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Effects of dietary SID lysine content on growth performance, feeding costs, and nitrogen excretion of growing and finishing pigs

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ABSTRACT

This study evaluated the effects of different SID lysine levels on growth performance, feed costs, and nitrogen excretion of growing pigs raised for dry-cured ham production. Ninety-six Goland-C21 × Camborough-43 pigs (initial body weight, BW: 44.5 ± 3.8 kg) were allocated to four dietary treatments (2 pens/treatment, 12 pigs/pen) with low (L: 6.9, 6.0, 4.2 g/kg), medium-low (ML: 7.8, 6.9, 5.2 g/kg), medium-high (MH: 8.3, 7.8, 6.0 g/kg), or high (H: 9.3, 8.3, 6.9 g/kg) SID lysine across the growing (90–118 days), early finishing (119–132 days), and late finishing (133–233, days) phases. Automated feeding stations recorded individual feed intake. Backfat (BF) thickness and BW were measured at five time points. Nitrogen excretion was estimated from intake, retention, and atmospheric losses. Data were analysed using the PROC MIXED procedure in SAS; the model included dietary treatment, sex, and their interaction as fixed effects and pen nested within treatment as a random effect. Compared with L pigs, ML pigs showed similar feed intake and final BF depth but achieved higher ($p < .05$) final BW, greater average daily gain, and improved gain-to-feed ratio, while reducing feed costs (€1.63 vs €1.77 per kg BW gain) without increasing nitrogen excretion. Growth performance of ML pigs was comparable to that of MH and H pigs; however, ML diets resulted in the lowest feed costs and nitrogen excretion. These findings suggest that a medium-low SID lysine diet is sufficient for this pig population, effectively supporting growth performance while reducing feeding costs and environmental impact.

HIGHLIGHTS

- The effects of varying SID lysine content in diets were studied in growing pigs until heavy body weight under ad libitum feed intake
- Decreasing SID lysine content from 7.8 to 5.2 g/kg from growing to finishing improved growth performance compared to diets with 15% lower contents
- Further increases in the SID lysine contents did not improve daily gain and feed efficiency, but increased feeding costs and N excretion

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Introduction

Nutrient recommendations are crucial for enhancing both the quantitative and qualitative aspects of production, optimising the use of economic and natural resources, and mitigating the environmental impact of swine production. It is well known that an insufficient intake of lysine negatively impacts growth rate and feed efficiency (Shelton et al. 2011; Ma et al. 2015; Song et al. 2022). On the other hand, an excess of dietary lysine may increase the feeding costs and nitrogen (N) excretion. Recommendations developed by various research institutions typically focused on fast-growing, lean pig genotypes that are primarily bred for fresh meat production, with slaughter body weight (BW) generally not exceeding 135 kg (van Milgen et al. 2008; NRC 2012; De Blas et al. 2013). However, such recommendations may not adequately address the requirements of pig chains focused on traditional products like dry-cured ham, which often involve heavier slaughter weights (up to 200 kg), older ages (up to nine months), and specific pig genotypes selected for preserving fat deposition and improving ham coverage (Latorre et al. 2004; Mondin et al. 2024).

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Consequently, pigs bred for dry-cured ham production are hypothesised to exhibit distinct traits compared to lean genotypes, such as higher voluntary feed intake and lower feed efficiency (Wecke and Liebert 2009), and these may affect the dietary SID lysine requirements. Data on the effects of varying dietary SID lysine content for heavy BW pigs, considering voluntary feed intake, growth performance, N retention and excretion, and feeding costs, is very limited (Schiavon et al. 2022, 2025). When lysine is the first limiting nutrient, a restriction below requirement reduces protein retention, thereby negatively impacting growth rate and feed efficiency (NRC 2012). On the other hand, excess lysine has a limited effect on protein retention or growth performance but increases nitrogen excretion proportionally relative to crude protein intake (Xiccato et al. 2005; NRC 2012). In previous research, we investigated the growth performance of purebred Goland-C21 pigs fed either ad libitum diets with excess amino acids or restricted diets insufficient in amino acids (Malgwi et al. 2021; Schiavon et al. 2022, 2025). Based on these studies, we hypothesised that Goland-C21 × Camborough-43 pigs would evidence greater feed intake and lower optimal dietary SID lysine content compared to the literature data on modern lean pigs. Therefore, the current research aimed to evaluate the impact of reduced dietary SID lysine content on voluntary feed intake, growth performance, N excretion, and feeding costs, contributing to the development of tailored nutritional strategies for this specific production system.

