Journal of Animal Science, 2026, **104**, skag279
https://doi.org/10.1093/jas/skag279
Published: 1 September 2026
Non Ruminant Nutrition

Effect of high dietary lysine on growth performance and body composition in weaned pigs following a period with dietary protein restriction: a preliminary study

Roberta Ruggeri[1], Marion Girard[2], Paolo Silacci[3], Giuseppe Bee[2], Christina Larsen[4], and Johannes Gulmann Madsen[4,*]

[1]Department of Clinical Veterinary Science, University of Bern, Bern, CH 3012, Switzerland
[2]Swine Research Group, Agroscope, Posieux, CH 1725, Switzerland
[3]Animal Biology Research Group, Agroscope, Posieux, CH 1725, Switzerland
[4]Department of Veterinary and Animal Sciences, University of Copenhagen, Frederiksberg C, DK 1870, Denmark
*Corresponding author. Email: johannes.g.madsen@sund.ku.dk

Abstract

Increasing dietary Lys and remaining essential amino acids (AA) above requirements might counter impaired growth resulting from pigs being fed a low-protein (LP) diet in the early weaning period. It was hypothesized that by increasing dietary Lys and remaining essential AA levels in a 4-week (W) non-reduced period (W5–8) after a 4-W reduced dietary crude protein period (W1–4) would potentially increase growth performance. At weaning, 67 piglets with an ADG of 200–220 g/day during the suckling period were selected based on their weaning weight for the study. On the day of weaning pigs were pre-allocated to 1 of 4 dietary treatments: control (STD-STD), standard (LP-STD), STD + 10% Lys (LP-STD10+) and STD + 20% Lys (LP-STD20+). From weaning to W4 after weaning LP-STD, LP-STD10+ and LP-STD20+ pigs were fed the same LP starter diet (81/79% total/digestible of CP level in STD diet), whereas STD-STD pigs were fed a diet formulated according to recommendations. From W5 to W8 after weaning LP-STD pigs were fed a diet with standard protein level, and LP-STD10+ and LP-STD20+, respectively, fed a diet with STD protein level plus 10% and 20% Lys including remaining essential AA. One day before weaning, and at W4, and at W8 after weaning, respectively, seven pigs (baseline Dual-energy X-ray absorptiometry (DXA) scanning), six STD and six LP pigs, and 12 STD-STD, 12 LP-STD, 12 LP-STD10+ and 12 LP-STD20+ pigs were slaughtered to DXA scan the carcasses. The data were analyzed using the ANOVA function in R, with dietary treatment as fixed and pig nested within pen as random effect for BW, ADG and DXA parameters. For ADFI, G: F per pig, G: CP dietary treatment was used as a fixed effect. For the fecal scoring, the model included dietary treatment and day as fixed and pen as random effect. Results revealed no difference ($P > 0.05$) in BW, ADG, total feed intake, or average daily feed intake between pigs fed STD and LP diet in W1–4, but LP pigs displayed greater ($P < 0.01$) gain-to-CP-ratio. Furthermore, pigs in the LP compared with STD group tended ($P < 0.10$) to display greater bone mass deposition, fat mass, and fat mass deposition after W4. In W5-8 ADG was similar between STD-STD (0.96 kg/day) and LP-STD20 + (0.90 kg/day), which were both numerically greater than LP-STD (0.83 kg/day) and LP-STD10 + (0.86 kg/day). In conclusion, pigs fed the LP diet did not display the expected reduction in ADG but tended to display an altered body composition after W4. This limited the study objective of investigating effect on increasing Lys and remaining essential AA levels, although it was observed that pigs fed the LP-STD20+ diet maintained an ADG numerically comparable to the STD-STD pigs throughout the non-reduced period in W5–8.

Lay Summary

A diet with a low protein content is a known effectful measure in reducing the incidences of post-weaning diarrhea. However, a negative side effect of this measure is that the pigs grow slower as their requirements for nutrients are not being met. A certain biological mechanism allows pigs to catch up with the lost BW gain after a period of reduced nutrient intake. To fully catch up with the reduced nutrient supply, especially essential amino acids, probably needs to be above the pig's normal physiological needs. Thus, increasing growth by supplying essential amino acids above requirements potentially allows for using a low-protein diet without compromising the growth performance.

Keywords weaner pigs, low protein diet, dietary lysine, body composition, growth recovery

Received: April 23, 2026. **Accepted:** August 26, 2026
© The Author(s) 2026. Published by Oxford University Press on behalf of the American Society of Animal Science.
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs licence (https://creativecommons.org/licenses/by-nc-nd/4.0/), which permits non-commercial reproduction and distribution of the work, in any medium, provided the original work is not altered or transformed in any way, and that the work is properly cited. For commercial re-use, please contact reprints@oup.com for reprints and translation rights for reprints. All other permissions can be obtained through our RightsLink service via the Permissions link on the article page on our site—for further information please contact journals.permissions@oup.com.

Downloaded from academic.oup.com/jas/article/doi/10.1093/jas/skag279/8778564 by Bibliothek am Guisanplatz user on 16 November 2026

Abbreviations: AID, apparent ileal digestible; DXA, dual-energy X-ray absorptiometry; EAA, essential amino acids; FI, feed intake; G:CP, gain-to-crude-protein ratio; GLMM, generalized linear mixed model; LP, low-protein (diet); PWD, post-weaning diarrhea; STD, standard (diet)

Introduction

The transition from suckling to weaning is a challenging period for the piglet. It imposes stressors on the animal, including change of diet (McCracken et al. 1995), change in environment (Colson et al. 2012), and mixing with other non-littermate piglets (Merlot et al. 2004). These stressors can cause feed refusal leading to a growth check (Pluske et al. 2007) and later incidence of post-weaning diarrhea (PWD). The PWD is likely caused by the vegetable-based weaning diet being less digestible compared with sows' milk (Heo et al. 2009), while not positively stimulating the immune system to the same degree as milk-based ingredients (Vodolazska et al. 2023). A major causal factor for PWD is the amount of undigested protein fermenting in the hindgut (Gilbert et al. 2019), which can also act as energy substrate for pathogenic bacteria, leading to a leaky gut (Pieper et al. 2016). Paradoxically, in the early phase of the piglet's life the demand for a high density of dietary protein and amino acids (AA) is high (NRC 2012) to support the high fractional protein synthesis rate in muscle tissue (Davis et al. 2008). To reduce the incidences of PWD, feeding a low-protein (LP) diet has shown to be a promising strategy (Lynegaard et al. 2021a, 2021b). However, despite balancing the diet with supplementation of synthetic essential AA (EAA), piglets fed LP diets displayed significantly impaired growth compared with those fed a diet with a standard CP level (Lynegaard et al. 2021a, 2021b).

