DETERMINATION OF THE OPTIMAL STANDARD ILEAL DIGESTIBLE ARGININE-TO-LYSINE RATIO IN NURSERY PIGS WEIGHING BETWEEN 6 AND 13 KG

Elevated Standard Ileal Digestible Arginine:Lysine Ratios Beyond NRC (2012): Enhancing Nursery Pig Growth Performance

ABSTRACT

Arginine (Arg) is recognized as a conditionally essential amino acid (EAA) for swine, meaning its dietary supplementation becomes necessary when endogenous synthesis is insufficient to meet physiological demands for growth and other biological processes. However, limited research has been conducted to establish the standardized ileal digestible (SID) Arg requirement relative to lysine (Lys) in young pigs. This study aimed to identify the optimal SID Arg:Lys ratio for growth performance in nursery pigs weighing 6 to 13 kg. A total of 480 newly weaned pigs, starting at an average body weight (BW) of 6.20 ± 0.61 kg, were utilized in a dose-response trial to evaluate the effects of increasing dietary SID Arg:Lys ratios on growth performance. Experimental diets were provided in two phases (day 0–10 and 10–27), with dietary adjustments to meet the pigs' Lys needs. Pigs and feeders were weighed at the beginning and end of each phase to calculate average daily gain (ADG), average daily feed intake (ADFI), and feed efficiency (G:F). Data analysis, based on linear regression, assessed the linear and quadratic effects of SID Arg:Lys and initial BW. From day 0 to 27, SID Arg:Lys demonstrated a quadratic effect on ADFI *(P = 0.058)*, with the maximum feed intake observed at 97.00 ± 7.63% SID Arg:Lys. Similarly, ADG was maximized at 95.65 ± 7.17% SID Arg:Lys *(P = 0.046)*, with corresponding effects on BW by day 27 *(P = 0.014)*. These trends persisted throughout the study, with quadratic effects observed on ADFI (*P = 0.006*), ADG *(P = 0.077)*, and BW on day 41 *(P = 0.028)*. However, no significant effects of SID Arg:Lys were noted on G:F across the trial (*P ≥ 0.315*). In conclusion, SID Arg:Lys ratios had a quadratic impact on ADFI and ADG in nursery pigs, with optimal values of 97.00% and 95.65%, respectively. These findings suggest a minimum SID Arg:Lys requirement of 81%, based on the lower bounds of the 95% confidence interval for maximum ADG and ADFI.

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Keyword Amino acids, Arginine, Swine, Weaning, Growth performance

Abbreviations AA amino acid, ADFI average daily feed intake, ADG average daily gain, BW body weight, CP crude protein, EAA essential amino acid, G:F gain-to-feed ratio, SID standardized ileal digestible

This article is an abbreviated article that has been published in Journal of Animal Science

Humphrey, D.[1], Hagen, C.[1], Wileman, C.[1], Putnam, M.[1], Haydon, K.[2] and Greiner, L.[1], (2024). Effect of standardized ileal digestible arginine:lysine on growth performance of 6- to 13-kg nursery pigs. Journal of Animal Science, 102.*

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BACKGROUND

Arginine (Arg) is a conditionally essential amino acid (EAA) in swine, typically assumed to meet physiological demands through dietary intake and endogenous synthesis under normal conditions (NRC, 2012). In pigs, Arg synthesis in the liver via the urea cycle does not contribute to net Arg availability for extrahepatic tissues due to its hydrolysis by arginase (Wu and Morris, 1998). Instead, the primary source of endogenous Arg production is the intestinal-renal axis, where citrulline synthesized in the small intestine is converted to Arg in the kidneys via arginosuccinate synthetase and arginosuccinate lyase (Brosnan and Brosnan, 2004).

Although Arg is essential for neonatal pigs due to its limited presence in sow milk, it is often considered non-essential in post-weaned pigs (Wu et al., 2007b). However, during periods of rapid growth or when dietary Arg intake is marginal, endogenous synthesis may be insufficient to support optimal growth.

