Peer reviewed **Original research**

Reduced vitamin supplementation with fat-soluble vitamins A, D, and E added at National Research Council requirements may not be adequate for optimal sow and progeny performance

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Summary

Objective: To evaluate performance and physiological vitamin status of sows and progeny fed 2 vitamin supplementation levels, industry vs reduced (all vitamins reduced with fat-soluble vitamins added at National Research Council recommendations).

Materials and methods: Sows (n = 244) were allotted in a randomized complete block design to 1 of 2 vitamin supplementation levels. At weaning, 765 progeny from a subset of sows were allotted to treatments in a 2 × 2 factorial arrangement of two sow and two nursery vitamin supplementation levels with 15 pens/treatment. Performance and vitamin status of sows and progeny were measured from farrowing to nursery exit.

Results: Reduced vitamin supplementation reduced sow lactation feed intake ($P = .01$), hepatic vitamin A ($P = .001$), and serum vitamin D ($P < .001$), but did not affect sow body weight or litter performance. Regardless of vitamin levels fed to the sow, progeny fed reduced levels post weaning had decreased circulating ($P < .001$) and stored ($P = .03$) vitamin levels and a reduction in average daily gain ($P < .001$), average daily feed intake ($P < .001$), gain:feed ratio ($P = .002$), and body weight ($P < .001$) at the end of the nursery period compared to progeny fed industry levels.

Implications: Reduced vitamin supplementation reduced sow feed intake without affecting sow or litter performance, but decreased circulating and stored vitamin levels in sows could impact long-term reproductive performance. Reduced vitamin inclusion levels in nursery diets reduced performance and serum vitamin concentrations compared to industry vitamin levels.

Keywords: swine, sow, vitamin, serum, performance

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Resumen - La reducción de suplementos vitamínicos con vitaminas A, D, y E solubles en grasa agregadas en los requisitos del Consejo Nacional de Investigación puede no ser adecuada para un rendimiento óptimo de la cerda y la progenie

Objetivo: Evaluar el rendimiento y el estado fisiológico vitamínico de cerdas y su progenie alimentadas con 2 niveles de suplementos vitamínicos, la recomendación de la industria frente a la reducida (todas las vitaminas reducidas con vitaminas liposolubles agregadas según las recomendaciones del Consejo Nacional de Investigación).

Materiales y métodos: Las cerdas (n = 244) fueron asignadas en un diseño de bloques completos al azar a 1 de 2 niveles de suplementación vitamínica. Al destete, 765 descendientes de un subconjunto de cerdas se asignaron a tratamientos en una disposición factorial 2 × 2 de dos niveles de suplementación vitamínica, dos de cerdas y dos de destetados con 15 corrales/tratamiento. Se midió el rendimiento y el estado vitamínico de las cerdas y la progenie desde el parto hasta la salida del destete.

Resultados: La reducción de la suplementación con vitaminas redujo la ingesta de alimento durante la lactancia ($P = .01$), la vitamina A hepática ($P = .001$), y la vitamina D en suero ($P < .001$), pero no afectó el peso corporal de la cerda ni el rendimiento de la camada. Independientemente de los niveles de vitamina alimentados a la cerda, la progenie alimentada con niveles reducidos después del destete tuvo niveles de vitamina circulantes ($P < .001$) y almacenados ($P = .03$) disminuidos y una reducción en la ganancia diaria promedio ($P < .001$), promedio diario de consumo de alimento ($P <. 001$),

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proporción ganancia: alimento ($P = .002$), y peso corporal ($P < .001$) al final del período de destete en comparación con los niveles recomendados por la industria para la alimentación de la progenie.

Implicaciones: La reducción de la suplementación con vitaminas redujo la ingesta de alimento de la cerda sin afectar el rendimiento de la cerda o de la camada, sin embargo, la disminución de los niveles de vitaminas circulantes y almacenadas en las cerdas podría afectar el rendimiento reproductivo a largo plazo. Los niveles reducidos de inclusión de vitaminas en las dietas de lechones destetados redujeron el rendimiento y las concentraciones séricas de vitaminas en comparación con los niveles de vitamina recomendados por la industria.

Résumé - Une supplémentation réduite en vitamines avec les vitamines liposolubles A, D, et E ajoutées selon les exigences du National Research Council peut ne pas être suffisante pour des performances optimales des truies et de leur progéniture

Objectif: Évaluer les performances et le statut vitaminique physiologique des truies et de leur descendance nourries avec deux niveaux de supplémentation vitaminique, industrie vs réduite (toutes les vitamines sont réduites avec des vitamines liposolubles ajoutées selon les recommandations du National Research Council).

Matériels et méthodes: Les truies (n = 244) ont été réparties dans un plan en blocs complets randomisés à un des deux niveaux de supplémentation en vitamines. Au sevrage, 765 descendants d'un sous-ensemble de truies ont été affectés aux traitements dans un arrangement factoriel 2 × 2 de deux truies et deux niveaux de supplémentation vitaminique en pouponnière avec 15 enclos/traitement. Les performances et le statut vitaminique des truies et de leur descendance ont été mesurés de la mise bas à la sortie de la pouponnière.

Résultats: Une supplémentation réduite en vitamines a réduit la consommation alimentaire de la truie en lactation ($P = .01$), la vitamine A hépatique ($P = .001$), et la vitamine D sérique ($P < .001$), mais n'a pas affecté le poids corporel de la truie ou les performances de la portée. Indépendamment des niveaux de vitamines donnés à la truie, la descendance nourrie à des niveaux réduits après le sevrage avait une diminution des niveaux de vitamines circulantes ($P < .001$) et stockées ($P = .03$) et une réduction du gain quotidien moyen ($P < .001$), de la moyenne quotidienne de prise alimentaire ($P < .001$), du rapport gain:aliment ($P = .002$), et du poids corporel ($P < .001$) à la fin de la période de pouponnière comparativement à la progéniture nourris avec les niveaux de l'industrie.

Implications: Une supplémentation réduite en vitamines a réduit la consommation alimentaire des truies sans affecter les performances de la truie ou de la portée, mais une diminution des niveaux de vitamines circulantes et stockées chez les truies pourrait avoir un impact sur les performances de reproduction à long terme. Les niveaux réduits de vitamines dans les régimes alimentaires en pouponnières ont réduit les performances et les concentrations de vitamines sériques par rapport aux niveaux de vitamines de l'industrie.

Recommendations from nutritionists, genetic suppliers, and academia offer a range of vitamin inclusion levels for each production phase. The most recently published vitamin requirement estimates from the National Research Council (NRC)[1] are below the current recommendations of genetic companies and standard inclusion levels observed in commercial industry diets.[1-4] Vitamins are included above requirement levels to provide a margin of error against losses in vitamin efficacy during storage and feed manufacturing and provide an insurance factor for ingredient variability and diet mixing imprecision. However, even after accounting for a liberal 15% safety margin,[5] current industry supplementation recommendations for fat-soluble vitamins (A, D, E, and K) are commonly 1.3 to 7.6 times greater than the current sow NRC requirements. The historical approach to vitamin research was to establish requirements based on levels required to alleviate or prevent symptoms of deficiency rather than establish requirements for optimal performance.[6] Therefore, the objective of this research is to evaluate the bodily vitamin concentrations and performance of sow and progeny fed current industry standard vitamin inclusion levels in sow and nursery diets. The hypothesis is commercial industry levels improve sow and progeny performance and vitamin status compared to reduced vitamin supplementation with added fat-soluble vitamins at NRC requirements.

Animal care and use

All experimental procedures were reviewed and approved by the Animal Care and Use Committee of United Animal Health, Inc.

Materials and methods

Animals, housing, and management

A total of 244 sows (PIC 1050, Pig Improvement Company) with mean body weight (BW) of 250.9 kg (range, 166.9-317.1 kg) and mean parity of 2.5 (range, 0-7) were used. The trial was set up as a randomized complete block design (RCBD) with two treatments (industry vs reduced vitamin supplementation level). The industry vitamin supplementation treatment levels were within ranges reported in commercial production surveys.[2,7] The reduced vitamin supplementation treatment contained vitamins A, D, E, and K added at NRC requirements[1] for gestation and water-soluble vitamins supplemented at approximately half the inclusion rate of the industry treatment. Gestating sows from three breeding groups within a batch farrow system were individually housed and received a common diet with industry standard vitamin levels prior to study enrolment. Due to the arrangement of the facility feeding system and pig flow, the two vitamin supplementation levels were fed for the entire lactation period as well as a portion of gestation immediately preceding lactation: group one was fed for 39 days of gestation, group two for 70 days, and group three for 81 days. Sows were sorted by vitamin supplementation level into separate gestation feed rows with equal representation of parity groupings per row to facilitate feeding of the two diets. Upon entry into farrowing, sows (n = 122/treatment) were randomly allotted to trial in replicate blocks based on parity and BW; blocks were contained within farrowing rooms.

Each lactation stall was equipped with a box feeder and individual hopper. When necessary, suckling litter sizes were standardized within 24 hours of birth according to farm standard procedure by transferring piglets among sows on the same treatment; sows that received piglets from a different treatment were removed from the trial. Piglets that were cross fostered were ineligible for serum vitamin analysis.