There is a possibility for pigs to catch-up on lost growth after a limited dietary protein reduced period if the period is followed by a non-reduced period with an excess amount of dietary protein and Lys, potentially resulting in pigs achieving growth performance level comparable with non-reduced counterparts (Menegat et al. 2020). One study has suggested that increasing growth performance and lean mass accretion in growing pigs depends on the dietary Lys level in the non-reduced period (Whang et al. 2003). Therefore, the study objective was to investigate the effect of increasing the dietary Lys level and remaining EAA to maintain an optimal Lys: EAA ratio, on growth performance and body composition in pigs exposed to reduced protein intake the first 4 weeks after weaning. It was hypothesized that increasing the dietary Lys level, and remaining EAA during a 4-week non-reduced period would stimulate growth performance and lean mass accretion in pigs that were reduced in dietary CP intake during the first 4 weeks after weaning.

Materials and methods

Animal ethics

The experimental plan was compliant with the Swiss regulation of animal welfare. The Swiss Federal Committee for Animal Care and Use of Canton Fribourg in Switzerland authorized the experiment (approval number 2024-21-FR).

Animals and experimental design

The experiment was performed at the Agroscope swine research facility in Posieux, Switzerland. Sixty-seven Swiss Large White piglets from 20 litters of one farrowing series were used in the experiment, where 33 were females and 34 were male castrates. Piglets were weighed at birth and again at weaning to categorize and select animals with average (200–220 g/day) pre-weaning growth rates. Of the 67 piglets, 60 piglets were randomly pre-allocated on the day of weaning to one of four dietary treatments implemented from week 5 to 5 (W5–8) after weaning. The remaining seven piglets were euthanized on the day before weaning to serve as a baseline for body composition. Within the first 14 h after birth, all piglets were ear-tagged and administered an iron injection (Ferridex® 10%, AMAG Pharmaceuticals, Inc., Waltham, USA). Male piglets were castrated under general anesthesia induced by isoflurane inhalation at 8 ± 3 days of age and received pain relief treatment with 2 mL/100 kg BW NSAIDs (Contacera (Meloxicam), Zoetis, Delémont, Switzerland).

Diets and housing

Throughout the experiment, pigs had unrestricted access to water via nipple drinkers. Straw was consistently provided in the pens to enhance environmental enrichment. Trained personnel monitored the pigs' health status daily. Dimension of all pens were 1.75 m × 2.85 m with a slatted concrete floor.

From weaning until 4 weeks after weaning (W1–4), pigs were divided into two groups, a control (STD, $n = 18$) receiving a diet with standard CP content and a group receiving a diet with a low protein CP content (LP, $n = 42$). The LP diet was 81/79% (total/digestible) of the CP in the STD diet to force a reduced protein intake during the first four weeks after weaning, while maintaining digestible AA at the requirement level in both diets (Table 1). Pigs had ad libitum access to feed. Animals were housed at six piglets per pen, resulting in three pens in the STD group and seven pens in the LP group. The average ambient temperature of the room was 19.9 ± 2.01 °C.

In weeks 5–8 (W5–8), pigs were assigned to four dietary treatments: a control group (STD-STD, $n = 12$), a standard diet after restriction (LP-STD, $n = 12$), and two groups receiving the standard diet supplemented with either 10% (LP-STD10+, $n = 12$) or 20% (LP-STD20+, $n = 12$) additional digestible Lys and remaining EAA. Both STD-STD and LP-STD received the standard (STD) diet, while LP-STD10+ and LP-STD20+ received the STD diet formulated with 10% and 20% higher digestible Lys, respectively, with all other digestible essential amino acids kept above requirement levels (Table 1).

The STD-STD group consisted only of pigs that had been in the STD group during weeks 1–4 (W1–4), whereas the LP-STD, LP-STD10+, and LP-STD20+ groups consisted only of pigs previously assigned to the LP diet in weeks 1–4. All pigs had ad libitum access to feed. Each treatment group was housed in three pens with four pigs per pen. The average ambient temperature during this period was 16.1 ± 1.25 °C.

Downloaded from academic.oup.com/jas/article/doi/10.1093/jas/skag279/8778564 by Bibliothek am Guisanplatz user on 16 November 2026

Table 1 Ingredient and nutrient composition of a control diet (STD), low-protein diet (LP), a diet with a lysine level 10% above requirement (STD10+) and a diet with a lysine level 20% above requirement (STD20+) fed during the weaner period.[1]

	Diets			
	STD	LP	STD10+	STD20+
Ingredients, as-fed (%)				
Barley	22.79	36.66	32.84	25.35
Corn[2]	14.72	36.75	5.00	13.29
Wheat	29.33	2.00	29.33	29.33
Whey permeate powder	5.00	5.00	5.00	5.00
Animal Fat[3]	0.57	0.35	1.219	0.40
Soybean meal	24.74	15.23	23.40	22.75
L-Lysine HCl	0.29	0.60	0.45	0.61
DL-Methionine	0.07	0.18	0.13	0.20
L-Threonine	0.06	0.20	0.13	0.20
L-Tryptophan	–	0.03	–	0.02
L-Valine	–	0.13	0.04	0.11
L-Isoleucine 93.4%	–	0.10	–	0.06
L-Leucine 98%	–	0.09	0.01	0.12
L-Histidine HCl 98%	–	0.09	0.02	0.07
Mono calcium phosphate	0.49	0.62	0.48	0.53
Calcium carbonate	1.05	1.05	1.06	1.05
Natrium chloride	0.27	0.29	0.27	0.29
Vitamin-mineral premix[4]	0.40	0.40	0.40	0.40
Aroma[5]	0.01	0.01	0.01	0.01
Calcium butyrate[6]	0.20	0.20	0.20	0.20
Phytase[7]	0.01	0.01	0.01	0.01
Calculated composition (Analyzed composition)				
Dry matter (g/kg)	896.9 (901.8)	901.1 (906.7)	896.6 (902.9)	897.8 (904.7)
Ash (g/kg)	52.6 (48.0)	49.5 (44.1)	53.2 (47.5)	52.8 (47.0)
Crude protein (g/kg)	185.0 (189.7)	150.4 (152.5)	185.0 (189.5)	185.0 (189.0)
Crude fat (g/kg)[8]	31.9 (28.7)	34.4 (31.6)	36.6 (32.5)	29.8 (26.6)
Crude fiber (g/kg)	30.0 (31.9)	30.5 (37.5)	32.9 (28.7)	30.2 (33.8)
Gross energy (MJ/kg)[9]	16.4	16.4	16.5	16.4
Digestible energy (MJ/kg)[10]	14.0	14.0	14.0	14.0
Net energy (MJ/kg)[10]	10.30	10.46	10.28	10.31
Calcium (g/kg)[11]	8.4 (6.4)	8.4 (6.2)	8.4 (6.1)	8.4 (6.0)
Phosphorous (g/kg)	5.4 (5.0)	5.2 (4.5)	5.5 (5.1)	5.4 (5.0)
Digestible crude protein (g/kg)[10]	154.8	122.9	154.2	155.7
Total amino acids (g/kg)[9]				
Lys	11.4	11.4	12.4	13.2
Met	3.2	3.7	3.7	4.3
Thr	7.2	7.0	7.6	8.1
Trp	2.3	2.0	2.3	2.4
Val	8.4	7.7	8.7	8.9
Ile	7.5	6.6	7.5	7.7
Leu	14.0	12.4	13.6	14.5
His	4.4	4.0	4.4	4.7
Apparent ileal digestible amino acids (g/kg)[10]				
Lys	10.17	10.17	11.19	12.21
Met	3.02	3.62	3.62	4.24
Thr	5.70	5.70	6.27	6.85
Trp	1.83	1.62	1.82	1.94
Val	6.79	6.28	7.05	7.53

