; 13.2 mg vitamin B12; 19,840 mg niacin; 11,040 mg pantothenic acid; and 3,308 mg riboflavin

Table 3.2. Composition of Exp. 2 diets (as-fed basis)

Item	Added iodine, mg/kg	Phase 1		Phase 2		Phase 3	
		0.3	30.0	0.3	30.0	0.3	30.0
Ingredient, %							
Corn		45.50	45.03	60.80	60.33	65.55	65.08
Soybean meal, 47.7% CP		22.09	22.09	22.90	22.90	30.54	30.54
Whey powder		12.50	12.50	7.00	7.00	---	---
Whey permeate, 80% lactose		7.50	7.50	---	---	---	---
Soy protein concentrate ²		7.50	7.50	5.00	5.00	---	---
Soybean oil		1.00	1.00	---	---	---	---
Calcium carbonate		0.58	0.58	0.70	0.70	0.75	0.75
Monocalcium phosphate, 21.5% P		1.10	1.10	1.10	1.10	1.05	1.05
Sodium chloride		0.50	0.50	0.70	0.70	0.60	0.60
L-Lys HCl		0.36	0.36	0.50	0.50	0.48	0.48
DL-Met		0.23	0.23	0.20	0.20	0.20	0.20
L-Thr		0.19	0.19	0.20	0.20	0.22	0.22
L- Tryptophan		0.03	0.03	0.05	0.05	0.05	0.05
L- Val		0.09	0.09	0.10	0.10	0.12	0.12
Trace mineral premix ³		0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix ⁴		0.25	0.25	0.25	0.25	0.25	0.25
Phytase ⁵		0.06	0.06	0.06	0.06	0.06	0.06
Zinc oxide		0.40	0.40	0.30	0.30	---	---
Iodine premix, 0.635% I ⁶		---	0.47	---	0.47	---	0.47
Calculated analysis							
SID ⁷ AA %							
Lys, %		1.40	1.40	1.35	1.35	1.30	1.30
Ile:Lys		60	60	57	57	56	56
Leu:Lys		116	116	116	116	117	117
Met:Lys		37	37	37	37	37	37
Met & Cys:Lys		58	58	58	58	58	58
Thr:Lys		65	65	65	65	65	65
Trp:Lys		20	20	20	20	20	20
Val:Lys		70	70	70	70	70	70
His:Lys		36	36	36	36	37	37
Net energy, kcal/kg		2,513	2,513	2,445	2,445	2,427	2,427
SID Lys: net energy, g/Mcal		5.57	5.57	5.52	5.52	5.36	5.36
Crude protein, %		21.7	21.7	21.0	21.0	20.8	20.8
Ca, %		0.72	0.72	0.72	0.72	0.68	0.68
P, %		0.68	0.68	0.65	0.65	0.61	0.61
STTD P ⁸ , %		0.58	0.58	0.53	0.53	0.48	0.48

¹Phases 1, 2, and 3 were fed from d 0 to 10 (6.3 to 8.3 kg), 10 to 24 (8.3 to 14.6 kg), and 24 to 39 (14.6 to 23 kg), respectively. The low added iodine diet was fed as a common phase from d 39 to 46.

²PurePro Soy (Bunge; Chesterfield, MO).

³Provided per kg of premix: 73.3 g Zn from zinc sulfate; 73.3 g Fe from ferrous sulfate; 22.0 g Mn from manganese oxide; 7.3 g Cu from copper sulfate; 0.22 g I from calcium iodate; and 0.20 g Se from sodium selenite.

⁴Provided per kg of premix: 4,409,200 IU vitamin A; 550,800 IU vitamin D3; 17,640 IU vitamin E; 1,760 mg vitamin K; 16 mg vitamin B12; 19,840 mg niacin; 11,040 mg pantothenic acid; and 3,320 mg riboflavin.

⁵Hiphorius 2400 (Novonesis, Kongens Lyngby, Denmark) provided 1,442 FTU/kg of feed in all phases, with an assumed release of 0.12% STTD P.

⁶Iodine premix was formulated to be 99 parts of corn and 1 of CaI (63.5% Iodine). The premix was added at the expense of corn.

⁷Standardized ileal digestible.

⁸Standardized total tract digestible phosphorus.