At weaning, a subsample (765 piglets; PIC 337 × PIC 1050, mean [SD] initial BW: 6.38 [1.09] kg) representative of all 96 litters of group three were allotted to pens (mean [SD]: 12.75 [0.44] pigs/pen) with .26 m^2/pig, round bar flooring, stainless-steel 2-hole feeders, and stainless-steel cup waterers. The trial was set up as a RCBD with blocking factors of sow parity and weaned piglet BW; litters were balanced across pens. There were 15 replicate pens for each of 4 treatments arranged in a 2 × 2 factorial design with two sow vitamin inclusion levels (industry vs reduced) and two nursery vitamin inclusion levels (industry vs reduced supplementation level for all vitamins and vitamins A, D, E, and K added at NRC requirement). The supplemented water-soluble vitamin levels of the reduced treatment were decreased proportionately to the reduction of the vitamin D level in the reduced treatment compared to the industry treatment. Porcine reproductive and respiratory syndrome and *Mycoplasma hyopneumoniae* were endemic in the herd but no clinical symptoms were present during the trial.

Experimental diets and feeding

All experimental diets were formulated to be adequate in all macronutrients according to NRC[1] and utilized up-to-date loading values for commodity grain ingredients. Sows were offered separate gestation and lactation diets (Table 1). In gestation, sows were fed once daily using a drop box set to deliver 1.8 to 2.7 kg feed in meal-form fed to maintain a target body condition score of 3 across all groups and treatments. Sows received experimental gestation diets for at least 6 weeks prior to being transferred to lactation. During lactation, sows were fed experimental lactation diets *ad libitum* and litters were not provided creep feed. At weaning, nursery diets were budgeted by weight until 6 weeks post weaning (Table 2). Within each production phase, diets were formulated to provide the same macronutrient and trace mineral nutrition with only the level of vitamin supplementation differing between treatments. Diets that were formulated to contain reduced levels of vitamins were manufactured and delivered to feeders before diets with industry levels of vitamins.

Performance measurements, sample collection, and analysis

Individual sow weights were recorded as sows were moved to farrowing (entry weight) 5 to 7 days prior to expected farrowing date, and at weaning. Sow weight post farrowing was calculated via a linear regression model (adjusted r^2 = 0.93):

Post-farrow sow weight = 29.31485 + (entry weight × 0.89191) + (parity × 1.30677) − (total born × 0.28966) − (native litter weight × 0.79842)

where entry weight is used to represent gravid sow weight at the conclusion of pregnancy and native litter weight indicates combined total weight of piglets born alive, stillborns, and mummified fetuses. Lactation feed intake was recorded. Litter performance was measured by recording native litter weight, standardized litter weight (standardization of litter size completed within first 24 hours post farrowing), number of pigs in standardized litters, piglet count at processing, litter wean weight, number of pigs weaned, and mortality. Litter average daily gain (ADG) was calculated as:

Litter ADG = (litter wean weight + mortality post-standardization weight − standardized litter weight) ÷ (piglet days of live pigs at weaning + piglet days of post-standardization mortality)

Piglet days represents the product of the number of piglets and their days of living for respective subsets ie, pigs alive at weaning, pigs that died post standardization, etc. Litter gain to feed ratio (G:F) was calculated as:

Litter G:F = (litter wean weight + mortality post-standardization weight − standardized litter weight) ÷ sow feed intake

Analysis of fat-soluble vitamin A (ultra-high performance liquid chromatography [UHPLC]), vitamin D (25-hydroxyvitamin D_2 and 25-hydroxyvitamin D_3; liquid chromatography with tandem mass spectrometry [LC/MS/MS]), and vitamin E (UHPLC) in blood serum and liver samples (wet-tissue basis) were performed through the Iowa State University Veterinary Diagnostic Laboratory. Sows from the third group (n = 96) were bled within 24 hours of farrowing (d 0) and 1 day prior to weaning. From the same group of sows, one average-sized pig per litter was tagged and bled on day 5 post farrowing. One day prior to weaning (d 19), pigs bled and tagged on day 5 post farrowing and two additional pigs per litter were bled (total n = 288). Simultaneously, pigs tagged on day 5 were euthanized and liver samples collected. At weaning, all sows from the third group were shipped to a packing plant and liver samples collected.

At 40 days post weaning, 2 pigs/sow of the third sow group from whom blood samples had been collected at weaning were reidentified (n = 192) and bled. One average-sized pig per pen, for a total of 15 pigs/treatment, was euthanized and liver sample collected.

Statistical analysis

Normality of distribution and identification of outliers were determined for all metrics using the UNIVARIATE procedure of SAS Enterprise Guide 7.1 (SAS Institute Inc). An observation more or less than 3 standard deviations from the mean for each metric was deemed an outlier and not included in the dataset. A linear mixed model (MIXED procedure of SAS) was used to analyse sow and litter performance data using sow as the experimental unit, dietary treatment as the fixed effect, and random effects of group and block nested within group. A linear mixed model was also used to analyse nursery performance metrics (experimental unit of pen) as a RCBD with fixed effects of sow diet, nursery diet, and the interaction, and random effect of nursery block. Physiological vitamin concentrations measured in sow progeny were averaged within litter at each timepoint (birth, weaning, nursery exit) and similarly analysed with block included as a random effect. Morbidity, mortality, and other health-related metrics were analysed using (negative) binomial distributions for count data with small means via proc GLIMMIX. The REG procedure of SAS was used to generate the prediction equation for post-farrowing weight. Sow entry weight was used as a covariate for post-farrowing and exit weights; sow entry weight was insignificant ($P \geq .28$) as a covariate for lactation feed intake, number of pigs at weaning, weaning weight, litter ADG, and litter G:F and therefore not included in the model for those metrics. Standardized litter size, birthweight, and nursery start weight were used as

Table 1: Ingredients and calculated nutrient composition of gestation and lactation diets

	Gestation		Lactation	
	Industry	Reduced	Industry	Reduced
Feed component, %				
Ground corn	79.77	80.02	66.07	66.31
Soybean meal	14.73	14.61	26.77	26.66
Choice white grease	1.00	1.00	2.75	2.75
Monocalcium phosphate	1.34	1.34	1.26	1.26
Limestone	1.23	1.23	1.16	1.16
Salt	0.18	0.18	0.21	0.21
L-Lysine HCl	0.21	0.21	0.29	0.29
L-Threonine	0.09	0.09	0.11	0.11
DL-Methionine	0.09	0.09	0.02	0.02
Industry sow VTM premix*	0.60	0.22	0.60	0.22
Reduced sow VTM premix†	0	0.25	0	0.25
Choline chloride, 60%	0.13	0.13	0.13	0.13
Feed additives‡	0.63	0.63	0.63	0.63
Total	**100.00**	**100.00**	**100.00**	**100.00**
Calculated analysis				
ME, kcal/kg	3213	3220	3290	3298
Crude protein, %	13.59	13.61	18.16	18.18
Total Lysine, %	0.79	0.79	1.17	1.17
SID Lysine, %	0.70	0.70	1.05	1.05
SID Methionine, %	0.29	0.29	0.27	0.27
SID Cysteine, %	0.21	0.21	0.26	0.26
SID Threonine, %	0.49	0.49	0.66	0.66
SID Tryptophan, %	0.13	0.13	0.19	0.19
SID Valine, %	0.52	0.52	0.71	0.72
SID Isoleucine, %	0.45	0.45	0.65	0.65
SID Leucine, %	1.11	1.12	1.38	1.38
SID Lysine:ME, g/Mcal	2.45	2.45	3.55	3.55
Calcium, %	0.85	0.81	0.85	0.81
Total Phosphorus, %	0.58	0.58	0.62	0.62
Added vitamin A, IU/kg	11,160	3999	11,160	3999
Added vitamin D, IU/kg	2213	794	2213	794
Added vitamin E, IU/kg	66.3	43.7	66.3	43.7
Added vitamin K, mg/kg	1.4	0.51	1.4	0.51

Table 1: Continued

	Gestation		Lactation	
	Industry	Reduced	Industry	Reduced
Total vitamin content				
Vitamin A, IU/kg	11,332	4173	11,316	4156
Vitamin D, IU/kg	2213	794	2213	794
Vitamin E, IU/kg	75.6	56.2	74.4	51.9
Vitamin K, mg/kg	1.4	0.51	1.4	0.51
Riboflavin, mg/kg	8.0	3.7	8.2	4.0
Niacin, mg/kg	66.0	37.7	65.4	37.1
Pantothenic acid, mg/kg	30.4	15.3	31.4	16.2
Biotin, mg/kg	0.53	0.25	0.56	0.27
Vitamin B_{12}, μg/kg	30.9	11.0	30.9	11.0
Vitamin B_6, mg/kg	6.17	6.01	7.16	7.01
Thiamin, mg/kg	3.43	3.28	3.34	3.19
Folic acid, mg/kg	1.9	0.89	2.1	1.0
Choline, mg/kg	1526	1528	1765	1766

* Industry treatment premix contained phytase (Huvepharma), retinyl propionate, vitamin A acetate (cross-linked beadlet), cholecalciferol (vitamin D_3), dl-alpha tocopheryl acetate (vitamin E), water-soluble vitamin supplements, and inorganic trace minerals.