(continued)

Downloaded from academic.oup.com/jas/article/doi/10.1093/jas/skag279/8778564 by Bibliothek am Guisanplatz user on 16 November 2026

Table 1 (continued)

	Diets			
	STD	**LP**	**STD10+**	**STD20+**
Ile	6.07	5.23	5.90	6.28
Leu	11.62	10.17	11.19	12.21
His	3.80	3.42	3.80	4.11
AID Lys: net energy ratio[12]	0.99	0.97	1.09	1.18

[1]From weaning to 4 weeks (W1–4) after weaning the STD and LP diets were given. From week 5 to week 8 after weaning the STD, STD10+ and STD20+ diets were given. Thus, non-reduced pigs (STD-STD) received the STD diet from weaning until week eight after weaning, whereas pigs reduced in dietary crude protein (LP) received the LP diet from weaning to week 4 (W1-4) after weaning, and from week 5 until week 8 (W5–8) after weaning either the STD (LP-STD), Lys10 (LP-STD10+) or Lys20 (LP-STD20+) diet.
[2]Notable difference in inclusion rate of corn between diets STD10+ and STD20+.
[3]Notable difference in inclusion rate of animal fat between diets STD10+ and STD20+.
[4]Supplied per kg diet: vitamin A, 8000 IU; vitamin D3, 1000 IU; vitamin E, 25 mg; menadione, 3 mg; thiamine, 2 mg; riboflavin, 5 mg; biotin, 0.1 mg; niacin, 20 mg; pantothenic acid, 15 mg; iron, 80 mg as iron sulfate monohydrate; iodine, 0.15 mg as calcium iodate; copper, 6 mg as copper sulfate; manganese, 10 mg as manganese oxide; zinc, 75 mg as zinc oxide; selenium, 0.2 mg as sodium selenite.
[5]Luctarom (Lucta, Montornès del Vallès, Spain).
[6]Coated calcium butyrate (Greencab 70-c, Brenntag, Denmark).
[7]Quantum Blue 5G (AB Vista, Marlborough, United Kingdom).
[8]Notable difference in crude fat content between diets STD10+ and STD20+.
[9]Based on analyzed values
[10]Based on calculated values. Apparent ileal digestible: Calculated for every single ingredient in the diet based on the analyzed value of CP content of each ingredient and the digestibility coefficient are taken from the Swiss feedbase (www.feedbase.ch/). Net energy: Calculated for every single ingredient based on Noblet et al. (2003) "Estimation of energy value of feeds for pigs" (en.evapig.com).
[11]Phytase added to the diet has an equivalent of 1.65 g Ca, corresponding to the analyzed Ca content being 8.4-1.65 = 6.75 as exemplified in STD diet.
[12]Based on calculated values. AID; Apparent ileal digestible.

Body weight, average daily gain and feed intake

All pigs were weighed weekly, and ADG was estimated on individual pig level for W1–4 and W5–8. In both the periods W1–4 and W5–8, feed intake (FI) was estimated per pen by weighing feed refusals daily from W1–2 and weekly from W3–8. In the period W1–4, total FI per pen was calculated over a period of 27 d by weighing the feed residues daily during the first 2 weeks and then weekly for the remaining period.

In the period W5–8, total FI was calculated per pen over 27/28 days (pigs were slaughtered over two consecutive days, see additional information below) by weighing the feed residues weekly. Total FI per pig per pen was calculated by dividing the total FI per pen by the number of pigs in the pen ($n = 6$ in W1–4 and $n = 4$ in W5–8). Average daily FI per pen was calculated by dividing the total FI of the pen by 27 (W1–4) and 27/28 (W5–8) days. The average daily feed intake (ADFI) per pig per pen was calculated by dividing the total FI of the pig by 27 days (W1-4) or 27/28 days (W5-8). Gain-to-feed ratio and gain-to-CP ratio (G:CP) were estimated on pen level. The gain-to-CP ratio was calculated by dividing the accumulated gain by the accumulated CP intake during the respective period.

Fecal scoring

Fecal scoring was performed daily per pig from weaning and until 2 weeks after weaning, by using a binomial scoring system with "0" equal to pigs not having diarrhea and "1" equal to pigs having diarrhea. Diarrhea was defined as very soft or viscous to liquid feces. Signs of diarrhea were checked daily in the pen and the individual piglets were examined for wet and irritated hindlimbs.

DXA scanning

The randomly selected pigs euthanized one day before weaning ($n = 7$) and four weeks postweaning ($n = 12$; STD = 6 and LP = 6) were euthanized at the Agroscope facility by exsanguination following electrical stunning, while the pigs euthanized eight weeks postweaning were euthanized at the Agroscope abattoir by exsanguination following CO_2 stunning ($n = 48$; STD-STD = 12, LP-STD = 12, LP-STD10+ = 12, LP-STD20+ = 12). Immediately after exsanguination, the animals were eviscerated. The carcasses and heads were split in half and chilled at 2 °C. The left side of each half-carcass was scanned the day after slaughter using a GE Lunar dual-energy X-ray absorptiometry (DXA; i-DXA, GE Healthcare Switzerland, Glattbrugg, Switzerland) with a narrow-angle fan beam (Collimator Model 42129). The procedures for handling the carcasses and analyzing the DXA scan images are described in detail in a previous study (Kasper et al. 2021). The images were processed to define the regions of interest. Total mass, total lean mass, total fat mass, total bone mineral content, and total bone mineral density were recorded as the DXA output variables. The deposition of bone, fat, lean, and total mass was calculated by subtracting the mean values of these components measured in the seven pigs euthanized at weaning (used as controls) from the corresponding values assessed on the 12 pigs euthanized at week 4, and on the 48 pigs euthanized at week 8 postweaning. The mean bone, fat, lean, and total mass at weaning were 0.15 kg, 0.80 kg, 4.79 kg, and 5.75 kg, respectively. An illustration of the experimental design and period is provided in Figure S1.