Table 3.3. Chemical analysis of experimental diets. Exp 2. (as-fed-basis) ¹

Analyzed iodine levels, mg/kg	Added iodine, mg/kg					
	0.3	6.2	12.2	18.1	24.0	30.0
Phase 1	3.04	5.32	10.02	12.97	18.59	21.54
Phase 2	2.94	5.99	11.07	15.08	19.96	24.16
Phase 3	1.25	4.86	7.95	12.56	16.77	24.43

¹ Representative samples of treatment diets were taken from the feed mill. Two samples per treatment were submitted to Michigan State University Veterinary Diagnostic Laboratory (East Lansing, MI) for iodine analysis and were analyzed in duplicate.

Table 3.4. Composition of Exp. 3 diets (as-fed basis)¹

Item	Added iodine, mg/kg	Phase 1		Phase 2		Phase 3	
		0.3	12.2	0.3	12.2	0.3	12.2
Ingredient, %							
Corn		46.40	46.21	61.11	60.92	65.53	65.34
Soybean meal, 47.7% CP		20.91	20.91	22.50	22.50	30.54	30.54
Whey powder		12.50	12.50	7.00	7.00	--	--
Whey permeate		7.50	7.50	--	--	--	--
Microbially enhanced SBM ²		7.50	7.50	5.00	5.00	--	--
Soybean oil		1.00	1.00	--	--	--	--
Calcium carbonate		0.53	0.53	0.68	0.68	0.75	0.75
Monocalcium phosphate, 21.5% P		1.15	1.15	1.10	1.10	1.05	1.05
Sodium chloride		0.50	0.50	0.70	0.70	0.60	0.60
L-Lys-HCl		0.48	0.48	0.52	0.52	0.48	0.48
DL-Met		0.30	0.30	0.26	0.26	0.20	0.20
L-Thr		0.22	0.22	0.23	0.23	0.22	0.22
L-Trp		0.03	0.03	0.05	0.05	0.05	0.05
L-Val		0.12	0.12	0.12	0.12	0.12	0.12
Trace mineral premix ³		0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix ⁴		0.25	0.25	0.25	0.25	0.25	0.25
Phytase ⁵		0.06	0.06	0.06	0.06	0.06	0.06
Zinc oxide		0.40	0.40	0.27	0.27	--	--
Iodine premix, 0.635% I ⁶		--	0.19	--	0.19	--	0.19
Calculated analysis							
SID ⁷ AA %							
Lys, %		1.40	1.40	1.35	1.35	1.30	1.30
Ile:Lys		59	59	57	57	56	56
Leu:Lys		113	113	115	115	117	117
Met:Lys		41	41	40	40	37	37
Met & Cys:Lys		58	58	58	58	58	58
Thr:Lys		65	65	65	65	65	65
Trp:Lys		20.0	20.0	20.2	20.2	20.1	20.1
Val:Lys		70	70	70	70	70	70
His:Lys		34	34	35	35	37	37
SID Lys:net energy, g/Mcal		5.56	5.56	5.52	5.52	5.36	5.36
Net energy, kcal/kg		2,515	2,515	2,445	2,445	2,427	2,427
Crude protein, %		21.7	21.7	21.0	21.0	20.8	20.8
Ca, %		0.69	0.69	0.69	0.69	0.68	0.68
P, %		0.66	0.66	0.62	0.62	0.61	0.61
Ca:P		1.05	1.05	1.10	1.10	1.11	1.11
STTD P ⁸ , %		0.58	0.58	0.52	0.52	0.48	0.48

Analyzed iodine, mg/kg ⁹	0.96	10.94	< 0.49	12.56	< 0.49	11.32
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¹Treatment diets were fed in 3 phases: Phase 1 in pellet form, from d 0 to 10 (6.2 to 8.0 kg), phase 2 in mash form, from d 10 to 24 (8.2 to 13.9 kg), and phase 3 in mash form, from d 24 to 38 (13.9 to 22.9 kg).

²Access Starter Protein; Prairie AquaTech, Brookings, SD.

³Provided per kg of premix: 73.3 g Zn from zinc sulfate; 73.3 g Fe from ferrous sulfate; 22.0 g Mn from manganese oxide; 7.3 g Cu from copper sulfate; 0.22 g I from calcium iodate; and 0.20 g Se from sodium selenite.