Modern swine nutrition emphasizes precision, including crystalline forms of EAAs such as lysine (Lys), threonine (Thr), tryptophan (Trp), methionine (Met), isoleucine (Ile), and valine (Val). While this approach reduces crude protein levels, it can inadvertently neglect conditionally essential AAs like Arg. The NRC (2012) estimates SID Arg requirements for 5–7 kg and 7–11 kg pigs as 1.8 g/d and 2.9 g/d, corresponding to SID Arg:Lys ratios of 45–46%. These values are based on Southern and Baker (1983), who observed linear improvements in growth with up to 0.48% bioavailable Arg but no additional benefits at higher levels.

Despite the NRC (2012) recommendations, Arg supplementation above these levels has been associated with various benefits in nursery pigs. Specifically, dietary supplementation of 0.6% to 1% Arg in young pig diets has been shown to improve growth performance (Hernandez et al., 2009; Wu et al., 2010b; Yun et al., 2020), enhance intestinal development and morphology (Zhan et al., 2008; Wu et al., 2010b; Yao et al., 2011; Zheng et al., 2017), and reduce inflammatory responses (Yao et al., 2011; Zheng et al., 2017). Furthermore, under challenging conditions, such as a deoxynivalenol-contaminated diet (6 mg/kg), Arg supplementation has been reported to significantly enhance amino acid utilization while decreasing circulating pro-inflammatory cytokines (Wu et al., 2013, 2015).

However, excessive Arg supplementation has been shown to negatively impact pig performance in some studies (Southern and Baker, 1982; Hagemeier et al., 1983; Anderson et al., 1984; Greiner et al., 2023). These adverse effects are influenced by the balance between Arg and Lys, as excessive Arg levels (1.94% to 3.27% total Arg, or 1.63% total Arg combined with 1.03% Lys) have been associated with impaired growth performance in pigs (Southern and Baker, 1982; Hagemeier et al., 1983).

To date, no research has specifically investigated the SID Arg requirement relative to Lys in young pigs. Given the potential for improved growth performance when feeding SID Arg:Lys ratios exceeding NRC (2012) recommendations, this study hypothesized that higher SID Arg:Lys levels would positively influence growth in nursery pigs.

This study was designed to determine the optimal SID Arg:Lys ratio for maximizing nursery pig growth, thereby establishing a foundation for more precise feed formulations and enhanced nutrient utilization in modern swine production.

MATERIAL AND METHODS

Animals, experimental design, diets, and growth performance

The experiment was conducted at the Iowa State Swine Nutrition Farm (Ames, IA). Four hundred eighty newly weaned pigs (PIC 337 × 1050, PIC Genus, Hendersonville, TN) with an initial BW of 6.2 ± 0.61 kg were randomly placed into 48 pens with five barrows and five gilts per pen.

Upon placement, pens were randomly assigned to one of six dietary treatments (n = 8) according to a completely randomized design. Pigs and feeders were weighed on days 0, 10, 27, and 41 of the trial to calculate ADG, ADFI, and G:F.

The experimental diets were formulated in a dose titration with increasing SID Arg:Lys by replacing corn starch, glycine, and l-alanine with l-arginine. The SID Arg:Lys levels of the experimental diets were equally spaced and ranged from 45% to 145%. The lowest SID Arg:Lys level evaluated corresponded to the NRC (2012) estimated requirement. The experimental diets were also supplemented with L-Lys HCl, L-Phe, L-Thr, L-Tyr, L-Met, L-Val, L-His HCl, L-Ile, and L-Trp. To appropriately evaluate arginine levels relative to lysine, the diets were formulated to be sub-limiting in SID Lys and exceed NRC (2012) and genetic supplier recommendations for all other EAAs (Boisen, 2003). Additionally, diets were formulated to be isocaloric and isonitrogenous through the inclusion of Gly, L-Ala, and cornstarch. Vitamin and mineral levels met or exceeded NRC (2012) recommendations.

The experimental diets were fed in two feeding phases, with phase one diets being fed from day 0 to 10 and phase two diets being fed from days 10 to 27. The same SID Arg:Lys levels were maintained across phases one and two, with Lys levels being adjusted according to the pigs' requirements. Following phases 1 and 2, all pigs were placed on a common diet for the remainder of the study (days 27 to 41) to evaluate the carryover effects of the experimental diets through the end of the nursery period Table 1.