Downloaded from academic.oup.com/jas/article/doi/10.1093/jas/skag279/8778564 by Bibliothek am Guisanplatz user on 16 November 2026

Statistical analyses

The statistical analyses were performed using the statistical software R studio version 4.4.2 (R Core Team 2024). All data were tested for normality with visual observations through a histogram quantile-quantile plot and plotted and residuals vs. predicted values, and all data were found to be normally distributed. The results are presented as least squares means with a pooled SEM. Statistical significance was declared at $P < 0.05$ and a tendency between $P \geq 0.05$ and $P < 0.10$.

Analysis of growth performance and body composition parameters for the first 4 weeks post-weaning with reduced dietary crude protein content

For W1–4 period the data were analyzed using a linear mixed-effects model. By applying ANOVA from the "nlme" package in R, BW, and ADG were estimated on an individual basis (pig as experimental unit) by including the fixed effect of dietary treatment (STD or LP) and, respectively, weaning weight and pre-weaning ADG as covariate, while the pig nested within the pen was used as random effect in the model. Effects on ADFI per pen and ADFI per pig were analyzed with pen as the experimental unit and were estimated by including dietary treatment (STD or LP) as a fixed effect. Similarly, G:F and G:CP were estimated with pen as the experimental unit and dietary treatment as fixed effect, but prior to estimation the difference between BW at week 4 and BW at weaning divided by, respectively, the total FI and total CP intake per pig from weaning to week 4 was calculated. Sex was omitted as a fixed effect in all models, as it was not significant for any of the analyzed parameters.

Analysis of fecal scoring during the first four weeks post-weaning with reduced dietary crude protein content

For the fecal scoring, the data regarding the fecal score was analyzed using a generalized linear mixed model (GLMM) with a binomial distribution. The model included dietary treatment (STD or LP) and day as fixed effects with pig as the experimental unit, while pen was included as random effects to account for clustering of pigs within pens and repeated measures over time, respectively. Pairwise comparisons between specific days were not computed due to insufficient day variation and irregular distribution of residuals. The analysis was performed using the "glmer" function from the lme4 package in Rstudio.

Analysis of growth performance and body composition parameters during week 5 to 8 post-weaning with a non-reduced crude protein and high lysine feeding regime

For the W5–8 period, the data were analyzed using a linear mixed-effects model. By applying ANOVA from the "nlme" package in R, BW and ADG were estimated on an individual basis (pig as experimental unit) by including the dietary treatment (STD-STD, or LP-STD, LP-STD10+ and LP-STD20+) as a fixed effect and, respectively, BW beginning of week 5 and weaning-W4 ADG as covariate, while pig nested within pen was used as a random effect in the model. The effect on ADFI per pen and ADFI per pig were analyzed with pen as the experimental unit and were estimated by including dietary treatment (STD-STD, or LP-STD, LP-STD10+ and LP-STD20+) as fixed effect. Similarly, G:F ratio and G:CP ratio was estimated with pen as experimental unit and dietary treatment as the fixed effect, but prior to estimation, the difference between BW at week 8 and BW at week 4 after weaning was divided by, respectively, the total FI and total CP intake per pig from week 4 after weaning to week 8. Sex was omitted as fixed effect in all models, as it was not significant for any of the analyzed parameters.

Results

Growth performance, fecal scoring, and body composition during first 4 weeks post-weaning with reduced dietary crude protein content

No difference between pigs in the STD and LP groups with respect to BW, average daily gain (ADG), and ADFI was observed (Table 2). Gain-to-CP ratio was 12.5% lower ($P < 0.01$) in pigs of the STD compared with the LP group, whereas the gain-to-feed ratio per pig did not differ between groups (Table 2). With respect to body composition, pigs in the LP group tended ($P < 0.10$) to display 20% lower bone mass deposition, 18.5% lower fat mass, and 70% lower fat mass deposition compared with pigs of the STD group (Table 3).

No differences in probability of diarrhea incidences were observed between the STD and LP pens, while an effect ($P < 0.01$) of day was observed (Table 2). A slight numerical ($P = 0.11$)

Table 2 Effect of a reduced dietary crude protein feeding regime during the first 4 weeks after weaning on growth performance parameters and fecal scoring.

Item	Dietary treatment[1]			*P*-Value
	STD	LP	SEM	Trt
BW (kg)				
Weaning	8.1	7.8	0.19	0.30
End of week 4	14.9	15.1	0.40	0.63
Average daily gain (kg/day)				
Week 1-4	0.26	0.26	0.016	0.99
Average daily feed intake[2]				
ADFI pen[3] (kg/day)	2.4	2.5	0.13	0.41
ADFI pig[4] (kg/day)	0.4	0.4	0.02	0.35
Gain-to-feed[5]				
G:F ratio (kg/kg)	0.66	0.62	0.015	0.10
G:CP ratio (kg/kg)	3.5	4.0	0.10	< 0.01
Fecal scoring				
Pen score, probability (%)[6]	57.4 (0.20)	28.5 (0.14)	–	0.11

[1]Control (STD) diet with standard CP content, and a low-protein diet (LP) with 81/79% (total/digestible) of the CP in the STD diet.
[2]Number of pens: STD = 6 pigs per pen in 3 pens. LP = 6 pigs per pen in 7 pens.
[3]Kg feed intake per pen per day.
[4]Kg feed intake per pig per day.
[5]Gain-to-feed and Gain-to-CP (G:CP) ratios estimated per pen.
[6]Standard errors in brackets, and corresponding means (logit scale); STD = −0.92 (0.67) and LP = −0.30 (0.81).

Downloaded from academic.oup.com/jas/article/doi/10.1093/jas/skag279/8778564 by Bibliothek am Guisanplatz user on 16 November 2026

decrease in probability of diarrhea incidences was noted in the LP pens compared with the STD pens (Table 2).

Growth performance and body composition during week 5 to 8 post-weaning with a non-reduced crude protein and high lysine feeding regime

Dietary treatment had no effect on BW, neither was ADG affected by the dietary lysine level (Table 4). No effect on ADFI was observed, neither did G:F per pig and G:CP per pig differ between any of the dietary treatments (Table 4). No effect of dietary treatment on body composition parameters was observed (Table 5).

Table 3 Effect of a reduced dietary crude protein feeding regime after the first 4 weeks after weaning on body composition.