Material and methods

Animals, experimental design and diets

In the trial, 96 pigs (Goland-C21 × Camborough-43), 76 days old, with an average initial BW of 32 kg, were used.

The pigs were allotted into groups of 12 in 8 pens, 6 barrows and 6 gilts per pen, based on individual BW, to obtain pens characterised by similar average BW (range: 31.8 to 32.2 kg) and coefficient of variation of BW (range: 9.8 to 11.3%). Each pen (5.8 × 3.8 m with fully slatted floors; 1.57 m^2/pig) was equipped with an automated feeding station (Compident Pig–MLP, Schauer Agrotronic, Prambachkirchen, Austria) programmed to measure the individual feed intake of each pig, day by day, over the entire experimental period. Pigs had free access to drinking water throughout the whole experiment. Two collective straw feeders and two other enrichment tools (beech wood provided with a dispenser fastened to the wall and a hard plastic ball) were available in each pen. During a transition period of 14 days, planned to allow pigs to acclimate to herd conditions and feeding stations, all the pigs had free access to the same commercial feed.

At the end of the transition period, when pigs averaged 44.5 ± 3.8 kg BW, each pen was assigned to one of four dietary treatments (2 pens per treatment) differing for the SID lysine content within a feeding program based on 3 periods: growing (90–118 days), early finishing (119–146 days), and late finishing (147–233 days), as detailed in Table 1. In each period, the SID lysine requirements for increasing BW ranges estimated by Schiavon et al. (2025) for purebred Goland-C21 pigs were taken as a basis to formulate the dietary treatments. In the different periods, the pigs received feeds with the following amount of SID lysine: 9.3, 8.3, and 6.9 g/kg feed in the high (H) treatment; 8.3, 7.8, and 6.0 g/kg in the medium-high treatment (MH); 7.8, 6.9, and 5.2 g/kg in the medium-low treatment (ML); and 6.9, 6.0, and 4.2 g/kg in the low (L) treatment. Compared to the values proposed by Schiavon et al. (2025), SID lysine was supplied in excess in the H and MH treatments and in deficit in the ML and L treatments. Thus, seven feeds were formulated by replacing soybean meal with barley grain, reducing dietary SID lysine content from 9.3 to 4.2 g/kg feed (Tables 2 and 3). Care was taken to ensure that lysine was the first limiting nutrient according to NRC (2012). Feeds were manufactured by a commercial feed manufacturer (Neviani S.r.l., Montecchio Emilia, RE, Italy).

Pigs were individually weighed using an electronic scale at 90, 118, 146, 202, and 251 days of age. At the same intervals, backfat depth (BF) was measured using an A-mode ultrasonic device (Renco Lean-Meater Series

Table 1. Feeds distributed to the pigs of the high, medium-high, medium-low and low lysine treatments with increasing ages.

	Dietary treatments[a]			
Age interval, days	Low lysine[a]	Medium-low lysine[a]	Medium-high lysine[a]	High lysine[a]
90–118	Lys-6.9	Lys-7.8	Lys-8.3	Lys-9.3
119–146	Lys-6.0	Lys-6.9	Lys-7.8	Lys-8.3
147–202	Lys-4.2	Lys-5.2	Lys-6.0	Lys-6.9
202–251	Lys-4.2	Lys-5.2	Lys-6.0	Lys-6.9

[a]The number in the feed names represents the dietary SID lysine contents (g/kg, as-fed basis).

Table 2. Ingredient composition and cost of the experimental feeds.