⁴Provided per kg of premix: 4,409,200 IU vitamin A; 550,800 IU vitamin D3; 17,640 IU vitamin E; 1,760 mg vitamin K; 16 mg vitamin B12; 19,840 mg niacin; 11,040 mg pantothenic acid; and 3,320 mg riboflavin.

⁵HiPhorius 2400 (Novonesis, Kongens Lyngby, Denmark), which provided an estimated release of 0.12% STTD P with 1,500 FYT/kg.

⁶Premix was formulated by diluting the iodine source (CaI, 63.5% iodine, Phibro Animal Health Corporation, Teaneck, NJ) with ground corn to create a premix concentration of 0.635% iodine.

⁷Standardized ileal digestible.

⁸Standardized total tract digestible phosphorus

⁹Feed samples were analyzed in duplicate for iodine concentration by the Veterinary Diagnostic Laboratory at Michigan State University (East Lansing, MI).

Table 3.5. Composition of Exp. 4 diets (Phases 1 to 3; as-fed basis)¹

Ingredient	Added iodine, mg/kg:	Phase 1		Phase 2		Phase 3	
		0.3	14.3	0.3	14.3	0.3	14.3
Corn		44.43	44.38	53.41	53.36	59.53	59.48
Soybean meal, 46% CP		23.15	23.15	31.95	31.95	37.55	37.55
Oat groats		10.00	10.00	5.00	5.00	--	--
Whey permeate, 80% lactose		7.50	7.50	--	--	--	--
Fermented SBM ²		5.00	5.00	2.50	2.50	--	--
Fish meal		5.00	5.00	2.50	2.50	--	--
Choice white grease		1.25	1.25	0.90	0.90	--	--
Monocalcium phosphate, 21% P		0.33	0.33	0.68	0.68	0.45	0.45
Limestone		0.17	0.17	0.46	0.46	0.84	0.84
Salt		0.70	0.70	0.75	0.75	0.60	0.60
L-Lys HCl		0.27	0.27	0.26	0.26	0.22	0.22
DL- Met		0.13	0.13	0.15	0.15	0.15	0.15
L-Thr		0.20	0.20	0.21	0.21	0.20	0.20
L-Tryptophan		0.03	0.03	0.03	0.03	--	--
Copper sulfate		--	--	--	--	0.07	0.07
Zinc oxide		0.40	0.40	0.33	0.33	--	--
Choline chloride		0.05	0.05	0.05	0.05	--	--
Vitamin premix ³		0.25	0.25	0.25	0.25	0.25	0.25
Trace mineral premix ⁴		0.15	0.15	0.15	0.15	0.15	0.15
Iodine premix, 2.8% I ⁵		--	0.05	--	0.05	--	0.05
Carbadox ⁶		1.00	1.00	--	--	--	--
Chlortetracycline ⁷		--	--	0.25	0.25	--	--
Tiamulin ⁸		--	--	0.18	0.18	--	--
Calculated analysis							
SID ⁹ AA %							
Lys, %		1.30	1.30	1.35	1.35	1.30	1.30
Ile:Lys		56	56	55	55	55	55
Leu:Lys		112	112	114	114	117	117
Met:Lys		35	35	35	35	35	35
Met & Cys:Lys		58	58	58	58	58	58
Thr:Lys		65	65	65	65	65	65
Trp:Lys		20	20	20	20	19	19
Val:Lys		67	67	67	67	68	68
His:Lys		36	36	37	37	39	39
SID Lys:net energy, g/Mcal		5.31	5.31	5.63	5.63	5.51	5.51
Net energy, kcal/kg		2,449	2,449	2,401	2,401	2,359	2,359
Crude protein, %		22.1	22.1	23.1	23.1	22.6	22.6
Ca, %		0.64	0.64	0.67	0.67	0.63	0.63
P, %		0.58	0.58	0.61	0.61	0.51	0.51
Ca:P		1.10	1.10	1.10	1.10	1.25	1.25

Standard digestible P, %	0.50	0.50	0.50	0.50	0.40	0.40
Analyzed iodine, mg/kg ¹⁰	1.94	7.10	7.02	13.85	0.50	10.20

¹Treatment diets were fed in 6 phases: Phase 1 and 2 in pellet form, from d 0 to 7 (5.7 to 7.5 kg) and from d 7 to 20 (7.5 to 13 kg) respectively. Phase 3 through 6 were fed in mash form, from d 20 to 42 (13 to 26 kg), from d 42 to 70 (26 to 53 kg), from d 70 to 98 (53 to 82 kg) and from d 98 to 126 (82 to 110 kg), respectively.