Table 1 Calculated SID Arg:Lys ratio experimental diets phase 1, 2 and 3

Treatment	45	65	85	105	125	145
Phase 1	0.45	0.65	0.85	1.05	1.25	1.45
Phase 2	0.45	0.65	0.85	1.05	1.25	1.45
Phase 3			0.91			

Statistical analysis

Growth performance data were analyzed according to the following linear model:

$$yi=\beta_0+\beta_1 xi1+\beta_{2xi1}{}^2+\beta_{3xi2}+\varepsilon i$$

Where yi is the response (ADG, ADFI, G:F) of the ith pen, β_0 is the intercept term, β_1 is the estimated linear coefficient for SID Arg:Lys, β_2 is the estimated quadratic coefficient for SID Arg:Lys, β_3 is the estimated coefficient for initial BW, and εi is the random error associated with yi, assuming εi~N(0,Iσε2). Linear-plateau and quadratic-plateau models were also evaluated; however, due to the quadratic nature of the response, these models did not converge. The linear regression models were fit using the lm function in R version 4.3.1 (R Core Team, 2023). Variance homogeneity was assessed using the Breusch–Pagan test (ncvTest, car v3.1.2). Studentized residuals (studres, MASS v7.3.60.2) were checked for normality (Shapiro–Wilk), and residual plots confirmed assumptions; values >3 SD were excluded. Model fit was evaluated via an omnibus F-test, RMSE, and R^2. The pen was the experimental unit, with significance at $P \le 0.05$ (trend: $0.05 < P \le 0.10$). Regression curves were generated using ggplot (v3.5.2)For models where the quadratic coefficient $P \le 0.10$, the SID Arg:Lys level that maximized the regression curve (Arg:Lysmax) was calculated through differentiation with respect to SID Arg:Lys, yielding the following equation:

$$\text{SID Arg:Lys}_{max} = (-\beta_1)/2\beta_2$$

The variance and corresponding standard error and 95% confidence intervals for SID Arg:Lys max were then calculated using the Delta Method.

RESULTS

The pigs began the study with BW of 6.20 ± 0.611 kg and concluded the trial on day 41 with a final BW of 21.17 ± 1.864 kg. According to the observed data Table 2, pigs fed diets formulated with either 45% or 145% SID Arg:Lys ratios exhibited numerically lower mean BW, ADG, and ADFI during both the experimental feeding period (days 0 to 27) and the entire study duration (days 0 to 41). In contrast, pigs receiving SID Arg:Lys ratios ranging from 65% to 125% demonstrated performance metrics that were more consistent with each other.

Table 2 Observed performance of nursery pigs fed increasing levels of SID Arg:Lys[1)]

Treatment[2)]	45	65	85	105	125	145
BW day 0, kg	6.26 (0.617)	6.27 (0.730)	6.41 (0.807)	6.02 (0.557)	6.25 (0.577)	6.01 (0.403)
Experimental diet period (days 0 to 27)						
BW day 27, kg	12.36 (1.692)	13.18 (1.593)	13.13 (1.513)	13.01 (1.027)	12.87 (1.062)	12.17 (0.896)
ADG, kg	0.22 (0.046)	0.25 (0.039)	0.24 (0.027)	0.24 (0.026)	0.24 (0.024)	0.22 (0.032)
ADFI, kg	0.31 (0.057)	0.35 (0.062)	0.34 (0.040)	0.34 (0.033)	0.33 (0.028)	0.31 (0.034)
G:F	0.70 (0.036)	0.72 (0.033)	0.71 (0.019)	0.72 (0.018)	0.73 (0.043)	0.70 (0.072)
SID Arg intake, g/d	1.79 (0.320)	2.86 (0.504)	3.65 (0.427)	4.55 (0.408)	5.25 (0.424)	5.78 (0.629)
Common diet period (days 27 to 41)						
BW day 41, kg	20.32 (2.483)	21.59 (2.360)	21.22 (1.595)	22.04 (1.469)	21.45 (1.574)	20.42 (1.333)
ADG, kg	0.57 (0.074)	0.60 (0.074)	0.57 (0.051)	0.63 (0.034)	0.61 (0.045)	0.58 (0.064)
ADFI, kg	0.84 (0.084)	0.85 (0.116)	0.85 (0.065)	0.91 (0.041)	0.86 (0.057)	0.82 (0.053)
G:F	0.68 (0.051)	0.70 (0.041)	0.67 (0.049)	0.70 (0.034)	0.71 (0.014)	0.70 (0.067)
Overall period (days 0 to 41)						
ADG, kg	0.34 (0.053)	0.37 (0.046)	0.35 (0.024)	0.37 (0.028)	0.36 (0.033)	0.33 (0.025)
ADFI, kg	0.49 (0.063)	0.52 (0.070)	0.51 (0.034)	0.53 (0.038)	0.51 (0.037)	0.48 (0.029)
G:F	0.69 (0.037)	0.71 (0.030)	0.69 (0.027)	0.70 (0.016)	0.71 (0.024)	0.70 (0.042)