Item	Dietary treatment[1]			*P*-value
	STD	LP	SEM	Trt
Bone mass (kg)	0.28	0.29	0.006	0.39
Bone mass deposition (kg/day)	0.004	0.005	0.0002	0.09
Fat mass (kg)	0.9	1.1	0.07	0.08
Fat mass deposition (kg/day)	0.003	0.010	0.0025	0.09
Lean mass (kg)	8.8	9.4	0.32	0.22
Lean mass deposition (kg/day)	0.15	0.17	0.321	0.23
Total mass (kg)	10.0	10.8	0.34	0.13
Total mass deposition (kg/day)	0.15	0.18	0.012	0.13

[1]Control (STD, $n = 6$) diet with standard CP content, and a low-protein diet (LP, $n = 6$) with 81/79% (total/digestible) of the CP in the STD diet.

Discussion

Lowering the dietary CP level during the early weaning phase has been shown to reduce number of antibiotic-treated pens from 9–15 kg BW while compromising the growth performance in the early and overall weaning period (Lynegaard et al. 2021a, 2021b). When LP diets are formulated to maintain the ideal protein profile by supplementation with crystalline AA, imbalances between EAA and non-EAA (Peng et al. 2016) or a too high EAA: total N ratio (Wellington et al. 2023) are often observed, which in turn compromises the pig's ability to catch-up on previous lost growth. Therefore, in the present study, a 4-week non-reduced period with dietary Lys levels above requirement after a 4-week reduced CP feeding regime following weaning to enhance growth was investigated. However, in the absence of a negative effect on ADG in LP pigs in the first four weeks post-weaning, it was not possible to conclude that increased dietary Lys levels could enhance growth in the following non-reduced period.

First 4 weeks post-weaning with a reduced crude protein feeding regime

While several studies have shown reduced ADG when dietary CP level is lowered from three to six percentage points from the standard level during the early weaning phase (Peng et al. 2016; Lynegaard et al. 2021a, 2021b; Wellington et al. 2023; Cho and Kong 2025), a few other findings support the observation that lowering the dietary CP level by three or more percentage points

Table 4 Effect of 10% (LP-STD10+) and 20% (LP-STD20+) lysine inclusion levels above requirement during a 4-week (week 5-8 after weaning) non-reduced dietary crude protein period after a 4-week (week 1–4 after weaning) reduced dietary crude protein period on growth performance parameters.

	Dietary treatment[1]					*P*-value
	STD-STD	LP-STD	LP-STD10+	LP-STD20+	SEM	Trt
BW (kg)						
Beginning of week 5	15.4	14.9	14.8	15.1	0.75	0.94
Week 8	38.5	37.0	38.3	38.8	0.91	0.24
Average daily gain (kg/day)						
Week 5–8	0.96	0.83	0.86	0.90	0.040	0.27
Feed intake[2]						
ADFI pen[3] (kg/day)	5.8	5.3	5.6	5.5	0.32	0.51
ADFI pig[4] (kg/day)	1.5	1.3	1.4	1.4	0.08	0.50
Gain-to-feed[5]						
G:F ratio (kg/kg)	0.49	0.47	0.47	0.49	0.029	0.76
G:CP ratio (kg/kg)	2.6	2.5	2.5	2.6	0.15	0.81

[1]STD-STD ($n = 12$); control pigs which were not reduced in dietary crude protein during week 1–4 and fed a standard diet from week 5-8 after weaning. LP-STD ($n = 12$); pigs fed a reduced dietary crude protein diet during week 1–4, but a diet with standard CP content from week 5–8 after weaning. LP-STD10 + ($n = 12$); pigs fed a reduced dietary crude protein diet during week 1–4, but a standard with 10% Lys and remaining essential AA above requirement level from week 5-8 after weaning. LP-STD20 + ($n = 12$); pigs fed a reduced dietary crude protein diet during week 1-4, but a standard with 20% Lys and remaining essential AA above requirement level from week 5–8 after weaning.
[2]Number of pens: STD-STD = 4 pigs per pen in 3 pens. LP-STD = 4 pigs per pen in 3 pens. LP-STD10+ = 4 pigs per pen in 3 pens. LP-STD20+ = 4 pigs per pen in 3 pens.
[3]Kg feed intake per pen per day
[4]Kg feed intake per pig per day
[5]Gain-to-feed and Gain-to-CP (G:CP) ratios estimated per pen.

Downloaded from academic.oup.com/jas/article/doi/10.1093/jas/skag279/8778564 by Bibliothek am Guisanplatz user on 16 November 2026

Table 5 Effect of 10% (LP-STD10+) and 20% (LP-STD20+) lysine inclusion levels above requirement after a 4-week (week 5–8 after weaning) non-reduced dietary crude protein period after a 4-week (week 1–4 after weaning) reduced dietary crude protein period on body composition.

Item	Dietary treatment[1]					*P*-value
	STD-STD	LP-STD	LP-STD10+	LP-STD20+	SEM	Trt
Bone mass (kg)	0.70	0.67	0.70	0.69	0.030	0.87
Bone mass deposition (kg/day)	0.01	0.01	0.01	0.01	0.001	0.88
Fat mass (kg)	3.6	3.2	3.4	3.3	0.32	0.89
Fat mass deposition (kg/day)	0.05	0.04	0.05	0.04	0.006	0.88
Lean mass (kg)	24.3	23.4	24.6	24.7	0.96	0.79
Lean mass deposition (kg/day)	0.35	0.34	0.36	0.36	0.017	0.83
Total mass (kg)	28.5	27.2	28.7	28.6	1.25	0.85
Total mass deposition (kg/day)	0.41	0.39	0.41	0.41	0.023	0.87

[1]STD-STD ($n = 12$); control pigs which were not reduced in dietary crude protein during week 1–4 and fed a standard diet from week 5–8 after weaning. LP-STD ($n = 12$); pigs fed a reduced dietary crude protein diet during week 1–4, but a diet with standard CP content from week 5–8 after weaning. LP-STD10 + ($n = 12$); pigs fed a reduced dietary crude protein diet during week 1–4, but a standard with 10% Lys and remaining essential AA above requirement level from week 5–8 after weaning. LP-STD20 + ($n = 12$); pigs fed a reduced dietary crude protein diet during week 1–4, but a standard with 20% Lys and remaining essential AA above requirement level from week 5–8 after weaning.

from the standard level as done in the current study did not impair ADG (Mavromichalis et al. 1998; Liu et al. 2021). This discrepancy among studies is likely explained by the variation in standard dietary CP level used as well as the degree of crystalline EAA supplementation, ultimately affecting the N efficiency utilization and consequently growth. In addition, findings related to FI during protein restriction are also not consistent. For example, Cloutier et al. (2016) observed reduced FI in pigs restricted to 70% of normal intake, whereas O'Connell et al. (2006) reported unchanged ADFI during a 35-d restriction period despite a large difference in CP (217 vs. 139 g/kg). These discrepancies likely reflect differences in the severity and duration of restriction, the age of pigs, and the extent to which diets met indispensable AA requirements. In the present study, pigs on the LP diet seem to compensate partially by numerically increasing FI, resulting in a CP intake equivalent to ∼83% of the STD group on a digestible basis. This partial compensation, combined with a diet still meeting essential AA requirements, may explain why LP pigs-maintained growth to a greater extent than in studies applying more severe or AA-limiting restrictions.