	Feeds[a]						
Ingredient, g/kg as fed basis	Lys-4.2	Lys-5.2	Lys-6.0	Lys-6.9	Lys-7.8	Lys-8.3	Lys-9.3
Corn grain	450.0	450.0	450.0	450.0	450.0	450.0	450.0
Barley grain	449.0	410.0	365.0	320.0	275.0	230.0	185.0
Soybean meal (48% crude protein)	1.0	40.0	85.0	130.0	175.0	220.0	265.0
Wheat bran	70.0	70.0	70.0	70.0	70.0	70.0	70.0
Cane molasses	10.0	10.0	10.0	10.0	10.0	10.0	10.0
$CaCO_3$	11.5	11.5	11.5	11.5	11.5	11.5	11.5
NaCl	4.0	4.0	4.0	4.0	4.0	4.0	4.0
$CaHPO_4$	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Mineral-vitamin mixture[b]	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Lysine-HCl	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Sum	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0
Cost, euro/t	480	493	508	523	539	554	569

[a]The number in the feed names represents the dietary SID lysine contents (g/kg, as-fed basis).
[b]Providing per kilogram of feed: vitamin A, 8000 IU; vitamin D3, 1200 IU; vitamin E, 8 mg; Vitamin B7, 0.08 mg; vitamin B12, 0.012 mg; niacin, 16.0 mg; biotin, 8 mg; iron, 170 mg; zinc, 117 mg; copper, 14 mg; cobalt, 0.11 mg; iodine, 0.06 mg; manganese, 65 mg; magnesium, 0.14 mg; selenium 10 mg.

Table 3. Nutrient content of the experimental feeds (g/kg as fed, unless different specification).

	Feeds[a]						
	Lys-4.2	Lys-5.2	Lys-6.0	Lys-6.9	Lys-7.8	Lys-8.3	Lys-9.3
Dry matter	916	921	907	902	901	902	894
Metabolisable energy (ME), MJ/kg	12.6	12.5	12.5	12.4	12.4	12.3	12.3
Net energy[b] (NE), MJ/kg	9.2	9.2	9.3	9.3	9.4	9.4	9.5
Starch	538	517	494	471	449	426	404
Ether extract	33	32	31	30	29	28	27
Ash	37	39	40	42	44	46	48
NDF[c]	190	185	178	172	166	160	153
Crude protein	110	121	132	143	160	180	191
Analysed AA:							
Lysine	4.9	6.0	6.8	7.8	8.7	9.3	10.4
Methionine	2.2	2.1	2.3	2.4	2.5	2.6	2.9
Methionine + cysteine	4.8	4.9	5.0	5.4	5.7	5.9	6.2
Threonine	4.4	4.7	5.2	5.6	6.2	6.4	7.0
Tyrosine	3.6	4.0	4.4	4.8	5.3	5.6	6.3
Tryptophan	1.3	1.4	1.6	1.7	1.9	2.1	2.2
Histidine	3.3	3.5	3.7	4.1	4.4	4.7	5.1
Isoleucine	4.2	4.7	5.2	5.9	6.5	7.0	7.8
Leucine	10.1	10.7	11.4	12.3	13.3	13.9	15.2
Valine	6.0	6.5	6.8	7.4	8.0	8.4	9.1
Arginine	6.5	7.5	8.4	9.5	10.5	11.3	12.6
Phenylalanine	9.2	10.1	10.9	12.1	13.2	13.9	15.4
SID lysine[d]	4.2	5.2	6.0	6.9	7.8	8.3	9.3

[a]The number in the feed names represents the dietary SID lysine contents (g/kg, as-fed basis). All the dietary nutrients resulted from chemical analysis, unless different specified.
[b]The energy values of the feeds were computed from the tabular values of the ingredients reported by NRC (2012).
[c]NDF: neutral detergent fibre.
[d]Estimated from the analysed total lysine content and the SID:total lysine ratio as reported NRC (2012).

12, Renco Corporation, Minneapolis, MN, USA) as described by Malgwi et al. (2021). Measurements were taken at the last rib, approximately 5.5–8.0 cm from the midline, with the distance increasing with increasing BW.

During the experiment, two pigs were removed due to health issues, and all their data, including feed consumption, were excluded, leaving 94 records per trait for analysis.

Feeding costs and N balance

The feeding costs were calculated using the actual feed consumption and the feed prices (Bologna 2025) and were expressed per pig produced and per unit of BW gain.

The N balance was computed according to Xiccato et al. (2005). Briefly, the N consumption was derived from the feed intake of each diet and its corresponding N content, while N retention was estimated from body protein gain divided by 6.25. Body protein gain was computed from repeated measurements of body weight and backfat depth as described in Schiavon et al. (2022). The N excreted was calculated as the difference between N consumed and retained. The annual N excretion per herd pig place was computed based on the N excreted to produce a pig by the number of production cycles completed in a year. The cycle count was calculated as the ratio between 365 days and the total time required to achieve the full growth of a pig, plus a 21–day downtime allocated for technical and sanitary management between the end and the beginning of production cycles. This 21–day interval accounts for the necessary downtime for cleaning, disinfection, and other procedures required for optimal hygiene and disease prevention. Net N excretion was scaled per unit of annual BW gain, offering a precise measure of production efficiency and environmental impact.