† Reduced treatment premix was specifically formulated to achieve NRC fat-soluble vitamin levels[1] when included at 0.25% in diets containing 0.22% of a standard industry VTM premix, and using the same vitamin sources as the standard industry VTM premix.

‡ Feed additives included a macromineral supplement (sulfur, magnesium, and potassium; Mosaic Company) and a hydrated sodium-calcium aluminosilicate/yeast cell wall/direct fed microbial bacillus product (United Animal Health).

VTM = vitamin and trace mineral; SID = standardized ileal digestibility; ME = metabolizable energy; NRC = National Research Council.

covariates for the analyses of number of pigs at weaning, litter wean weight, and nursery growth performance metrics, respectively. Results were considered statistically significant at $P \le .05$; results with P values > .05 and ≤ .10 were considered a trend.

Results

Sow and litter performance

Sow weight at entry into lactation was significantly heavier ($P = .05$) for sows fed the reduced vitamin supplementation treatment than for sows fed the industry vitamin levels treatment. After accounting for entry weight, there was no evidence for difference in sow weights post farrowing ($P = .43$) or at the end of lactation ($P = .26$; Table 3). There was a 5% reduction ($P = .02$) in lactation average daily feed intake (ADFI) of sows fed reduced vitamin supplementation levels compared with sows fed industry vitamin levels. There was no evidence for differences in native litter or standardized litter performance with the exception that sows fed industry levels of vitamins tended to improve ($P = .08$; Table 4) litter G:F.

There was no evidence for differences in sow serum vitamin A concentrations on day 0 ($P = .96$; Figure 1) or day 19 ($P = .98$) of lactation regardless of vitamin supplementation level. However, vitamin A supplementation at NRC requirement for gestation reduced ($P = .001$) vitamin A concentrations in the liver by 15.67% compared with sows fed industry vitamin level. Serum vitamin A in piglets did not differ ($P = .15$) between sow vitamin supplementation levels at day 5, but on day 19 serum vitamin A was 18.81% greater ($P = .003$) in piglets from sows receiving NRC level compared to piglets from sows fed industry level. On day 19, numerically lower ($P = .27$) hepatic vitamin A concentration was observed among offspring of sows receiving NRC level compared to offspring of sows fed industry level.

For sows fed NRC recommended level compared with industry vitamin level, serum vitamin D was decreased ($P < .001$; Figure 2) by 24.52% and 31.24% on days 0 and 19, respectively. In piglets from sows fed NRC recommended level, serum vitamin D was less ($P < .001$) on both day 5 (49.13% less) and day 19 (37.03% less) compared to piglets from sows fed industry vitamin level.

Serum vitamin E on day 0 was reduced ($P = .01$; Figure 3) in sows fed NRC recommended level compared with industry vitamin level, but no evidence of difference ($P = .92$) was observed on day 19. No evidence for a difference ($P = .91$) in sow liver vitamin E concentration was observed between treatments. Maternal vitamin supplementation level did not affect ($P = .29$) piglet serum vitamin E at day 5 but by day 19 serum vitamin E was 16.42% less ($P < .001$) in offspring from sows fed NRC recommended level compared to offspring of sows fed industry level. Moreover, vitamin E liver concentration was reduced ($P < .001$) over 25% in piglets from sows fed NRC recommended level compared to sows fed industry level.

Table 2: Ingredients and calculated nutrient composition of nursery diets fed to weaned pigs for 40 days

Diet: Feed budget:	Phase 1 0.91 kg/pig		Phase 2 1.81 kg/pig		Phase 3 3.63 kg/pig		Phase 4 until week 6	
	Industry	Reduced	Industry	Reduced	Industry	Reduced	Industry	Reduced
Feed component, %								
Ground corn	28.67	28.57	41.22	41.12	42.54	42.43	50.49	50.47
Soybean meal	14.92	14.92	32.40	32.39	32.98	32.96	33.66	33.66
Basemix*	54.30	54.30	22.55	22.55	10.05	10.05	0.05	0.05
Dried distillers grains & solubles	0	0	0	0	10.00	10.00	10.00	10.00
Choice white grease	1.00	1.00	1.00	1.00	1.00	1.00	2.00	2.00
Limestone	0.02	0.14	0.50	0.61	0.86	0.99	1.13	1.15
Monocalcium phosphate	0.07	0.07	0.51	0.51	0.55	0.55	0.37	0.37
Salt	0.02	0	0.43	0.43	0.41	0.41	0.61	0.61
L-Lysine HCl	0	0	0.19	0.19	0.33	0.33	0.36	0.36
DL-Methionine	0	0	0.10	0.10	0.15	0.15	0.18	0.18
L-Threonine	0	0	0.06	0.06	0.08	0.08	0.09	0.09
Copper chloride, 54%	0	0	0.02	0.02	0.03	0.03	0.04	0.04
Phytase[†]	0	0	0.02	0.02	0.02	0.02	0.02	0.02
Industry nursery VTM premix[‡]	1.00	0	1.00	0	1.00	0	1.00	0
Reduced nursery VTM premix[§]	0	1.00	0	1.00	0	1.00	0	1.00
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
Calculated analysis								
ME, kcal/kg	3332	3329	3221	3220	3198	3197	3237	3237
Crude protein, %	20.45	20.46	22.06	22.06	23.28	23.27	22.44	22.44
Total Lysine, %	1.49	1.49	1.51	1.51	1.54	1.54	1.45	1.45
SID Lysine, %	1.34	1.34	1.35	1.35	1.36	1.36	1.28	1.28
SID Methionine, %	0.58	0.58	0.55	0.55	0.54	0.54	0.50	0.50
SID Cysteine, %	0.27	0.27	0.27	0.27	0.29	0.29	0.29	0.29
SID Threonine, %	0.83	0.83	0.81	0.81	0.82	0.82	0.77	0.77
SID Tryptophan, %	0.24	0.24	0.25	0.25	0.24	0.24	0.23	0.23
SID Valine, %	0.94	0.94	0.88	0.88	0.88	0.88	0.83	0.83
SID Isoleucine, %	0.72	0.72	0.81	0.81	0.83	0.83	0.80	0.80
SID Leucine, %	1.41	1.41	1.49	1.49	1.66	1.66	1.63	1.63
SID Lys:ME, g/Mcal	4.03	4.02	4.19	4.19	4.25	4.25	3.95	3.95
Calcium, %	0.90	0.90	0.80	0.80	0.76	0.77	0.65	0.65
Total Phosphorus, %	0.82	0.82	0.71	0.71	0.65	0.65	0.52	0.52
Zinc, mg/kg	3025	3025	1532	1532	766	766	127	127
Added vitamin A, IU/kg	11,111	2249	11,111	2249	11,111	2249	4012	1742
Added vitamin D, IU/kg	2800	220	2800	220	2800	220	948	198
Added vitamin E, IU/kg	132.3	16.1	132.3	16.1	132.3	16.1	26.7	10.9
Added vitamin K, mg/kg	1.23	0.51	1.23	0.51	1.23	0.51	0.51	0.51

Table 2: Continued

Diet: Feed budget:	Phase 1 0.91 kg/pig		Phase 2 1.81 kg/pig		Phase 3 3.63 kg/pig		Phase 4 until week 6	
	Industry	Reduced	Industry	Reduced	Industry	Reduced	Industry	Reduced
Total vitamin content								
Vitamin A, IU/kg	11,462	2553	11,222	2313	11,226	2315	4134	1881
Vitamin D, IU/kg	2800	220	2800	220	2800	220	946	201
Vitamin E, IU/kg	135.6	19.3	137.0	20.7	137.1	20.8	32.4	16.7
Vitamin K, mg/kg	1.25	0.50	1.25	0.50	1.25	0.50	0.51	0.50
Riboflavin, mg/kg	8.2	2.0	8.3	2.1	8.2	2.1	6.0	2.5
Niacin, mg/kg	102.4	20.5	107.0	25.0	106.7	24.8	53.4	26.5
Pantothenic acid, mg/kg	61.0	10.3	62.7	12.0	62.5	11.8	26.8	11.8
Biotin, mg/kg	0.08	0.08	0.11	0.11	0.11	0.11	0.11	0.11
Vitamin B_{12}, µg/kg	33.1	2.2	33.1	2.2	33.1	2.2	22.0	4.4
Vitamin B_6, mg/kg	7.3	4.1	10.0	6.8	10.1	6.9	7.1	7.1
Thiamin, mg/kg	5.0	2.8	6.3	4.0	6.2	4.0	4.0	4.0
Folic acid, mg/kg	0.85	0.37	1.04	0.56	1.04	0.56	0.54	0.52
Choline, mg/kg	1286	1287	1427	1427	1392	1392	1316	1316

* Nursery basemix unique to each nursery phase containing one or more of plasma, animal-derived protein products, grain byproducts, direct fed microbial bacillus strains, or specialty ingredients for gut health and conditioning (United Animal Health).

† Natuphos-P E 2500 (BASF Corporation) providing 400 phytase units/kg diet.

‡ Industry treatment premix contained vitamin A acetate (cross-linked beadlet), cholecalciferol (vitamin D_3), dl-alpha tocopheryl acetate (vitamin E), water-soluble vitamin supplements, and inorganic trace minerals.

§ Reduced treatment premix was specifically formulated to achieve NRC A, D, E, and K vitamin levels when included at 1.00% in diets and used the same vitamin sources as the Industry nursery VTM premix.