²Fermex 200 (Purina Animal Nutrition, Shoreview, MN)

³Provided per kg of premix: 1,653,500 IU vitamin A; 661,400 IU vitamin D3; 17,640 IU vitamin E; 1,320 mg vitamin K; 13.2 mg vitamin B12; 19,840 mg niacin; 11,020 mg pantothenic acid; and 3,310 mg riboflavin. Quantum Blue G phytase (AB Vista, Plantation, FL) was included in the premix to provide 500 FTU/kg of complete diet, with an assumed release of 0.12% STTD P.

⁴Provided per kg of premix: 73.4 g Zn from zinc sulfate; 73.4 g Fe from ferrous sulfate; 22.0 g Mn from manganese oxide; 11.0 g Cu from copper sulfate; 0.20 g I from calcium iodate; and 0.20 g Se from sodium selenite.

⁵Iodine premix pack was formulated using calcium iodate (63.5% iodine; Phibro Animal Health Corporation, Teaneck, NJ) and ground corn to provide exactly 14.0 mg/kg of added iodine when included at 0.05% (0.5 kg per metric ton) of the complete diet.

⁶Mecadox 2.5 (Phibro Animal Health; Teaneck, NJ).

⁷Aureo 100 (Zoetis, Parsippany, NJ)

⁸Denegard 10 (Elanco, Indianapolis, IN)

⁹Standardized ileal digestible.

¹⁰Representative samples of treatment diets were taken from the feed bin and feeders. Two samples per treatment were submitted to Michigan State University Veterinary Diagnostic Laboratory (East Lansing, MI) for iodine content determination and were analyzed in duplicate. Results are expressed as an average of feed samples collected from feed bin and feeders.

Table 3.6. Composition of Exp. 4 diets (Phases 4 to 6; as-fed basis)¹

Ingredient	Added iodine, mg/kg:	Phase 4		Phase 5		Phase 6	
		0.3	14.3	0.3	14.3	0.3	14.3
Corn		67.40	67.35	73.86	73.81	78.53	78.48
Soybean meal, 46% CP		29.95	29.95	23.90	23.90	19.65	19.65
Monocalcium phosphate, 21% P		0.40	0.40	0.18	0.18	---	---
Limestone		0.87	0.87	0.80	0.80	0.76	0.76
Salt		0.53	0.53	0.55	0.55	0.55	0.55
L-Lys HCl		0.23	0.23	0.19	0.19	0.14	0.14
DL- Met		0.11	0.11	0.05	0.05	---	---
L-Thr		0.17	0.17	0.12	0.12	0.07	0.07
Copper sulfate		0.05	0.05	0.05	0.05	0.05	0.05
Vitamin premix ²		0.15	0.15	0.15	0.15	0.13	0.13
Trace mineral premix ³		0.15	0.15	0.15	0.15	0.13	0.13
Iodine premix, 2.8% I ⁴		---	0.05	---	0.05	---	0.05
Calculated analysis							
SID ⁵ AA %							
Lys, %		1.12	1.12	0.94	0.94	0.79	0.79
Ile:Lys		55	55	57	57	61	61
Leu:Lys		123	123	135	135	151	151
Met:Lys		34	34	32	32	29	29
Met & Cys:Lys		58	58	58	58	58	58
Thr:Lys		65	65	65	65	65	65
Trp:Lys		19	19	19	19	20	20
Val:Lys		68	68	71	71	77	77
His:Lys		39	39	42	42	45	45
SID Lys:net energy, g/Mcal		4.65	4.65	3.84	3.84	3.18	3.18
Net energy, kcal/kg		2,405	2,405	2,443	2,443	2,469	2,469
Crude protein, %		19.7	19.7	17.3	17.3	15.6	15.6
Ca, %		0.60	0.60	0.51	0.51	0.44	0.44
P, %		0.46	0.46	0.39	0.39	0.34	0.34
Ca:P ratio		1.30	1.30	1.30	1.30	1.30	1.30
Standard digestible P, %		0.37	0.37	0.32	0.32	0.27	0.27
Analyzed iodine, mg/kg ⁶		0.54	9.52	0.51	7.43	0.51	9.33