1) A total of 480 pigs across 48 pens (10 pigs/pen) with eight pens per treatment.
2) Data reported as observed mean (standard deviation).

Table 3 provides the predicted performance means and standard errors for nursery pigs based on quadratic regression models adjusted for the average initial BW (6.20 kg). The predicted trends closely align with the observed data, though the variation explained by the models differed across performance metrics, as shown in Table 4. From days 0 to 27, there was a tendency for a quadratic effect of SID Arg:Lys on ADFI (*P = 0.058;* Table 3), with predicted ADFI reaching its maximum at a SID Arg:Lys ratio of 97.00 ± 7.631% (95% CI: [81.6%, 112.4%]; Table 4).

Table 3 Predicted performance of nursery pigs fed increasing levels of SID Arg:Lys estimated from the fitted quadratic regression models[1)]

	Dietary SID Arg:Lys, %2,3						P value		
Treatment[2),3)]	45	65	85	105	125	145	Arg:Lys	Arg:Lys2	Initial BW
BW day 0, kg	6.26 (0.198)	6.28 (0.121)	6.27 (0.133)	6.22 (0.133)	6.14 (0.121)	6.03 (0.198)	0.373	0.637	–
Experimental diet period (days 0 to 27)									
BW day 27, kg	12.35 (0.244)	12.82 (0.150)	13.07 (0.164)	13.09 (0.164)	12.89 (0.149)	12.47 (0.246)	0.718	0.014	<0.001
ADG, kg	0.22 (0.009)	0.24 (0.005)	0.24 (0.006)	0.24 (0.006)	0.24 (0.005)	0.22 (0.009)	0.928	0.046	<0.001
ADFI, kg	0.32 (0.011)	0.33 (0.007)	0.34 (0.008)	0.34 (0.007)	0.33 (0.007)	0.32 (0.011)	0.792	0.058	<0.001
G:F	0.71 (0.010)	0.71 (0.006)	0.72 (0.007)	0.72 (0.006)	0.71 (0.006)	0.71 (0.011)	0.976	0.315	0.676
SID Arg intake, g/d	1.75 (0.110)	2.80 (0.068)	3.72 (0.074)	4.52 (0.074)	5.19 (0.069)	5.73 (0.117)	<0.001	0.003	<0.001
Common diet period (days 27 to 41)									
BW day 41, kg	20.25 (0.459)	21.12 (0.282)	21.62 (0.309)	21.73 (0.308)	21.46 (0.281)	20.82 (0.462)	0.358	0.028	<0.001
ADG, kg	0.57 (0.020)	0.59 (0.012)	0.60 (0.013)	0.61 (0.013)	0.60 (0.012)	0.58 (0.020)	0.485	0.149	0.557
ADFI, kg	0.82 (0.020)	0.86 (0.012)	0.89 (0.013)	0.89 (0.013)	0.87 (0.012)	0.83 (0.019)	0.791	0.005	0.127
G:F	0.68 (0.013)	0.68 (0.008)	0.69 (0.009)	0.69 (0.009)	0.70 (0.008)	0.71 (0.014)	0.103	0.605	0.195
Overall period (days 0 to 41)									
ADG, kg	0.34 (0.011)	0.36 (0.007)	0.36 (0.007)	0.36 (0.007)	0.36 (0.007)	0.35 (0.011)	0.751	0.077	0.007
ADFI, kg	0.48 (0.012)	0.50 (0.007)	0.52 (0.008)	0.52 (0.008)	0.51 (0.007)	0.49 (0.012)	0.637	0.006	<0.001
G:F	0.69 (0.010)	0.70 (0.006)	0.70 (0.007)	0.70 (0.007)	0.70 (0.006)	0.70 (0.010)	0.521	0.482	0.29