Chemical analysis

Representative feed samples were collected during manufacturing, with ten samples pooled and mixed to obtain a 1–kg composite sample for analysis. The samples were analysed in duplicate according to AOAC (2003) for dry matter (DM; AOAC #934.01), nitrogen (N; AOAC #976.05), ether extract (EE; AOAC #920.29), ash (AOAC #942.05), and neutral detergent fibre with amylase treatment, including residual ash (aNDF; Van Soest et al. 1991). Starch content was determined *via* glucose hydrolysis using liquid chromatography (Bouchard et al. 1988).

The amino acid content of the feed samples was analysed, as detailed by Schiavon et al. (2022), following methods from the Council of Europe (2005) and Slump et al. (1991). The SID lysine content were estimated from the analytical values multiplied by the ratio between the SID and the total lysine content based on NRC (2012). Dietary metabolisable energy (ME) and net energy (NE) were computed from the actual ingredient composition of the feeds and the tabular values for each ingredient as reported by NRC (2012).

Statistical analysis

The required sample size was calculated *a priori* using the PROC GLMPOWER in SAS software (SAS Inst. Inc., Cary, NC, USA), and taking the average daily gain (ADG) as the representative parameter. Based on our previous experiment with a comparable genetic line fed ad libitum (Malgwi et al. 2021), we hypothesised an ADG of 805 g/d with a standard deviation of 190 g/d. A two-tailed test was performed with an α of 0.05 and a power of 0.90 (1 – β), based on a mean difference among treatment groups of 64 g/d. Under these conditions, the minimum sample size required to detect significant differences among treatments was 92 pigs (23 pigs per treatment). Therefore, to account for a potential 5% mortality rate, 96 animals were enrolled. Data were analysed with the MIXED procedure of SAS (SAS Inst. Inc., Cary, NC, USA) according to the following model:

$$y_{ijkl} = \mu + \text{treatment}_i + \text{sex}_j + (\text{treatment} \times \text{sex})_{ij} + \text{pen}(\text{treatment})_{k:i} + \varepsilon_{ijkl}$$

where y_{ijkl} was the observed trait; μ was the overall intercept of the model, treatment was the fixed effect of the ith treatment ($i = 1, \ldots, 4$); sex$_j$ was the fixed effect of the jth sex (j: 1 = barrow, 2 = gilt); (treatment × sex)$_{ij}$ was the interaction effect between treatment and sex; pen(treatment)$_{k:i}$ was the random effect of the kth pen within treatment, and ε_{ijkl} was the random residual error. The pen(treatment) and residual were assumed to be independent and normally distributed with a mean of zero and variances of $\sigma^2{}_k$, and $\sigma^2{}_l$, respectively. The effect of treatment was tested on the pen(treatment) variance, whereas sex and the treatment × sex interaction were tested on the residual variance. To evaluate treatment differences, pre-planned contrasts were performed. Specifically, contrasts were set to compare the ML treatment against L, MH, and H treatments. The ML treatment was selected as the reference for comparisons based on findings from our previous pilot studies (Schiavon et al. 2022, 2025). The level of significance was set at $p < .05$.

Results

Growth performance and feed intake

Pigs fed the L diet had lower body weight than those on the ML diet at day 202 ($p = .011$) and day 251 ($p = .005$), resulting in a final BW nearly 10% lower than ML-fed pigs at the end of the experiment (Table 4). Feeding treatment did not influence backfat depth, which increased from 7.2 mm to 28.7 mm.

Feed intake was not affected by dietary treatments, while voluntary feed consumption increased from 2590 g/d in the early growing period to 3041 g/d by the end of finishing. A peak intake of 3315 g/day occurred between 119 and 146 days, when pigs' BW ranged between 75 to 106 kg. The voluntary feed intake, expressed as daily ME intake, is shown in Figure 1.