VTM = vitamin and trace mineral; SID = standardized ileal digestibility; ME = metabolizable energy; NRC = National Research Council.

Nursery performance

Across treatments, nursery mortality, removals, and medication rates were low (Table 5). No interactions ($P \geq .26$) between sow vitamin supplementation and nursery pig supplementation levels were observed for nursery growth performance. Pigs fed industry levels in nursery had increased ADG ($P < .001$), ADFI ($P < .001$), G:F ($P = .002$), and BW ($P < .001$) at the end of the nursery period compared to pigs fed reduced levels in the nursery, regardless of vitamin level fed to the sow (Table 6). Pigs weaned from sows fed industry vitamin levels tended to be heavier ($P = .09$) at 40 days post weaning than pigs weaned from sows fed reduced vitamin levels.

Nursery pig vitamin levels

Downstream impact of maternal supplementation level on piglet serum vitamin levels at 40 days post weaning reduced serum vitamin A ($P = .02$) concentration among offspring whose dams were fed NRC recommended compared to industry levels (Table 5 and Figure 4). An interaction was observed (sow × nursery, $P = .02$) between sow and nursery vitamin supplementation level for serum vitamin E due to the NRC level fed to the sow ($P = .02$) or nursery pig ($P < .001$) reducing nursery pig serum vitamin E, although the reduction observed among nursery pigs fed NRC recommended levels and whose dams were fed industry levels was not as severe as the reduction observed in pigs fed NRC levels and whose dams also were fed NRC levels. Regardless of vitamin levels fed to their dam, hepatic stores of vitamin E were also less ($P = .03$) at 40 days post weaning in pigs fed NRC levels compared to pigs fed industry vitamin levels. Nursery vitamin supplementation at NRC levels compared to industry levels also reduced piglet serum concentrations of vitamin A ($P < .001$) and vitamin D ($P < .001$) after 40 days, regardless of sow vitamin supplementation. An interactive effect (sow × nursery, $P = .01$) of sow and nursery vitamin supplementation on hepatic vitamin A stores at the end of nursery was observed because industry supplementation level in the nursery improved ($P < .001$) stores compared to NRC level supplementation, but the improvement was less pronounced in offspring of sows which had been fed industry vitamin levels compared to offspring of sows which had been fed NRC vitamin levels.

Discussion

When provided in excess, fat-soluble vitamins accumulate within the animal. One limitation of this study is that initial body stores of vitamins were not controlled for, nor was the study designed to measure the impact of the duration of reduced vitamin supplementation during gestation. Since NRC vitamin requirements do not change throughout gestation, further research is needed to understand how stage of gestation might influence vitamin requirements and depletion of maternal reserves.

Table 3: The effect of vitamin inclusion levels in gestation and lactation diets on sow performance*

	Vitamin Level		Pooled	
	Industry	Reduced	SEM	*P*†
Sows completing trial, No.	116	117		
Sow BW at entry, kg	248.05	251.95	7.574	.05
Sow BW post farrowing, kg‡,§	233.40	233.90	1.013	.43
Sow BW at exit, kg§	216.56	218.76	5.353	.26
Sow BW loss from entry, kg	33.45	32.91	6.832	.79
Sow BW loss post farrowing, kg¶	15.93	15.57	5.437	.83
Lactation length, d	19.00	19.03	0.520	.74
Lactation ADFI, kg	5.89	5.57	0.386	.02
G:F, kg:kg**	0.308	0.315	0.040	.70
Sows treated, No.	11	15	NA	.46
Therapeutic medication treatments, No.	24	35	NA	.59

* A total of 244 sows (PIC 1050 genetics) were allotted to dietary treatments supplemented with either standard industry vitamin levels (n = 122; mean parity 2.5) or reduced vitamin levels with fat-soluble vitamins added at 2012 NRC levels[1] for gestation (n = 122; mean parity 2.6). Experimental diets were fed from ≥ 6 weeks before farrowing through weaning.

† Performance data analyzed using linear and generalized linear mixed models and $P \leq .05$ was considered significant.

‡ Post-farrowing sow weight = 29.31485 + (Entry weight, kg × 0.89191) + (parity × 1.30677) – (total born × 0.28966) – (native litter weight, kg × 0.79842)

§ Sow entry weight at time of placement into farrowing room was used as a covariate for post-farrowing and exit weight.

¶ Weight difference post farrowing = exit weight – post-farrowing weight.

** Sow G:F = (sow lactation weight change + litter weight gain) ÷ sow feed intake

BW = body weight; ADFI = average daily feed intake; G:F = body weight gain to feed intake ratio; NA = not applicable; NRC = National Research Council.

Apart from vitamin supplementation level impacting pig physiology and performance in this study, measured physiological concentrations of vitamins A and D were low compared to longstanding reference values[8] used as the basis for veterinary diagnostics (Scott L. Radke, DVM, email communication, September 2019). Serum vitamin A levels measured in both sows and piglets were well below the minimum thresholds of reference ranges (0.25-0.40 mg/kg for sows; 0.40-0.50 mg/kg for neonates) as were piglet liver concentrations (36-57 mg/kg for weaned pigs; 57-114 mg/kg for grow-finish pigs). Serum vitamin D levels measured in NRC-level fed sows of this study were below historic "normal" reference ranges (35-100 ng/mL for sows) and regardless of maternal feeding level, both neonates and especially weaning-age piglets had levels below or well-below the "normal" reference ranges (5-15 ng/mL for neonates; 25-30 ng/mL for weaned piglets; 30-35 ng/mL for grow-finish pigs). Although sow vitamin E concentrations fell just below or aligned with historic reference values for serum and liver depending on sampling timepoint, notably suckling piglet levels were well above historic reference values (1.5-2.5 mg/kg serum; 3.0-5.0 mg/kg liver). However, post weaning piglet serum vitamin E concentrations were lower than "normal" range (2.0-2.5 mg/kg serum).

Serum and tissue levels are not positioned for use as sole diagnostic criterion for establishing deficiencies since immunological and physiological anomalies can impact the dynamic levels measured; clinical or pathological signs of deficiency should be used to support diagnoses of vitamin deficiencies.[8] Expected tissue levels as reported by Puls[8] are based on literature and case studies from 1981-1993 (vitamin A) or dating back even farther to 1969 (vitamin E) and 1964 (vitamin D). While management and rearing conditions from that era would be hardly recognizable today, documented changes in pig physiology include greater reproductive prolificacy, faster growth, more efficient nutrient utilization, later maturation, and altered tissue deposition of chemical components accompanying high lean-gain genotypes.[9-11] These changes not only could be responsible for shifting nutrient requirements and highlight the need for updated vitamin supplementation recommendations, but could also impact vitamin accumulation in tissues. Caution should be exercised in interpreting tissue vitamin levels against traditional "normal" ranges until research validates expected tissue levels in healthy pigs of modern genotypes reared in commercial environments.

The results of the current study suggest there is an industry wide need to re-evaluate vitamin supplementation levels. The vitamin A requirement for optimal reproductive performance is age dependent and likely greater in younger sows.[12] Gilts that received adequate dietary vitamin A through nine months of age completed two reproductive cycles without vitamin A supplementation without developing deficiency symptoms, suggesting adequate vitamin A stores in the liver.[13,14] Moreover, mature sows without vitamin A supplementation required 4 parities before deficiency symptoms became evident.[15] Thus, it is important that females receive adequate

Table 4: The effect of vitamin inclusion levels in gestation and lactation diets on litter performance*

	Vitamin Level		Pooled	
	Industry	Reduced	SEM	P†
Litters, No.	116	117		
Total born, No.	15.14	15.39	0.353	.65
Born alive, No.	13.62	13.61	0.306	.98
Stillborn, No.	1.10	1.28	NA	.32
Mummies, No.	0.29	0.23	NA	.30
Native litter weight, kg	21.71	21.11	0.421	.24
Standardized litter size, No.	12.57	12.46	0.131	.41
Standardized litter weight, kg	18.92	18.38	0.315	.13
Pigs weaned, No.‡	11.90	11.69	0.112	.11
Total wean weight, kg‡	70.84	71.28	1.712	.69
Mean wean weight, kg	5.96	6.01	0.116	.57
ADG, kg§	0.23	0.24	0.003	.39
G:F, kg:kg¶	0.50	0.53	0.038	.08
Total mortality, No.	185	219	NA	.16
Mortality post standardization, No.**	74	87	NA	.29
Nutritional mortality, No.††	20	25	NA	.52

* A total of 244 sows (PIC 1050 genetics) were allotted to dietary treatments supplemented with either standard industry vitamin levels (n = 122; mean parity 2.5) or reduced vitamin levels with fat-soluble vitamins added at 2012 NRC levels[1] for gestation (n = 122; mean parity 2.6). Experimental diets were fed from ≥ 6 weeks before farrowing through weaning.

† Performance data analyzed using linear mixed and generalized linear mixed models and $P \leq .05$ was considered significant.

‡ Number of pigs weaned was adjusted for standardized litter size, and weight was adjusted for the birthweight of the standardized litter.