1) A total of 480 pigs across 48 pens (10 pigs/pen) with eight pens per treatment.
2) Data reported as predicted mean (standard error); SID Arg intake evaluated using calculated diet SID Arg:Lys values.
3) Initial BW in the regression models was set at the mean (6.20 kg).

Table 4 Model fit statistics and calculated maximum of quadratic regression curves

Item	R^2	RMSE	Omnibus F-test		SID Arg:Lys_{max}[1)]	S.E.	SID Arg:Lys_{max} 95% CI	
			F-statistic	P value			Lower limit	Upper limit
BW day 0, kg	0.023	0.598	0.52	0.599	–	–	–	–
Experimental diet period (day 0 to 27)								
BW day 27, kg	0.69	0.728	32.59	<0.001	97.09	5.834	85.34	108.85
ADG, kg	0.371	0.026	8.63	<0.001	95.65	7.165	81.21	110.09
ADFI, kg	0.416	0.033	10.43	<0.001	97	7.632	81.62	112.39
G:F	0.027	0.029	0.39	0.759	–	–	–	–
Common diet period (days 27 to 41)								
BW day 41, kg	0.449	1.369	11.94	<0.001	101	6.986	86.92	115.07
ADG, kg	0.065	0.058	1.02	0.395	–	–	–	–
ADFI, kg	0.224	0.056	4.04	0.013	96.34	5.026	86.19	106.48
G:F	0.115	0.04	1.86	0.15	–	–	–	–
Overall period (days 0 to 41)								
ADG, kg	0.218	0.033	4.08	0.012	97.59	8.267	80.93	114.25
ADFI, kg	0.376	0.035	8.64	<0.001	97.41	5.113	87.1	107.72
G:F	0.047	0.03	0.73	0.54	–	–	–	–

1) Calculated maximum of quadratic regression curve. Maximum of the curve was calculated when quadratic coefficient $P \leq 0.1$.

The estimated regression equation for ADFI (days 0 to 27; Figure 1) was

$$\text{ADFI, kg/d} = -0.0139 + 0.1901(\text{Arg : Lys}) - 0.0980(\text{Arg : Lys})^2 + 0.0426(\text{initial BW, kg})$$

In the equation, SID Arg:Lys is expressed as a proportion (e.g., 0.45) rather than a percentage. This pattern persisted throughout the study, resulting in a significant quadratic effect of SID Arg:Lys on overall ADFI (days 0 to 41; *P = 0.006*), with maximum ADFI predicted at a SID Arg:Lys of 97.41 ± 5.113% (95% CI: [87.1%, 107.7%]). Similarly, a quadratic effect of SID Arg:Lys on ADG was observed during days 0 to 27 (*P = 0.046*), with predicted ADG peaking at a SID Arg:Lys of 95.65 ± 7.165% (95% CI: [81.2%, 110.1%]).

The estimated regression equation for ADG (days 0 to 27; Figure 2) was

$$\text{ADG, kg/d} = -0.0136 + 0.1564(\text{Arg : Lys}) - 0.0817(\text{Arg : Lys})^2 + 0.0296(\text{initial BW, kg})$$

Also, there was a tendency for a quadratic effect of SID Arg:Lys on overall ADG (days 0 to 41; *P = 0.077*), with predicted ADG peaking at a SID Arg:Lys of 97.59 ± 8.267% (95% CI: [80.9%, 114.3%]). Additionally, on day 27, a significant quadratic effect of SID Arg:Lys on pig BW was observed (*P = 0.014*), with predicted BW reaching its maximum at a SID Arg:Lys of 97.09 ± 5.834% (95% CI: [85.3%, 108.9%]).