The improved G:CP ratio in LP pigs suggests enhanced N utilization under reduced CP supply. This contrasts with Le Bellego and Noblet (2002), who found no reduction in growth or carcass protein content when lowering CP in slightly older piglets, although N excretion decreased. The difference may stem from age and physiological stage, as younger weaners have higher fractional protein synthesis rates and may respond more sensitively to CP reductions, whereas older piglets can maintain protein accretion more effectively when AA requirements are met.

Because the LP diet was formulated to meet digestible indispensable amino acid requirements through crystalline amino acid supplementation, the reduction in dietary CP represented primarily a reduction in total nitrogen supply rather than a deficiency of essential amino acids. Consequently, the absence of a reduction in ADG suggests that the nutritional challenge was insufficient to limit whole-body protein deposition under the conditions of this study. However, it remains unclear whether the observed responses were driven primarily by reduced nitrogen availability, a lower supply of non-essential amino acids, or by the slightly altered energy-to-protein ratio in the LP diet. These mechanisms are closely linked, but the present study was not designed to distinguish between them. Nevertheless, the improved G:CP ratio indicated that LP pigs utilized the available dietary nitrogen more efficiently while maintaining growth, suggesting that essential amino acid supply remained the primary determinant of growth performance under the CP-reduced level applied.

Fecal scoring was used to assess potential PWD during the restriction period. Earlier work showed that markedly reducing CP can alleviate PWD by limiting substrate for hindgut protein fermentation (Heo et al. 2009, 2010). In the present study, only a slight numerical reduction in fecal score was observed in LP pigs. This likely reflects that overall PWD incidence in this herd was moderate, or pigs may not have been sufficiently challenged for a clear CP-related effect on PWD to emerge. The sanitary conditions of the research facility are in general at a high level, and thus for future purposes it could be considered beneficial to include an enterotoxigenic *Escherichia coli* challenge model to elicit a more robust demonstration of the LP diet's effect on gut health.

The numerical compensation in FI and improved N utilization during CP restriction may have reduced the capacity to increase growth during W5–8. Combined with the relatively mild challenge during the first 4 weeks, this could have limited the pigs' responsiveness to elevated dietary Lys during the non-reduced period as further discussed.

The tendency for greater body fat mass in LP pigs is consistent with an imbalance between energy intake and the reduced availability of AA for protein deposition. When AA supply does not support the high rate of protein synthesis typical of young weaners, surplus energy is redirected toward adipose accretion (Campbell and Dunkin 1983). Similar increases in whole-body lipid content have been reported in pigs subjected to AA restriction during early growth (Martínez-Ramírez et al. 2008a, 2008b). Despite this, LP pigs did not show reduced lean mass or lean deposition, which aligns with their improved CP utilization and suggests that muscle fiber hypertrophy was not markedly impaired, consistent with earlier findings (Lodge et al. 1977). The tending greater bone mass deposition in LP pigs could not be supported by any previous studies.

Downloaded from academic.oup.com/jas/article/doi/10.1093/jas/skag279/8778564 by Bibliothek am Guisanplatz user on 16 November 2026

Week 5 to 8 post-weaning with a non-reduced crude protein and high dietary lysine feeding regime

It has previously been shown that a shift from a deficient to a sufficient dietary Lys level positively affected ADG in rats (Ishida et al. 2011) and pigs (Ishida et al. 2012; Cloutier et al. 2016). This was not confirmed by the present study, where no difference in ADG between pigs in the STD-STD and LP-STD groups was observed in the recovery period (W5–8). However, most interestingly, LP-STD20+ pigs maintained a numerical ADG closest to STD-STD pigs, whereas LP-STD10+ pigs displayed lower numerical daily gain compared with LP-STD and LP-STD20+ pigs. Although no difference in ADG between dietary treatments during the non-reduced period (W5–8) was observed, numerical trends could indicate that a Lys level above requirement may potentially enhance growth following a period of reduced CP intake. Lysine is a well-recognized driver for improving growth performance and whole-body growth of growing pigs (Liao et al. 2015) and has also been suggested to increase growth in grower-finisher pigs after a period of reduced protein supply (O'Connell et al. 2006). While the study did not allow for distinguishing between the effect of Lys and remaining EAA, it was most likely the combination of increasing the dietary Lys level without compromising the Lys: EAA ratio that maintained ADG at STD-STD level in the LP-STD20+ group. As the FI did not differ between the STD-STD and LP-STD groups, nor between STD-STD and LP-STD20+, the numerical increased ADG was likely the consequence of elevated dietary Lys level.

As reviewed in Menegat et al. (2020), to completely uphold growth optimally after a protein reduced period requires a proportion of 37% reduced and 63% non-reduced of the overall period. Thus, the high dietary Lys level may have elicited a stronger growth response if the restriction period had been shorter or the following non-reduced period had been longer. However, the risk of PWD is extended into the third week and fourth week of the weaner period, which is why the LP was applied for 4 weeks postweaning creating a 50% reduced and 50% non-reduced period. In this context, it should be noted that the review by Menegat et al. (2020) concerned grower-finishers, which compared with weaners, likely display markedly lower fractional protein synthesis as this declines with age (Davis et al. 1996) and therefore potentially influences the proportions of the reduced and non-reduced period in an unknown direction.

In line with the growth performance results, no effect of dietary Lys level was observed on body composition within the group of reduced CP pigs, as well as no difference was found between the STD-STD and previous reduced pigs (LP-STD, LP-STD10+ and LP-STD20+). The latter finding is supported by a previous study reporting that pigs shifting from a Lys deficient to a Lys sufficient diet after a 21-d reduced period displayed similar N retention and N utilization as pigs fed a Lys sufficient diet in the same period (Ishida et al. 2012). This suggests that only a Lys level at or above requirement level is required to maintain body composition after a period of reduced CP intake.