¹Treatment diets were fed in 6 phases: Phase 1 and 2 in pellet form, from d 0 to 7 (5.7 to 7.5 kg) and from d 7 to 20 (7.5 to 13 kg) respectively. Phase 3 through 6 were fed in mash form, from d 20 to 42 (13 to 26 kg), from d 42 to 70 (26 to 53 kg), from d 70 to 98 (53 to 82 kg) and from d 98 to 126 (82 to 110 kg), respectively.

²Provided per kg of premix: 1,653,500 IU vitamin A; 661,400 IU vitamin D3; 17,640 IU vitamin E; 1,320 mg vitamin K; 13.2 mg vitamin B12; 19,840 mg niacin; 11,020 mg pantothenic acid; and 3,310 mg riboflavin. Quantum Blue G phytase (AB Vista, Plantation, FL) was included in the premix to provide 500 FTU/kg of complete diet, with an assumed release of 0.12% STTD P.

³Provided per kg of premix: 73.4 g Zn from zinc sulfate; 73.4 g Fe from ferrous sulfate; 22.0 g Mn from manganese oxide; 11.0 g Cu from copper sulfate; 0.20 g I from calcium iodate; and 0.20 g Se from sodium selenite.

⁴Iodine premix pack was formulated using calcium iodate (63.5% iodine; Phibro Animal Health Corporation, Teaneck, NJ) and ground corn to provide 14.0 mg/kg of added iodine when included at 0.05% (0.5 kg per metric ton) of the complete diet.

⁵Standardized ileal digestible

⁶Representative samples of treatment diets were taken from the feed bin and feeders. Two samples per treatment were submitted to Michigan State University Veterinary Diagnostic Laboratory (East Lansing, MI) for iodine analysis and were analyzed in duplicate. Results are expressed as an average of feed samples collected from feed bin and feeders.

Table 3.7. Effect of dietary iodine on the growth performance of nursery pigs. Exp. 1¹

Item	Added iodine, mg/kg					SEM	<i>P</i> =	
	0	0.14	1.4	14	140		Linear	Quadratic
BW, kg								
d 0	5.7	5.8	5.8	5.9	5.8	0.05	0.335	0.561
d 10	7.1	7.3	7.3	7.6	7.3	0.09	0.016	0.367
d 21	11.6	11.9	12.1	12.7	12.0	0.24	0.034	0.908
d 35	19.2	19.9	20.5	21.1	20.2	0.38	0.006	0.432
d 0 to 10								
ADG, g	130	154	155	176	152	9.9	0.028	0.442
ADFI, g	262	306	287	338	296	14.1	0.022	0.385
G:F, g/kg	510	520	560	540	530	26.0	0.330	0.745
d 10 to 21								
ADG, g	410	414	435	459	422	17.4	0.186	0.668
ADFI, g	795	792	822	838	836	38.7	0.264	0.743
G:F g/kg	550	540	550	580	520	30.0	0.857	0.441
d 21 to 35								
ADG, g	550	576	597	613	595	17.0	0.028	0.343
ADFI, g	1,014	1,099	1,128	1,112	1,097	28.0	0.036	0.065
G:F, g/kg	560	540	540	570	560	10.0	0.522	0.597
Overall (d 0 to 35)								
ADG, g	384	405	420	440	414	10.0	0.008	0.461
ADFI, g	731	779	791	819	782	20.0	0.006	0.207
G:F g/kg	550	540	550	550	550	20.0	0.504	0.867

¹ A total of 180 pigs (Camborough × 337, PIC; initially 5.8 ± 0.05 kg) were used in a 35-d study to evaluate the effects of elevated dietary iodine concentration on nursery growth performance. Treatments were assigned in a randomized complete block design with 4 pigs per pen and 9 pens per treatment. Diets were fed in 3 phases, including: phase 1, d 0 to 10; phase 2, d 10 to 21; phase 3, d 21 to 35. BW= body weight; ADG = average daily gain; ADFI = average daily feed intake; G:F = gain:feed ratio.