Figure 1 A quadratic regression model (R^2 = 0.416) estimated maximum ADFI at 97.00% SID Arg:Lys (95% CI: [81.6%, 112.4%]) for 6- to 13-kg nursery pigs (days 0–27), with initial BW set at 6.20 kg

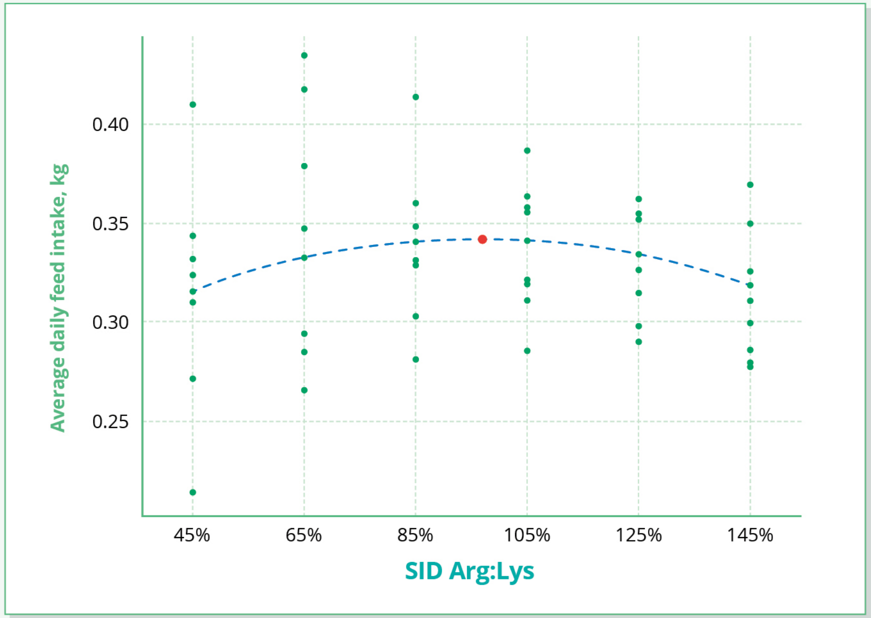
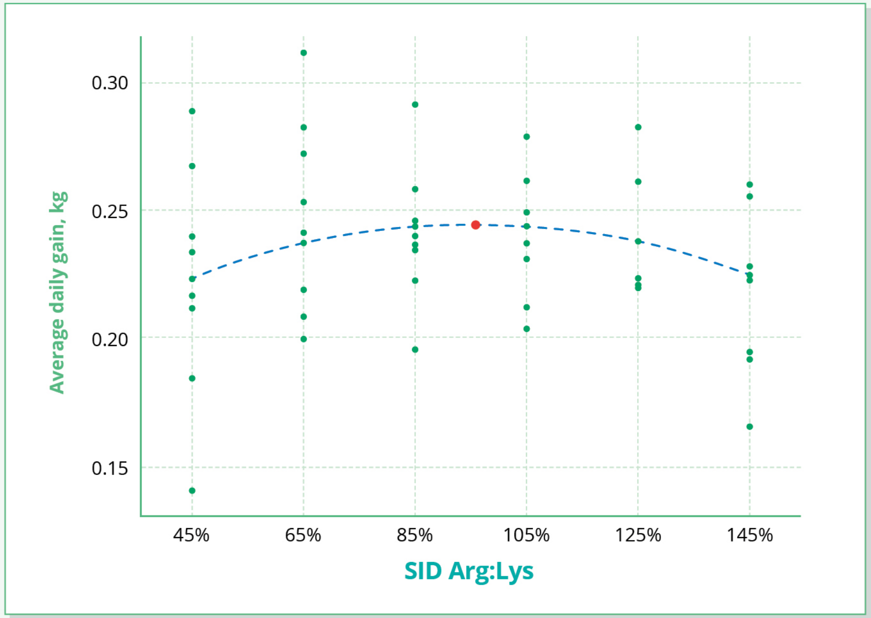