§ Litter ADG = (litter wean weight + mortality post-standardization weight − standardized weight) ÷ (piglet days of live pigs at weaning + piglet days of post-standardization mortality)

¶ Litter G:F = (litter wean weight + mortality post-standardization weight - standardized weight) ÷ sow feed intake

** Pre-wean mortality post standardization (Industry = 4.94%; NRC = 5.77%) = No. of piglet deaths post standardization ÷ No. of piglets standardized.

†† Piglets that died post standardization were classified as a nutritional mortality if they were emaciated, thin, non-eater, etc.

G:F = body weight gain to feed intake ratio; ADG = average daily gain; NA = not applicable; NRC = National Research Council.

vitamin supplementation during gilt development for long-term reproductive success and might explain why vitamin supplementation level in gestation and lactation diets had no direct impact on sow or litter performance over the single reproductive cycle measured in this study. Nonetheless, serum and liver concentrations in this study suggest NRC-level fed sows deplete liver vitamin A stores to sustain circulating levels and offspring serum levels at birth via placental transfer. Since vitamin transfer from sow to offspring is a dynamic process, the serum concentration at birth provides minimal information on how fetal and neonatal hepatic vitamin A stores were established then modulated during lactation and could be responsible for the elevated serum vitamin A observed in offspring of NRC-level fed sows by the time of weaning.

Supplementation of vitamin D at current industry levels compared to NRC levels consistently increased serum vitamin D concentrations in both sows and piglets from birth to weaning. Current NRC requirements for vitamin D may be inadequate not only due to genetic advances in reproductive output, but a majority of vitamin D trials that established requirements were conducted when pigs had access to sunlight thus facilitating endogenous synthesis of vitamin D.[6,11] Placental transfer of vitamin D from sow to progeny is low and since piglets are born with low serum concentrations of 25-hydroxycholecalciferol [25(OH)D_3], a biomarker for vitamin D status, pigs are susceptible to vitamin D deficiency.[16-18] Nonetheless, providing supplemental 25(OH)D_3 to the dam can improve both sow and fetal vitamin D status.[19] Vitamin D supplementation can also improve the vitamin D status of young pigs without influencing growth performance or bone mineralization.[20] In a different study, litter weight gain from sows fed a diet with vitamin D at 2000 IU/kg was greater than that of litters from sows fed a diet with vitamin D at 200 IU/kg.[21] Larger doses of vitamin D (1400 and 2000 IU/kg) decreased the number of stillborn piglets compared with smaller doses in the diet (200 and 800 IU/kg).[17] In the present study, dietary

Figure 1: Impact of sow diet vitamin supplementation on sow and litter vitamin A levels. Sows were allotted to dietary treatments supplemented with either standard industry vitamin levels or reduced vitamin levels with fat-soluble vitamins added at 2012 National Research Council[1] gestation requirement. **A)** Sows (n = 96) were bled within 24 h of farrowing (d 0) and 1 d prior to weaning (d 19). **B)** Liver samples were collected from sows (n = 96) following weaning for liver vitamin analysis. **C)** Three average-sized piglets per sow were tagged (n = 144/treatment) and bled on d 5 and 19 post farrowing. **D)** One average-sized piglet per sow which had been bled on d 5 and 19 was subsequently euthanized for liver vitamin analysis (n = 48 per treatment). Historic physiological reference ranges are provided for context.[8] Data was analyzed using a linear mixed model with $P \leq .05$ considered significant (*). Error bars depict the standard error of the treatment means.

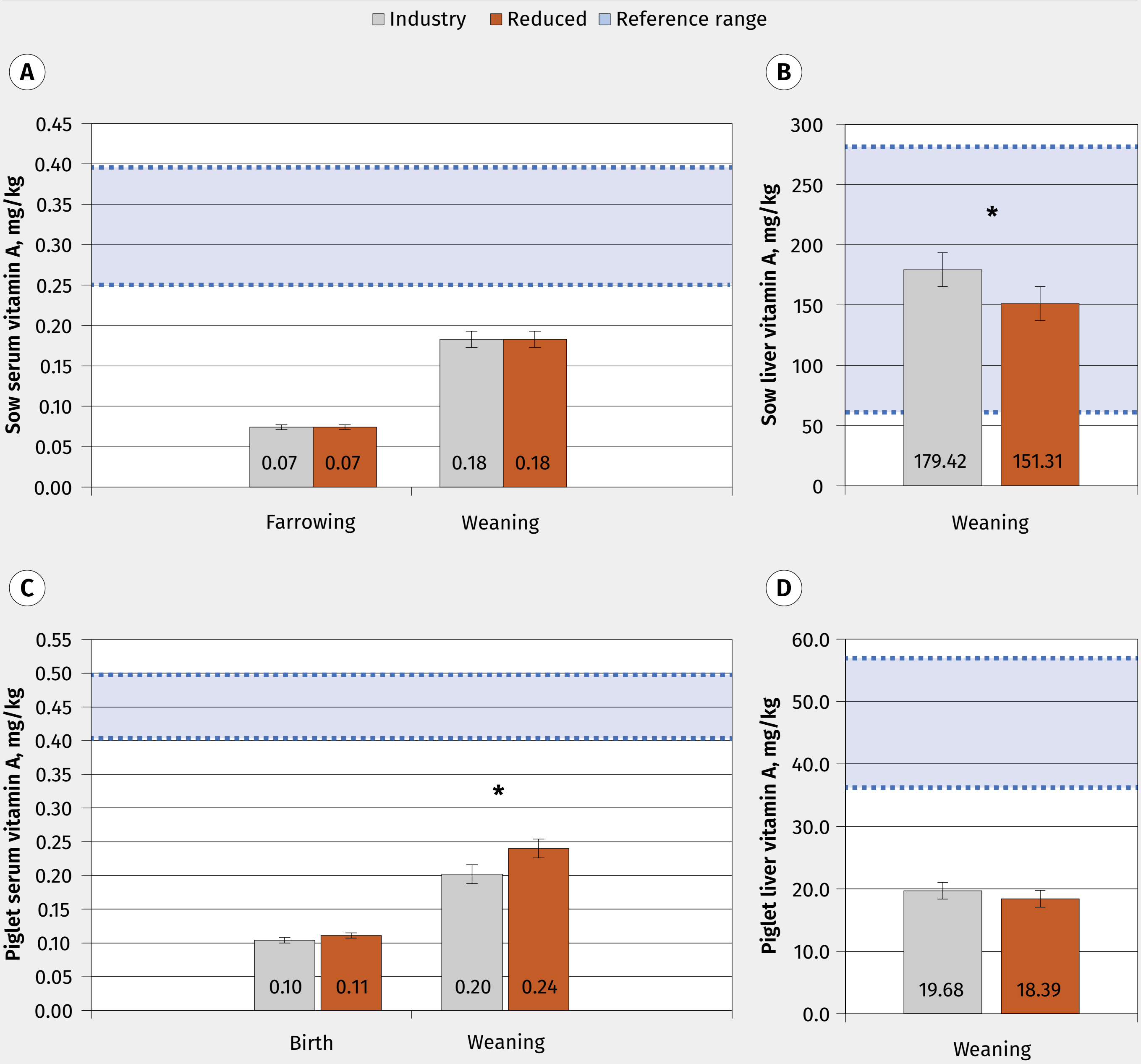
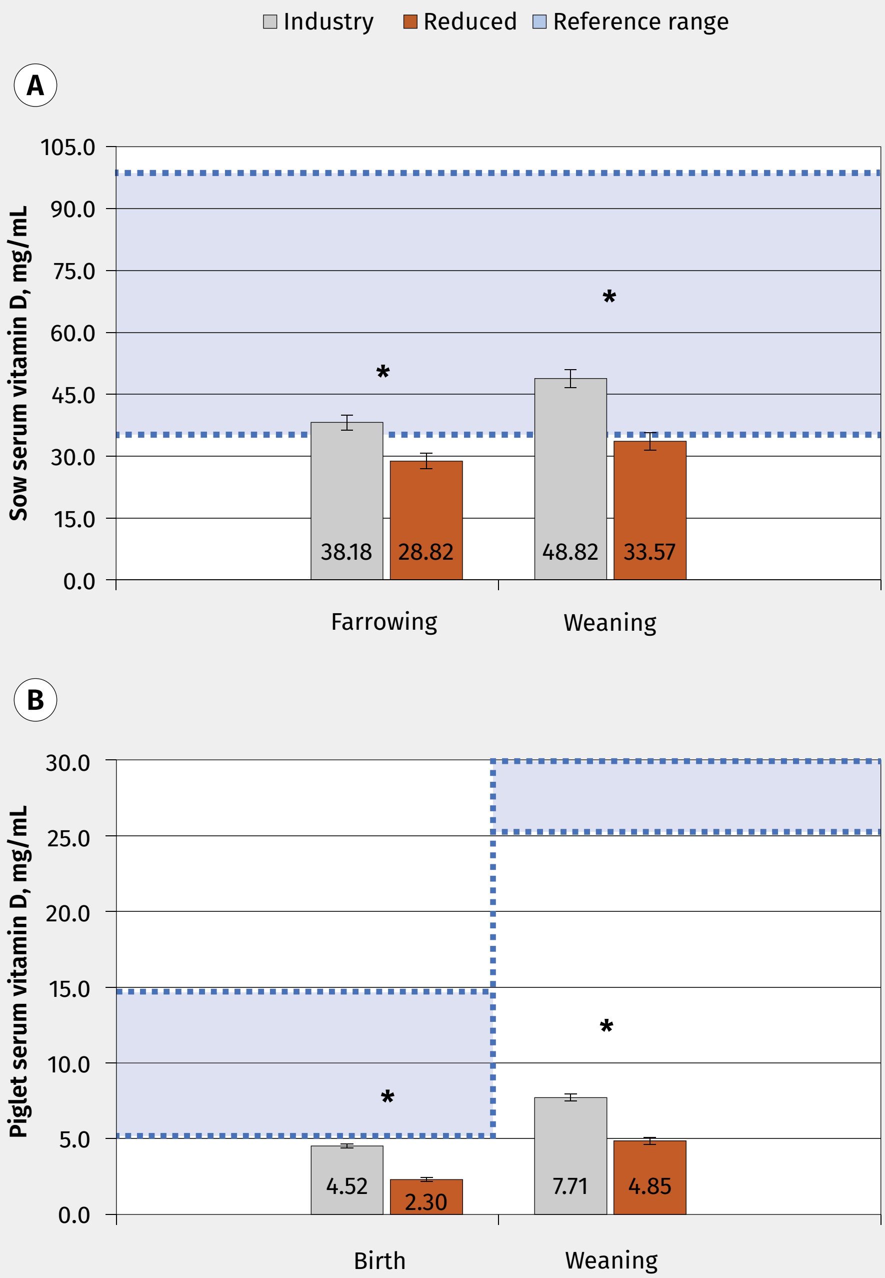