Table 3.8. Effect of dietary iodine on thyroid hormone concentrations on d 21 and d 35 in the nursery, Exp. 1

Item	Added iodine, mg/kg					SEM	<i>P</i> = ¹	
	0	0.14	1.4	14	140		Linear	Quadratic
d 21								
T4 ² , nmol/L	63.9	63.6	66.3	71.3	68.4	2.27	0.021	0.874
T3 ³ , nmol/L	1.7	1.6	1.6	1.7	1.7	0.06	0.311	0.863
T4:T3	39.6	40.1	42.2	43.0	41.5	1.60	0.178	0.848
d 35								
T4, nmol/L	48.4	51.4	58.3	59.3	59.9	2.18	0.001	0.026
T3, nmol/L	1.7	1.3	1.5	1.4	1.4	0.16	0.400	0.249
T4:T3	36.6	41.3	40.9	45.2	44.6	1.70	0.001	0.025

¹The *P*-values presented are for the main effect of iodine, the linear effect of iodine, and the quadratic effect of iodine, respectively.

² Thyroxine,

³ Triiodothyronine.

Table 3.9. Effect of increasing dietary iodine on nursery pig growth performance, Exp 2¹

Item	Added iodine, mg/kg						SEM	<i>P</i> =		
	0.3	6.2	12.2	18.1	24	30		Linear	Quadratic	Cubic
BW, kg										
d 0	6.3	6.3	6.3	6.3	6.3	6.3	0.01	0.747	0.992	0.950
d 10	8.3	8.3	8.4	8.3	8.2	8.4	0.07	0.429	0.504	0.064
d 24	14.3	14.6	14.8	14.6	14.4	14.9	0.14	0.079	0.625	0.008
d 39	22.6	22.8	23.5	23.1	22.6	23.4	0.20	0.119	0.289	0.014
d 0 to 10										
ADG, g	200	200	209	204	191	218	7.7	0.410	0.507	0.067
ADFI, g	200	195	204	195	191	209	6.4	0.828	0.248	0.279
G:F g/kg	990	1,010	1,031	1,031	990	1,053	19.7	0.122	0.694	0.072
d 10 to 24										
ADG, g	422	440	458	449	440	458	7.7	0.009	0.230	0.062
ADFI, g	599	603	608	608	599	635	10	0.091	0.868	0.034
G:F g/kg	704	725	719	730	735	719	7.3	0.060	0.086	0.762
d 24 to 39										
ADG, g	558	558	581	558	549	567	7.7	0.845	0.546	0.056
ADFI, g	857	853	880	853	835	866	10.9	0.596	0.904	0.054
G:F g/kg	649	654	662	658	658	654	5.6	0.330	0.193	0.967
Overall (d 0 to 39)										
ADG, g	417	422	440	426	417	440	5.9	0.057	0.440	0.010
ADFI, g	594	594	617	599	581	612	8.2	0.406	0.913	0.023
G:F g/kg	699	709	714	714	714	714	4.6	0.018	0.058	0.600

¹ A total of 720 barrows (DNA 200 × 400; initially 6.3 ± 0.01 kg) were used in a 39-d study to evaluate the effects of increasing concentrations of added dietary iodine on nursery growth performance. Treatments were assigned in a generalized randomized block design with 5 pigs per pen and 24 pens per treatment. Diets were fed in 3 phases, including: phase 1, d 0 to 10; phase 2, d 10 to 24; and phase 3, d 24 to 39. BW= body weight; ADG = average daily gain; ADFI = average daily feed intake; G:F = gain:feed ratio.

Table 3.10. Effect of feeding duration of elevated iodine diets on growth performance of nursery pigs, Exp. 3¹