Figure 2 A quadratic regression model (R^2 = 0.371) estimated maximum ADG at 95.65% SID Arg:Lys (95% CI: [81.21%, 110.09%]) for 6- to 13-kg nursery pigs (days 0–27), with initial BW set at 6.20 kg

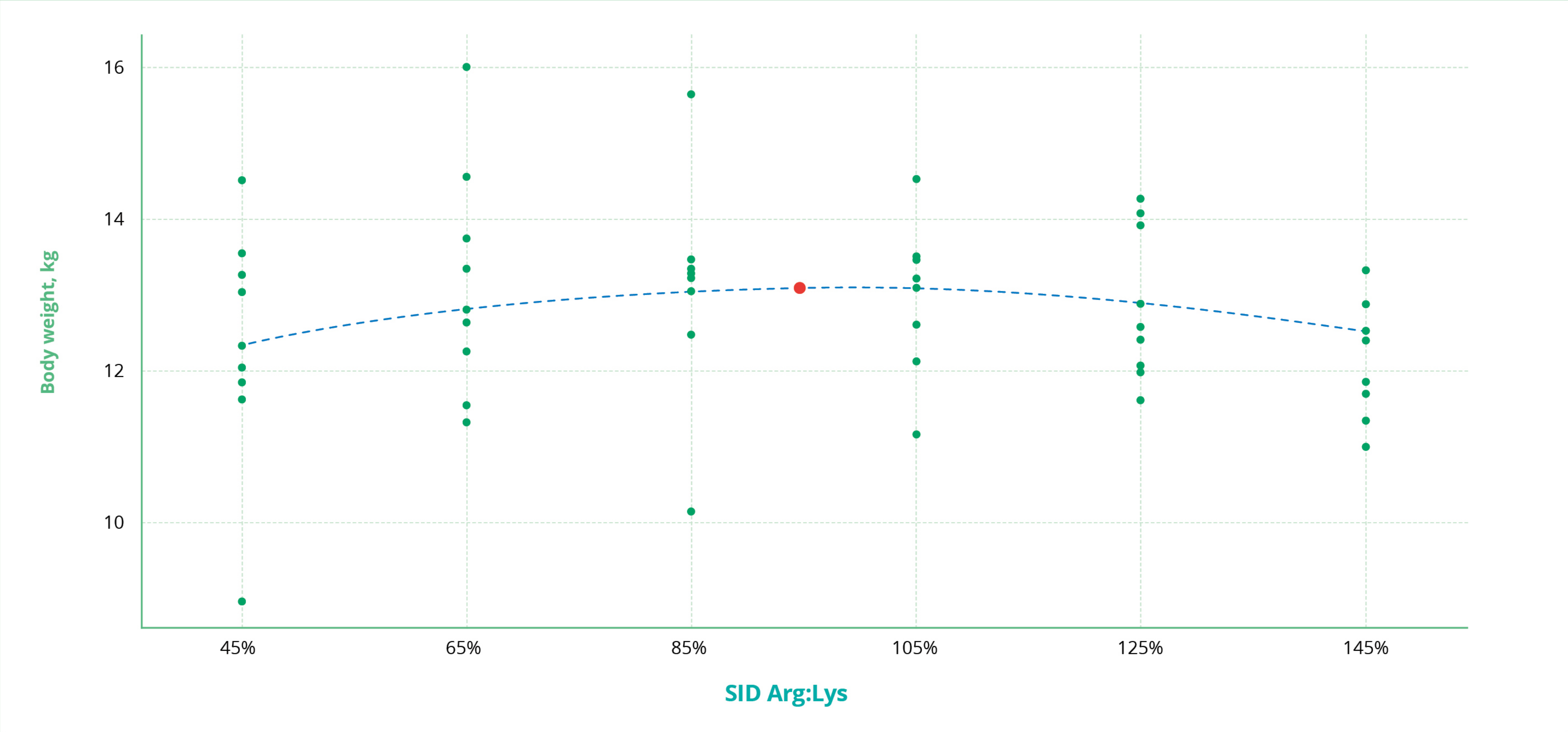


The estimated regression equation for BW on day 27 Figure 3 was

$$BW, kg = -0.1216 + 5.4537(Arg : Lys) - 2.8084(Arg : Lys)^2 + 1.7074(initial BW, kg)$$

These effects persisted through the end of the study on day 41, with a significant quadratic relationship observed for BW (*P = 0.028*), where the predicted BW was maximized at a SID Arg:Lys of 101.00 ± 6.986% (95% CI: [86.9%, 115.1%]). However, there was no evidence of an effect of SID Arg:Lys on G:F throughout the study (*P ≥ 0.315*).