Study limitations

Several limitations of the study need to be considered. First, it can be speculated whether pigs in the LP-STD10+ and LP-STD20+ groups would display a stronger response in growth during the non-reduced protein period if ADG as expected had been diminished in the LP pigs due to the lower CP intake during the reduced period. In addition, while the experiment was designed to detect a difference of 50 g daily gain with 12 animals per dietary treatment at a, respectively, 80% and 0.05% power and significance level (Aaron and Hays 2004), it is possible that the herd coefficient of variance was greater than expected and thereby compromised the possibility of observing smaller differences in ADG namely during the non-reduced period. In addition, the number of pens allocated to each treatment should be considered with caution when interpreting the FI and feed efficiency results. Furthermore, it should be recognized that although diets were isoenergetic, namely the LP-STD10+ diet differed from the STD-STD and LP-STD20+ diets with respect to inclusion rates of corn and animal fat. The latter contributed to a marked increase in crude fat content of the LP-STD10+ diet, potentially influencing the energy digestibility of the diet. This discrepancy in the basic feed ingredients between diets creates a challenge to isolate the specific effects of the supplemented amino acids and thereby challenge to conclude on a potential growth effect in the non-reduced protein period. Furthermore, this particularly complicates direct and fair interpretation of growth performance and body composition results between pigs receiving 10% and 20% lysine supplementation in the W5-8 period. However, LP-STD20+ still performed numerically closest to the STD-STD, which did not differ in ingredient nor nutrient composition. In both periods the average ambient temperatures were lower than widely recommended, which could potentially have increased the pigs' requirements for maintenance energy and thereby affected compensatory FI and fat mass deposition in the LP group. Finally, in the period of reduced CP, it cannot be excluded that by applying a less coarse fecal scoring system would have detected clearer differences with respect to PWD between the dietary treatments.

Conclusions

In conclusion, pigs fed the LP diet did not display impaired ADG compared with pigs fed the non-reduced CP diet in the first four weeks after weaning, and it was therefore not possible to evaluate whether increased dietary Lys levels could increase growth in the following four-week non-reduced period. In addition, feeding the LP diet only to a minor degree positively affected the fecal scoring values during the first four weeks after weaning. On the contrary, the tending greater body fat mass and fat mass deposition in LP pigs was likely the result of a suboptimal dietary energy-to-CP ratio. A numerical difference in ADG between LP-STD20+ and LP-STD pigs was not manifested in any changes of body composition after the four-week non-reduced period.

Downloaded from academic.oup.com/jas/article/doi/10.1093/jas/skag279/8778564 by Bibliothek am Guisanplatz user on 16 November 2026

Acknowledgments

The authors would like to thank Guy Maikoff and his staff for their excellent work in the Agroscope piggery, and the staff of the laboratory for their valuable support. This study was funded by the PIGWEB project which has received funding from The European Union's Horizon 2020 research and innovation program under Grant Agreement No 101004770, and conducted at Agroscope swine research facility in Posieux, Switzerland.

Author contributions

R. Ruggeri (Data curation [true], Formal analysis [true], Investigation [true], Methodology [true], Resources [true], Writing—original draft [true], Writing—review & editing [true]), M. Girard (Conceptualization [true], Data curation [true], Formal analysis [true], Investigation [true], Methodology [true], Resources [true], Writing—original draft [true], Writing—review & editing [true]), P. Silacci (Investigation [true], Methodology [true], Resources [true], Writing—review & editing [true]), G. Bee (Conceptualization [true], Funding acquisition [true], Project administration [true], Resources [true], Validation [true], Writing—review & editing [true]), C. Larsen (Data curation [true], Investigation [true], Methodology [true], Writing—review & editing [true]), and J.G. Madsen (Conceptualization [true], Funding acquisition [true], Investigation [true], Project administration [true], Validation [true], Writing—original draft [true], Writing—review editing [true])

Supplementary data

Supplementary data is available at *Journal of Animal Science* online.

Conflict of interest statement. The authors declare no real or perceived conflicts of interest.

Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

References

Aaron DK, Hays VW. 2004. How many pigs? Statistical power considerations in swine nutrition experiments. J Anim Sci. 82 (13_suppl):E245–E254. https://doi.org/10.2527/2004.8213_supplE245x

Campbell RG, Dunkin AC. 1983. The influence of protein nutrition in early life on growth and development of the pig. 1. Effects on growth performance and body composition. Br J Nutr. 50: 605–617. https://doi.org/10.1079/bjn19830132

Cho I, Kong C. 2025. Growth performance of pigs fed low-protein diets supplemented with crystalline amino acids at different growth stages. Anim Biosci. 38:316–324. https://doi.org/10.5713/ab.24.0339

Cloutier L, Létourneau-Montminy M-P, Bernier J, Pomar J, Pomar C. 2016. Effect of a lysine depletion–repletion protocol on the compensatory growth of growing-finishing pigs. J Anim Sci. 94:255–266. https://doi.org/10.2527/jas.2015-9618

Colson V, Martin E, Orgeur P, Prunier A. 2012. Influence of housing and social changes on growth, behaviour and cortisol in piglets at weaning. Physiol Behav. 107:59–64. https://doi.org/10.1016/j.physbeh.2012.06.001

National Research Council. 2012. Nutrient requirements of swine. 11th rev ed. National Academies Press.

Davis T, Suryawan A, Orellana R, Nguyen H, Fiorotto M. 2008. Postnatal ontogeny of skeletal muscle protein synthesis in pigs. J Anim Sci. 86:E13-E18. https://doi.org/10.2527/jas.2007-0419

Davis TA, Burrin DG, Fiorotto ML, Nguyen HV. 1996. Protein synthesis in skeletal muscle and jejunum is more responsive to feeding in 7-than in 26-day-old pigs. Am J Physiol. 270: E802–809. https://doi.org/10.1152/ajpendo.1996.270.5.E802

Gilbert M, Van der Hee B, Gerrits W. 2019. The role of protein fermentation metabolites in post-weaning diarrhoea in piglets, Energy and protein metabolism and nutrition. Wageningen Academic. p. 361–362.

Heo J et al. 2009. Feeding a diet with decreased protein content reduces indices of protein fermentation and the incidence of postweaning diarrhea in weaned pigs challenged with an enterotoxigenic strain of Escherichia coli. J Anim Sci. 87: 2833–2843. https://doi.org/10.2527/jas.2008-1274

Heo JM et al. 2010. Effects of dietary protein level and zinc oxide supplementation on the incidence of post-weaning diarrhoea in weaner pigs challenged with an enterotoxigenic strain of Escherichia coli. Livest Sci. 133:210–213. https://doi.org/10.1016/j.livsci.2010.06.066

Ishida A, Kyoya T, Nakashima K, Katsumata M. 2011. Muscle protein metabolism during compensatory growth with changing dietary lysine levels from deficient to sufficient in growing rats. J Nutr Sci Vitaminol (Tokyo). 57:401–408. https://doi.org/10.3177/jnsv.57.401