		Added iodine, mg/kg					
	d 0 to 10:	0.3	12.2	12.2	12.2		
	d 10 to 24:	0.3	0.3	12.2	12.2		
Item	d 24 to 38:	0.3	0.3	0.3	12.2	SEM	P =
BW, kg							
	d 0	6.2	6.2	6.2	6.2	0.04	0.999
	d 10	8.3	8.2	8.2	8.2	0.07	0.715
	d 24	14.0	13.9	13.8	13.8	0.13	0.707
	d 38	23.0	23.0	22.9	22.8	0.17	0.802
d 0 to 10							
	ADG, g	222	213	213	218	5.4	0.571
	ADFI, g	213	209	204	209	4.1	0.561
	G:F, g/kg	1,031	1,010	1,010	1,042	18.8	0.745
d 10 to 24							
	ADG, g	408	404	399	395	5.9	0.252
	ADFI, g	558	553	549	540	7.3	0.302
	G:F, g/kg	730	730	725	725	5.8	0.848
d 24 to 38							
	ADG, g	644	649	649	640	6.4	0.789
	ADFI, g	943	957	957	939	8.6	0.267
	G:F, g/kg	685	676	676	680	4.6	0.558
d 0 to 38 (overall)							
	ADG, g	449	449	445	440	4.5	0.509
	ADFI, g	617	617	612	603	5.9	0.396
	G:F, g/kg	730	725	725	730	3.2	0.249

¹A total of 720 barrows (DNA 200 × 400; initially 6.2 ± 0.04 kg) were used in a 38-d study to evaluate the effects of feeding duration of elevated dietary iodine on nursery growth performance. Treatments were assigned in a generalized randomized block design with 5 pigs per pen and 36 pens per treatment. Diets were fed in 3 phases, including: phase 1, d 0 to 10; phase 2, d 10 to 24 and phase 3, d 24 to 38. BW= body weight; ADG = average daily gain; ADFI = average daily feed intake; G:F = gain:feed ratio.

Table 3.11. Effect of elevated dietary iodine supplementation and feeding duration on wean-to-finish growth performance, Exp. 4¹

Item	Treatment	Added iodine, mg/kg				SEM	P =
		Control	Early nursery	Entire nursery	Wean to finish		
	d 0 to 20	0.3	14.3	14.3	14.3		
	d 20 to 42	0.3	0.3	14.3	14.3		
	d 42 to 126	0.3	0.3	0.3	14.3		
BW, kg							
d 0		5.7	5.7	5.7	5.7	< 0.01	0.886
d 20		12.9	12.9	12.9	12.9	0.08	0.591
d 42		26.1	26.0	26.0	26.0	0.18	0.940
d 126		107.8	108.1	107.2	108.2	0.62	0.327
d 0 to 20							
ADG, g		360	355	356	359	3.8	0.677
ADFI, g		417	409	408	405	4.1	0.097
G:F, g/kg		864 ^a	867 ^{ab}	872 ^{ab}	888 ^b	6.2	0.029
d 20 to 42							
ADG, g		590	588	588	592	6.2	0.944
ADFI, g		911	908	895	895	8.6	0.331
G:F, g/kg		647 ^b	647 ^b	658 ^{ab}	662 ^a	4.0	0.006
d 0 to 42							
ADG, g		479	475	477	480	4.4	0.727
ADFI, g		673	667	661	660	5.7	0.206
G:F, g/kg		712 ^b	713 ^b	721 ^{ab}	728 ^a	3.2	< 0.001
d 42 to 126							
ADG, g		970	973	962	973	6.3	0.221
ADFI, g		2316	2341	2303	2312	13.4	0.180
G:F, g/kg		419	416	418	421	2.0	0.107
d 0 to 126							
ADG, g		804	802	796	805	5.3	0.350
ADFI, g		1760	1767	1743	1750	10.8	0.386
G:F, g/kg		457 ^{ab}	454 ^b	457 ^{ab}	460 ^a	1.9	0.022
Removals, %		4.0	5.0	3.8	4.2	0.96	0.808
Mortality on test, %		1.34	2.50	1.92	1.54	0.505	0.531
Total removals, %		5.38	7.5	5.77	5.77	1.155	0.489

¹A total of 2,080 pigs (337 × 1050, PIC, initially 5.7 ± 0.004 kg) were used in a 126-d study. Treatments were assigned in a randomized complete block design with 26 pigs per pen and 20 pens per treatment. Diets were fed in 6 phases, including: phase 1, d 0 to 7; phase 2, d 7 to 20; phase 3, d 20 to 42; phase 4, d 42 to 70; phase 5, d 70 to 98; phase 6, d 98 to 126. BW= body weight; ADG = average daily gain; ADFI = average daily feed intake; G:F = gain:feed ratio.