Figure 3 **A quadratic regression model (R^2 = 0.690) estimated maximum BW on day 27 at 97.09% SID Arg:Lys (95% CI: [85.34%, 108.85%]) for nursery pigs, with initial BW set at 6.20 kg**



DISCUSSION

The NRC (2012) classified Arg as a conditionally EAA, meaning its utilization rate can exceed endogenous synthesis under certain conditions, necessitating dietary supplementation for optimal growth. The ability for endogenous Arg synthesis varies with age. In neonatal pigs, it primarily occurs in the small intestine, where proline and glutamine are converted to citrulline and subsequently to Arg through arginosuccinate synthetase and lyase (Wu and Knabe, 1995; Bertolo et al., 2003; Brosnan and Brosnan, 2004). In post-weaned pigs, however, enterocyte arginosuccinate lyase activity decreases (Wu and Knabe, 1995), and high arginase activity leads to the catabolism of approximately 40% of absorbed Arg (Wu et al., 2007a). Consequently, endogenous Arg synthesis shifts to the kidney, using citrulline derived from the intestine—referred to as the intestinal-renal axis (Wu et al., 2018). Despite this capability, little research has been conducted to determine the optimal dietary Arg level for maximizing growth. Thus, this study aimed to quantify the dietary SID Arg level required for nursery pigs.

Determining AA requirements depends on experimental design and diet formulation. Following the ideal protein concept, requirements are often expressed relative to Lys, which must be the second-limiting AA behind the one of interest (Boisen, 2003). In this study, SID Lys levels were set below NRC (2012) recommendations for nursery pigs, while other EAAs exceeded requirements, ensuring Lys was second limiting. Gly and Ala were added as nonspecific nitrogen sources to maintain isonitrogenous diets and prevent growth effects unrelated to Arg supplementation.

The NRC (2012) estimated the SID Arg requirement for 5–7 kg and 7–11 kg pigs at 1.8 g/d (SID Arg:Lys 45%) and 2.9 g/d (SID Arg:Lys 46%), respectively. However, this study estimated that the SID Arg:Lys requirement to maximize feed intake and growth in 6–13 kg pigs lies between 81% and 112% (95% confidence interval), which is nearly double NRC (2012) recommendations and aligns with Wu (2014).

Several studies have reported improved growth performance in nursery pigs with dietary Arg supplementation (e.g., Greiner et al., 2023; Perez-Palencia et al., 2024). Greiner et al. (2023) observed optimal feed intake, growth, and efficiency at 1.55% SID Arg (103–109% SID Arg:Lys), consistent with this study's findings. Similarly, Perez-Palencia et al. (2024) reported linear improvements in growth and feed intake in newly weaned pigs fed diets with higher SID Arg levels. All the evidence supports feeding higher Arg levels than NRC (2012) recommendations to improve growth performance in nursery pigs.

DECLARATIONS

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Funding

Keith Haydon is an employee of CJ America—Bio. CJ America—Bio provided financial support for this project.

Acknowledgements

The authors would like to acknowledge individuals at Iowa State University for their assistance with the live animal portion of the project, which includes Trey Faaborg, Mariah Meyer, Ayva Bohr, and the Iowa State Swine Nutrition Farm staff. This project was fully funded by CJ America—Bio. The assigned grant number for the project was GR-027949-00001.

CONCLUSIONS

SID Arg:Lys quadratically impacted ADFI and ADG in 6- to 13-kg nursery pigs, where ADFI was maximized at a SID Arg:Lys of 97.00%, and ADG was maximized at a SID Arg:Lys of 95.65.