Figure 2: Impact of sow diet vitamin supplementation on sow and litter vitamin D (25-hydroxyvitamin D_2 and 25-hydroxyvitamin D_3) levels. Sows were allotted to dietary treatments supplemented with either standard industry vitamin levels or reduced vitamin levels with fat-soluble vitamins added at 2012 National Research Council[1] gestation requirement. **A)** Sows (n = 96) were bled within 24 h of farrowing (d 0) and 1 d prior to weaning (d 19). **B)** Three average-sized piglets per sow were tagged (n = 144/treatment) and bled on d 5 and 19 post farrowing. Historic physiological reference ranges are provided for context.[8] Data was analyzed using a linear mixed model with $P \leq .05$ considered significant (*). Error bars depict the standard error of the treatment means.



vitamin D level failed to impact stillborn numbers possibly due to insufficient power to detect a statistical difference, or due to differences in farrowing management practices and limited ability to detect response patterns with just two treatment levels (800 and 2000 IU/kg).

It is curious that sow vitamin E serum concentration was less among NRC-level fed sows compared to industry-level fed sows at the beginning of lactation yet sows of both treatments had similar concentrations in both serum and liver by the end of lactation. The inability to control for initial sow hepatic vitamin E concentration between treatments limits fully understanding the effects of vitamin supplementation on maternal vitamin E status. Moreover, since gestational intake of vitamin E was around 126 to 170 IU/day (median NRC and industry treatment intakes, respectively) but lactation mean intake was > 300 IU/day for both treatments (305 IU/day for NRC level, 462 IU/day for industry level) with *ad libitum* feed intake, the higher total vitamin E intake during lactation may have been satisfactory to maintain maternal homeostatic levels while simultaneously deprioritizing lactational transfer to offspring.

Unsurprisingly, no difference in neonate vitamin E concentration between treatments was observed at birth since transfer of vitamin E from dam to offspring occurs primarily postnatally via milk.[22] Yet reductions in circulating and stored vitamin E concentrations of NRC-level fed sows' offspring were apparent by the end of the suckling period despite sow vitamin E status not showing a response to treatment. Piglet vitamin E status is important to combat oxidative stresses, especially those incurred early in life such as iron injection[22] and establish hepatic vitamin E reserves to support performance in subsequent production phases. Improved immune response can be elicited with high doses of supplemental vitamin E; additional vitamin E in sow diets increased serum IgG in sows at farrowing and in pigs on days 1 and 28 post partum.[23] In the same study, vitamin E supplementation increased number of pigs born per litter and improved weaning weights.

In agreement with the present study, gestation vitamin supplementation levels had limited impact on farrowing and litter performance.[24] However, increasing gestation vitamin supplementation from NRC levels to approximately twice

Figure 3: Impact of sow diet vitamin supplementation on sow and litter vitamin E levels. Sows were allotted to dietary treatments supplemented with either standard industry vitamin levels or reduced vitamin levels with fat-soluble vitamins added at 2012 National Research Council[1] gestation requirement. **A)** Sows (n = 96) were bled within 24 h of farrowing (d 0) and 1 d prior to weaning (d 19). **B)** Liver samples were collected from sows (n = 96) following weaning for liver vitamin analysis. **C)** Three average-sized piglets per sow were tagged (n = 144/treatment) and bled on d 5 and 19 post farrowing. **D)** One average-sized piglet per sow which had been bled on d 5 and 19 was subsequently euthanized for liver vitamin analysis (n = 48 per treatment). Historic physiological reference ranges are provided for context.[8] Data was analyzed using a linear mixed model with $P \leq .05$ considered significant (*). Error bars depict the standard error of the treatment means.

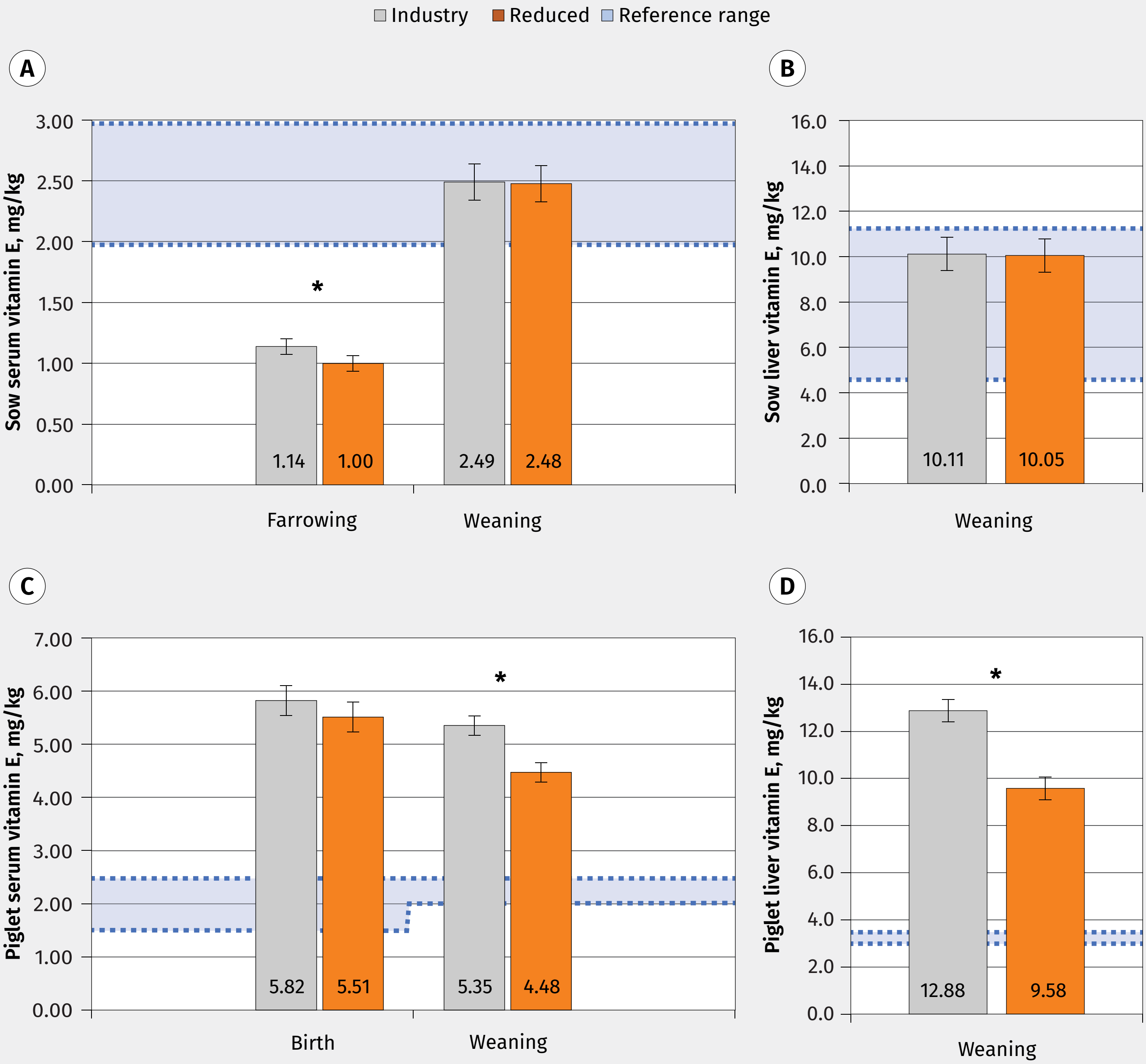
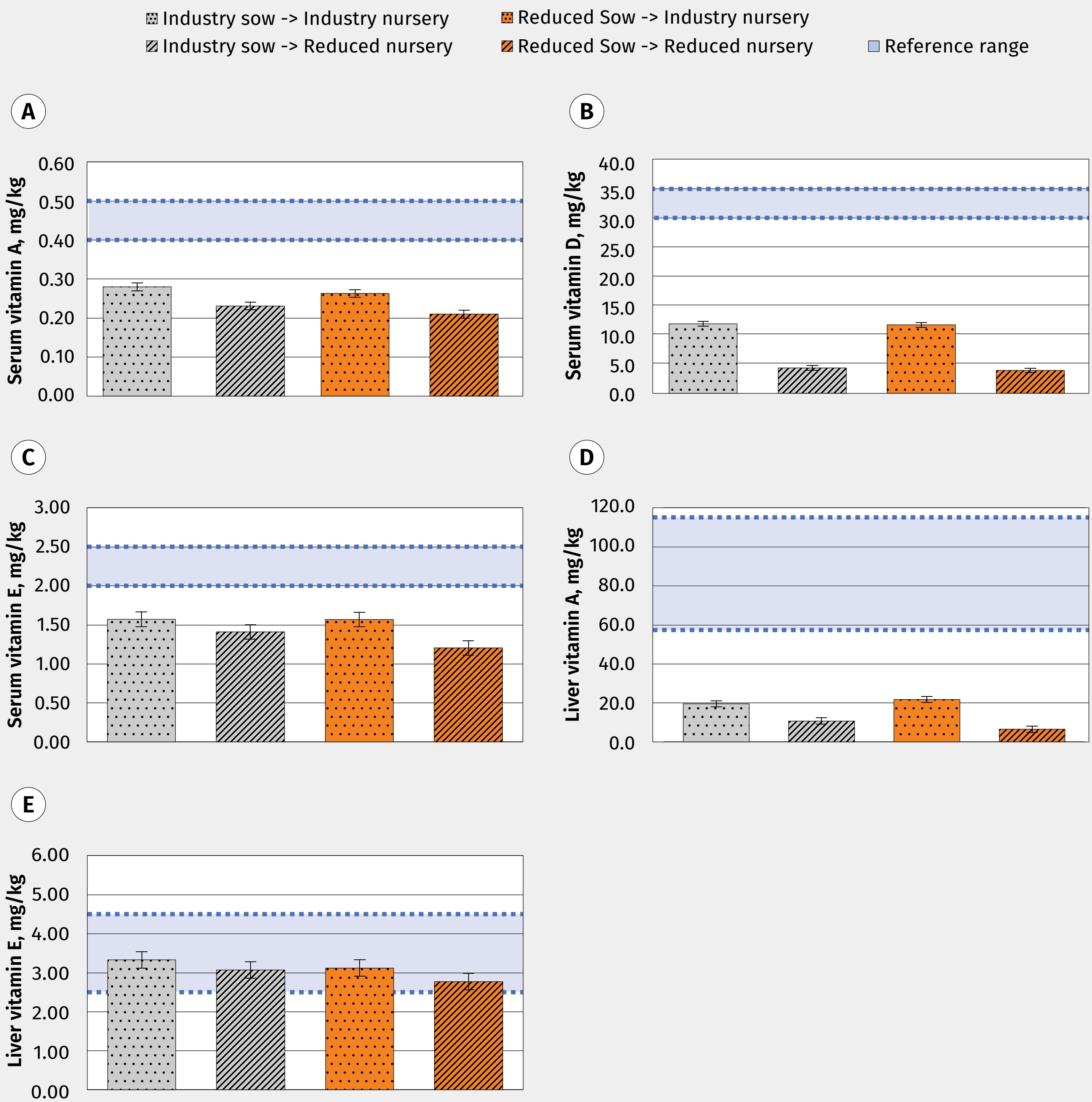