Ishida A, Kyoya T, Nakashima K, Katsumata M. 2012. Nitrogen balance during compensatory growth when changing the levels of dietary lysine from deficiency to sufficiency in growing pigs. Anim Sci J. 83:743–749. https://doi.org/10.1111/j.1740-0929.2012.01018.x

Kasper C, Schlegel P, Ruiz-Ascacibar I, Stoll P, Bee G. 2021. Accuracy of predicting chemical body composition of growing pigs using dual-energy X-ray absorptiometry. Animal. 15: 100307. https://doi.org/10.1016/j.animal.2021.100307

Le Bellego L, Noblet J. 2002. Performance and utilization of dietary energy and amino acids in piglets fed low protein diets. Livest Prod Sci. 76:45–58. https://doi.org/10.1016/S0301-6226(02)00008-8

Liao SF, Wang T, Regmi N. 2015. Lysine nutrition in swine and the related monogastric animals: muscle protein biosynthesis and beyond. Springerplus. 4:147. https://doi.org/10.1186/s40064-015-0927-5

Liu R, He J, Ji X, Zheng W, Yao W. 2021. A moderate reduction of dietary crude protein provide comparable growth performance and improve metabolism via changing intestinal microbiota in Sushan nursery pigs. Animals (Basel). 11. https://doi.org/10.3390/ani11041166

Downloaded from academic.oup.com/jas/article/doi/10.1093/jas/skag279/8778564 by Bibliothek am Guisanplatz user on 16 November 2026

Lodge G, Sarkar N, Friend D. 1977. Hyperplasic and hypertrophic growth in brain, liver and muscle of undernourished suckled pigs. J Anim Sci. 45:1346–1352. https://doi.org/10.2527/jas1977.4561346x

Lynegaard J et al. 2021a. Low protein diets without medicinal zinc oxide for weaned pigs reduced diarrhea treatments and average daily gain. Animal. 15:100075. https://doi.org/10.1016/j.animal.2020.100075

Lynegaard JC et al. 2021b. A very low CP level reduced diarrhoea and productivity in weaner pigs, but no differences between post-weaning diets including soybean meal or soy protein concentrate were found. Animals. 11:678. https://doi.org/10.3390/ani11030678

Martínez-Ramírez HR, Jeaurond EA, De Lange CFM. 2008b. Dynamics of body protein deposition and changes in body composition after sudden changes in amino acid intake: II. Entire male pigs. J Anim Sci. 86:2168–2179. https://doi.org/10.2527/jas.2007-0236 18441077

Martínez-Ramírez HR, Jeaurond EA, De Lange CFM. 2008a. Dynamics of body protein deposition and changes in body composition after sudden changes in amino acid intake: I. Barrows. J Anim Sci. 86:2156–2167. https://doi.org/10.2527/jas.2007-0235 18441081

Mavromichalis I, Webel DM, Emmert JL, Moser RL, Baker DH. 1998. Limiting order of amino acids in a low-protein corn-soybean meal-whey-based diet for nursery pigs. J Anim Sci. 76:2833–2837. https://doi.org/10.2527/1998.76112833x

McCracken BA, Gaskins HR, Ruwe-Kaiser PJ, Klasing KC, Jewell DE. 1995. Diet-dependent and diet-independent metabolic responses underlie growth stasis of pigs at weaning. J Nutr. 125:2838–2845. https://doi.org/10.1093/jn/125.11.2838

Menegat MB et al. 2020. A review of compensatory growth following lysine restriction in grow-finish pigs. Transl Anim Sci. 4:txaa014. https://doi.org/10.1093/tas/txaa014

Merlot E, Meunier-Salaün M-C, Prunier A. 2004. Behavioural, endocrine and immune consequences of mixing in weaned piglets. Appl Anim Behav Sci. 85:247–257. https://doi.org/10.1016/j.applanim.2003.11.002

National Research Council. 2012. Nutrient requirements of swine. 11th rev. ed. National Academy Press.

Noblet J, Bontems V, Tran G. 2003. Estimation de la valeur énergétique des aliments pour le porc. INRA Prod Anim. 16:197–210. https://doi.org/10.20870/productions-animales.2003.16.3.3660

O'Connell MK, Lynch PB, O'Doherty JV. 2006. The effect of dietary lysine restriction during the grower phase and subsequent dietary lysine concentration during the realimentation phase on the performance, carcass characteristics and nitrogen balance of growing–finishing pigs. Livest Sci. 101:169–179. https://doi.org/10.1016/j.livprodsci.2005.11.024

Peng X et al. 2016. Effects of low-protein diets supplemented with indispensable amino acids on growth performance, intestinal morphology and immunological parameters in 13 to 35 kg pigs. Animal. 10:1812–1820. https://doi.org/10.1017/S1751731116000999

Pieper R et al. 2016. Health relevance of intestinal protein fermentation in young pigs. Anim Health Res Rev. 17:137–147. https://doi.org/10.1017/S1466252316000141

Pluske JR et al. 2007. Piglet growth before and after weaning in relation to a qualitative estimate of solid (creep) feed intake during lactation: a pilot study. Arch Anim Nutr. 61:469–480. https://doi.org/10.1080/17450390701664249

R Core Team. 2024. R: A Language and Environment for Statistical Computing. Version 4.4.2. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Vodolazska D, Feyera T, Foldager L, Lauridsen C. 2023. The influence of supplementary feeding during suckling and later weaning on growth performance, incidences of post-weaning diarrhoea and immunity of piglets. Livest Sci. 276:105321. https://doi.org/10.1016/j.livsci.2023.105321

Wellington MO et al. 2023. The effect of supplementation of essential amino acid combinations in a low crude protein diet on growth performance in weanling pigs. Transl Anim Sci. 7:txad008. https://doi.org/10.1093/tas/txad008

Whang K, Kim S, Donovan S, McKeith F, Easter R. 2003. Effects of protein deprivation on subsequent growth performance, gain of body components, and protein requirements in growing pigs. J Anim Sci. 81:705–716.https://doi.org/10.2527/2003.813705x

Downloaded from academic.oup.com/jas/article/doi/10.1093/jas/skag279/8778564 by Bibliothek am Guisanplatz user on 16 November 2026

© The Author(s) 2026. Published by Oxford University Press on behalf of the American Society of Animal Science.
This is an Open Access article distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs licence (https://creativecommons.org/licenses/by-nc-nd/4.0/), which permits non-commercial reproduction and distribution of the work, in any medium, provided the original work is not altered or transformed in any way, and that the work is properly cited. For commercial re-use, please contact reprints@oup.com for reprints and translation rights for reprints. All other permissions can be obtained through our RightsLink service via the Permissions link on the article page on our site—for further information please contact journals.permissions@oup.com.
Journal of Animal Science, 2026, 104, 1–10
https://doi.org/10.1093/jas/skag279
Non Ruminant Nutrition