Average daily gain increased from 1046 g/d in the first period to a peak value close to 1200 g/d until 146 days, and declined later, reaching nearly 660 g/d on average in the last period of the trial. Significant differences in ADG between ML and L pigs were detected on age intervals 119–146 days ($p = .024$), 147–202 days ($p = .006$), 203–251 days ($p = .026$) and overall ($p = .004$), while ML showed no difference from other treatments with higher dietary SID lysine content.

Table 4. Growth performance traits of pigs receiving feeds with different SID lysine content at different ages and sexes.

	Treatments[a]				SEM[b]	Contrast (*p*)			Sex		SEM	*p*
	L	ML	MH	H		ML vs L	ML vs MH	ML vs H	Gilts	Barrows		
BW[c], kg, at the age of:												
90 d	44.6	44.9	45.2	43.1	0.78	0.768	0.834	0.167	43.7	45.2	0.55	0.055
118 d	71.7	74.4	75.6	73.2	1.28	0.222	0.533	0.561	72.2	75.3	0.90	0.019
146 d	102.8	108.7	109.0	106.4	1.64	0.067	0.895	0.394	104.1	109.3	1.16	0.002
202 d	147.9	162.0	160.5	158.1	2.22	0.011	0.652	0.281	154.7	159.6	1.57	0.028
251 d	174.9	196.9	192.9	192.8	2.70	0.005	0.351	0.337	187.4	191.4	1.91	0.143
Average daily gain, g/d, at the age of:												
90–118 d	970	1052	1087	1077	28	0.108	0.420	0.551	1019	1074	20	0.051
119–146 d	1109	1224	1192	1186	23	0.024	0.373	0.301	1140	1215	16	0.001
147–202 d	806	953	920	923	19	0.006	0.296	0.335	902	898	14	0.838
203 –251 d	552	710	661	707	32	0.026	0.341	0.940	667	648	19	0.380
Overall	859	985	965	973	15	0.004	0.391	0.600	932	959	21	0.077
Feed intake, g/d, at the age of												
90–118 d	2532	2578	2693	2558	64	0.630	0.258	0.834	2477	2704	44	0.001
119–146 d	3249	3382	3368	3261	66	0.233	0.890	0.261	3083	3547	47	<0.001
147–202 d	3036	3141	3111	3103	61	0.299	0.740	0.681	2992	3203	43	0.001
203–251 d	2951	3117	3045	3051	56	0.109	0.410	0.445	2951	3131	40	0.002
Overall	2927	3052	3035	2993	49	0.153	0.827	0.446	2883	3121	35	<0.001
Gain:feed at the age of:												
90 –118 d	0.382	0.408	0.404	0.423	0.006	0.029	0.604	0.129	0.412	0.397	0.004	0.009
119 –146 d	0.342	0.363	0.356	0.366	0.005	0.031	0.303	0.682	0.370	0.344	0.003	<0.001
147–202 d	0.265	0.304	0.297	0.298	0.004	0.002	0.270	0.349	0.301	0.281	0.003	<.0001
203 –251 d	0.186	0.228	0.218	0.232	0.010	0.041	0.506	0.767	0.225	0.207	0.006	0.002
Overall	0.283	0.316	0.309	0.319	0.003	0.002	0.189	0.542	0.316	0.298	0.002	<0.001
Backfat depth, mm, at the age of:												
90 d	7.18	7.35	7.17	7.01	0.19	0.582	0.545	0.279	7.16	7.19	0.12	0.788
118 d	8.91	9.28	9.21	8.48	0.37	0.511	0.890	0.195	8.63	9.32	0.22	0.006
146 d	14.36	14.83	14.29	13.21	0.78	0.695	0.649	0.213	13.2	15.2	0.44	<0.001
202 d	25.98	25.68	25.83	25.18	1.01	0.847	0.921	0.741	24.48	26.86	0.60	0.001
251 d	28.34	30.34	28.88	27.44	1.16	0.291	0.491	0.151	27.86	29.64	0.68	0.015

[a]L = low dietary SID lysine content (Lys 6.9, 6.0, 4.2); ML = medium-low dietary SID lysine content (Lys 7.8, 6.9, 5.2); MH = medium-high dietary SID lysine content (Lys 8.3, 7.8, 6.0); H = high dietary SID lysine content (Lys 9.3, 8.3, 6.9).

[c]SEM = pooled standard error of the mean.