Figure 4: Comparison of vitamin status of nursery pigs receiving different vitamin supplementation strategies to historic physiological reference ranges. Dams were allotted to dietary treatments supplemented with either standard industry vitamin levels or reduced vitamin levels with fat-soluble vitamins added at 2012 National Research Council[1] gestation requirement. Sow offspring (PIC 337 × PIC 1050; n = 765; 15 pens/treatment) were allotted to nursery treatments in a 2 × 2 factorial with nursery diets containing either standard industry vitamin levels or reduced vitamin levels with fat-soluble vitamins added at 2012 NRC levels. Error bars denote the pooled standard error of the means. Offspring bled on d 19 post farrowing were rebled at the end of the nursery period (d 41 post weaning, 2 pigs per sow) for analysis of **A)** vitamin A, **B)** vitamin D (25-hydroxyvitamin D_2 and 25-hydroxyvitamin D_3), and **C)** vitamin E. Liver samples were collected from one representative pig per pen (n = 60) on d 41 post weaning for analysis of **D)** vitamin A and **E)** vitamin E. Samples were collected from 30 littermate pairs, one pig allotted to each nursery treatment and with 15 litters from each sow treatment represented to achieve a balanced sample.



the industry treatment levels of the current study has been shown to increase body condition and suppress lactational feed intake of a common diet fed *ad libitum*. Stressful conditions increase vitamin requirements; moreover, B-vitamin (niacin, thiamine, pantothenic acid, and vitamin B_6) deficiencies can suppress appetite while deficiencies in vitamins A and E lessen immunocompetence and antioxidative capacity which could impact subclinical health status and indirectly affect appetence.[1] The greater lactational feed intake of the industry-level fed sows in the present study tended to reduce litter gain efficiency since the higher caloric intake did not convert to heavier weaning weights. Although the greater feed consumption also did not prevent BW loss, body composition was not measured. Thus, it is possible that body condition of the industry-level fed sows increased with potential benefit to subsequent reproductive performance.

Despite limited growth benefits, the downstream impact of maternal supplementation on weaned pig vitamin status was clearly demonstrated. The feeding of both dam and offspring fat-soluble vitamins at NRC levels compounded to yield even lower serum vitamin E and hepatic vitamin A concentrations than supplementing either production phase alone at NRC levels yielded. Therefore, vitamin supplementation decisions should consider lifecycle supplementation risks and opportunities.

The magnitude of improved growth (10%-12%) observed due to the industry supplementation level is notable considering expected improvement in weight gain due to feed-grade antibiotics is generally only 3% to 9%[25] yet extensive resources are allocated to identifying antibiotic-alternative growth promoters. Similar magnitude improvements in ADG, ADFI, and feed efficiency due to similar vitamin supplementation strategies over NRC levels have been reported by others.[26,27] However, which specific vitamins are responsible for growth improvements has yet to be established. Supplementation of B vitamins at levels similar to the industry concentrations fed in the present study do not always elicit improvements relative to NRC feeding levels,[28] but high-lean growth potential pigs have greater demand for B vitamins to support optimum growth efficiency[29]; indeed, the pigs of the present study had 4% less ADFI yet 6.5% greater ADG than those which failed to respond to B-vitamin supplementation.[28] To identify optimal vitamin supplementation beyond NRC levels, further research is needed to determine the impact of specific vitamins for pigs of varying growth potential and possible interactions between vitamins.

Implications

Under the conditions of this study:

- Reduced vitamins suppress sow ADFI and potentially impact future performance.
- Vitamin supplementation above NRC levels benefits nursery pigs.
- Physiological vitamin levels are "deficient" by historic reference values.

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Conflict of interest

None reported.

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References

1. National Research Council. *Nutrient Requirements of Swine*. 11th ed. National Academy Press; 2012.

2. Flohr JR, DeRouchey JM, Woodworth JC, Tokach MD, Goodband RD, Dritz SS. A survey of current feeding regimens for vitamins and trace minerals in the US swine industry. *J Swine Health Prod.* 2016;24:290-303.

*3. DNA Genetics. DNA Nutritional Recommendations for Sows and Gilts. 2020.

*4. PIC. 2020 Nutrition Manual. 2020.

5. Shurson GC, Salzer TM, Koehler DD, Whitney MH. Effect of metal specific amino acid complexes and inorganic trace minerals on vitamin stability in premixes. *Anim Feed Sci Technol.* 2011;163:200-206. **https://doi.org/10.1016/j.anifeedsci.2010.11.001**

6. Lauridsen C. Triennial growth symposium - Establishment of the 2012 vitamin D requirements in swine with focus on dietary forms and levels of vitamin D. *J Anim Sci.* 2014;92:910-916. **https://doi.org/10.2527/jas.2013-7201**

7. Yang P, Wang HK, Li LX, Ma YX. The strategies for the supplementation of vitamins and trace minerals in pig production: surveying major producers in China. *Anim Biosci.* 2021;34(8):1350-1364. **https://doi.org/10.5713/ajas.20.0521**

8. Puls R. *Vitamin Levels in Animal Health*. Sherpa International; 1994.

9. Schinckel AP, Mahan DC, Wiseman TG, Einstein ME. Growth of protein, moisture, lipid, and ash of two genetic lines of barrows and gilts from twenty to one hundred twenty-five kilograms of body weight. *J Anim Sci.* 2008;86:460-471. **https://doi.org/10.2527/jas.2007-0625**

10. Knauer MT, Hostetler CE. US swine industry productivity analysis, 2005 to 2010. *J Swine Health Prod.* 2013;21:248-252.

11. Matte JJ, Lauridsen C. Vitamins and vitamin utilization in swine. In: Chiba LI, ed. *Sustainable Swine Nutrition*. Wiley-Blackwell; 2013:139-172.

12. Lindemann MD, Brendemuhl JH, Chiba LI, Darroch CS, Dove CR, Estienne MJ, Harper AF. A regional evaluation of injections of high levels of vitamin A on reproductive performance of sows. *J Anim Sci.* 2008;86:333-338. **https://doi.org/10.2527/jas.2007-0153**

13. Hjarde WA, Neimann-Sorensen A, Palludan B, Havskov Sorensen P. Investigations concerning vitamin A requirement, utilization and deficiency symptoms in pigs. *Acta Agric Scand.* 1961;11:13-53. **https://doi.org/10.1080/00015126109435653**

14. Selke MR, Barnhart CE, Chaney CH. Vitamin A requirement of the gestating and lactating sow. *J Anim Sci.* 1967;26:759-763. **https://doi.org/10.2527/jas1967.264759x**

15. Braude R, Foot SA, Henry KM, Kon SK, Thompson SY, Mead TH. Vitamin A studies with rats and pigs. *Biochem J.* 1941;35:693-707. **https://doi.org/10.1042/bj0350693**

16. Horst RL, Littledike ET. Comparison of plasma concentrations of vitamin D and its metabolites in young and aged animals. *Comp Biochem Physiol B.* 1982;73:485-489. **https://doi.org/10.1016/0305-0491(82)90064-5**

17. Lauridsen C, Halekoh U, Larsen T, Jensen SK. Reproductive performance and bone status markers of gilts and lactating sows supplemented with two different forms of vitamin D. *J Anim Sci.* 2010;88:202-213. **https://doi.org/10.2527/jas.2009-1976**

18. Institute of Medicine Committee to Review Dietary Reference Intakes for Vitamin D and Calcium. *Dietary References Intakes for Calcium and Vitamin* D. 2011. National Academy Press, 2011.

19. Coffey JD, Hines EA, Starkey JD, Starkey CW, Chung TK. Feeding 25-hydroxycholecalciferol improves gilt reproductive performance and fetal vitamin D status. *J Anim Sci.* 2012;90:3783-3788. **https://doi.org/10.2527/jas.2011-5023**

20. Flohr JR, Tokach MD, Dritz SS, DeRouchey JM, Goodband RD, Nelssen JL, Henry SC, Tokach LM, Potter ML, Goff JP, Koszewski NJ, Horst RL, Hansen EL, Fruge ED. Effects of supplemental vitamin D3 on serum 25-hydroxycholecalciferol and growth of preweaning and nursery pigs. *J Anim Sci.* 2014;92:152-163. **https://doi.org/10.2527/jas.2013-6630**

21. Weber GM, Witschi A-KM, Wenk C, Martens H. Triennial growth symposium - Effects of dietary 25-hydrocholecalciferol and cholecalciferol on blood vitamin D and mineral status, bone turnover, milk composition, and reproductive performance of sows. *J Anim Sci.* 2014;92:899-909. **https://doi.org/10.2527/jas.2013-7209**

22. Mahan DC, Vallet JL. Vitamin and mineral transfer during fetal development and the early postnatal period in pigs. *J Anim Sci.* 1997;75:2731-2738. **https://doi.org/10.2527/1997.75102731x**

23. Mavromatis J, Koptopoulos G, Kyriakis SC, Papasteriadis A, Saoulidis K. Effects of alpha-tocopherol and selenium on pregnant sows and their piglets' immunity and performance. *Zentralbl Veterinarmed A.* 1999;46:545-553. **https://doi.org/10.1046/j.1439-0442.1999.00244.x**

24. Jeong JH, Hong JS, Han TH, Fang LH, Chung WL, Kim YY. Effects of dietary vitamin levels on physiological responses, blood profiles, and reproductive performance in gestating sows. *J Anim Sci Technol.* 2019;61:294-303. **https://doi.org/10.5187/jast.2019.61.5.294**

25. Van Lunen TA. Growth performance of pigs fed diets with and without tylosin phosphate supplementation and reared in a biosecure all-in all-out housing system. *Can Vet J.* 2003;44:571-576.

26. Cho JH, Lu N, Lindemann MD. Effects of vitamin supplementation on growth performance and carcass characteristics in pigs. *Livest Sci.* 2017;204:25-32. **https://doi.org/10.1016/j.livsci.2017.08.007**

27. Yang, P, Zhao J, Wang H, Li L, Ma Y. Effects of vitamin forms and levels on vitamin bioavailability and growth performance in piglets. *Appl Sci.* 2020;10:4903. **https://doi.org/10.3390/app10144903**

28. Mahan DC, Carter SD, Cline TR, Hill GM, Kim SW, Miller PS, Nelssen JL, Stein HH, Veum TL, North Central Coordinating Committee on Swine Nutrition. Evaluating the effects of supplemental B vitamins in practical swine diets during the starter and grower-finisher periods - a regional study. *J Anim Sci.* 2007;85:2190-2197. **https://doi.org/10.2527/jas.2007-0118**

29. Stahly TS, Williams NH, Lutz TR, Ewan RC, Swenson SG. Dietary B vitamin needs of strains of pigs with high and moderate lean growth. *J Anim Sci.* 2007;85:188-195. **https://doi.org/10.2527/jas.2006-086**

* Non-refereed references.

Table 5: The impact of vitamin level in sow and nursery diets on nursery pig performance and physiology*

Sow Vitamin Level:	Industry		Reduced		Pooled	*P*†		
Nursery Vitamin Level:	**Industry**	**Reduced**	**Industry**	**Reduced**	**SEM**	**Sow**	**Nursery**	**Sow × Nursery**
Medications, No.‡	25	25	25	21	NA	.69	.69	.69
Total removals, No.	3	6	3	0	NA	.97	.98	.97
Nutritional removals, No.§	0	5	3	0	NA	> .99	> .99	.98
Mortality, No.	2	1	0	1	NA	.76	.98	.81
Serum vitamin A, mg/kg¶	0.280	0.231	0.263	0.210	0.010	.02	< .001	.75
Serum vitamin D, ng/mL¶	11.847	4.307	11.669	3.883	0.407	.39	< .001	.72
Serum vitamin E, mg/kg¶	1.571	1.411	1.568	1.205	0.093	.02	< .001	.02
Liver vitamin A, mg/kg**	19.55	10.73	21.80	6.53	1.580	.59	< .001	.01
Liver vitamin E, mg/kg**	3.33	3.07	3.12	2.77	0.210	.35	.03	.70

* Sows were allotted to dietary treatments supplemented with either standard industry vitamin levels or reduced vitamin level with fat-soluble vitamins added at 2012 NRC[1] levels. Sow offspring (PIC 337 × PIC 1050; n = 765) were allotted to nursery treatments in a 2 × 2 factorial with nursery diets containing either standard industry vitamin levels or reduced vitamin levels. Performance was monitored from day 0 (weaning) to 40 days post weaning (n = 15 pens/treatment).

† Health, serum, and liver data were analyzed as a 2 × 2 factorial using linear mixed and generalized linear mixed models. Values were considered significant when $P \leq .05$.

‡ Medications are the total number of instances a pig received therapeutic medications regardless of reason.

§ Nutritional removals occur when pigs are removed off trial for reasons which could be attributed to malnutrition ie, emaciation, inability to find feed or water, or low bodyweight.

¶ The same offspring that had been bled on day 19 post farrowing were subsequently bled at the end of the nursery period (d 41 post weaning, 2 pigs/sow) for analysis of vitamins A, D (25-hydroxyvitamin D_2 and 25-hydroxyvitamin D_3), and E.

** One representative pig per pen (n = 60) was selected for liver sample collection on day 41 post weaning. Liver samples were collected from 30 littermate pairs, one pig allotted to each nursery treatment and with 15 litters from each sow treatment to achieve a balanced sample.

NA = not applicable; NRC = National Research Council.

Table 6: The main effects of vitamin supplementation level in sow and in nursery diets on nursery pig performance*

	Sow		Nursery		Pooled SEM	P†		
	Industry	Reduced	Industry	Reduced		Sow	Nursery	Sow × Nursery
D 0 BW, kg	6.43	6.33	6.36	6.39	0.288	< .001	.30	.28
D 40 BW, kg	22.20	21.86	23.01	21.04	0.203	.09	< .001	.26
ADG, kg	0.39	0.39	0.41	0.36	0.005	.22	< .001	.34
ADFI, kg	0.56	0.56	0.59	0.53	0.009	.35	< .001	.36
G:F, kg:kg	0.70	0.69	0.70	0.69	0.004	.34	.002	.75

* Sows were allotted to dietary treatments supplemented with either standard industry vitamin levels or reduced vitamin levels with fat-soluble vitamins added at 2012 NRC[1] levels. Sow offspring (PIC 337 × PIC 1050; n = 765) were subsequently allotted to nursery treatments in a 2 × 2 factorial arrangement with nursery diets containing either standard industry vitamin levels or reduced vitamin levels. Performance was monitored from day 0 (weaning) to 40 days post weaning (n = 15 pens/treatment).

† Performance data was analyzed as a randomized complete block experimental design with a 2 × 2 treatment factorial using a linear mixed model. Weight at day 0 was used as a covariate for the analysis of growth performance metrics. Values were considered significant when $P \leq .05$.

BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; G:F = body weight gain to feed intake ratio.