[c]BW = body weight.

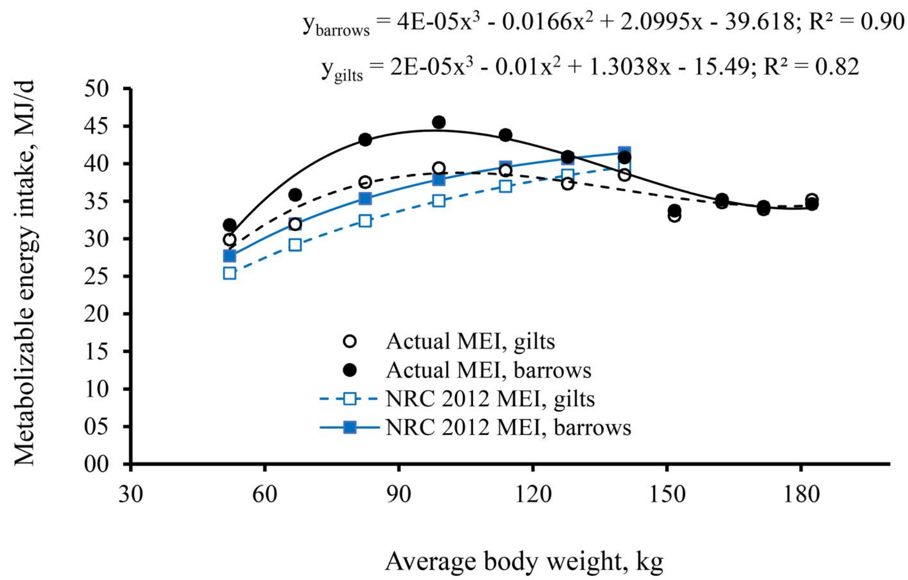

Figure 1. Voluntary metabolisable energy intake (MEI) of experimental gilts and barrows at increasing body weight compared with MEI predicted from NRC (2012) equations.

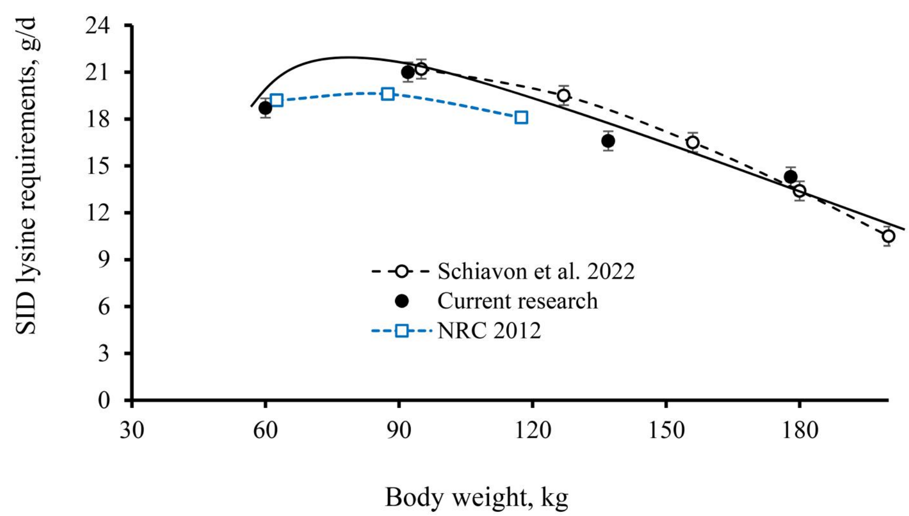

Figure 2. SID lysine requirements of NRC (2012) compared to the optimal daily SID lysine intake of our previous experiments (Schiavon et al. 2022) and the intakes realised with the medium-low treatment of current research.

Feed efficiency (gain: feed) decreased from 0.40 in the early period to 0.22 by the final period. Overall, the feed efficiency of the ML group was significantly greater than that of the L treatment during the whole feeding trial ($p < .05$), whereas increasing the SID-Lysine content over that of the ML group did not affect the gain-to-feed ratio. The SID lysine intake throughout the feeding trial is shown in Figure 2.

For sex effect, gilts exhibited lower BW than barrows at 118, 146, and 202 days of age, attributable to reduced early growth rates; however, a partial compensatory growth in the latter phase resulted in a final BW not significantly different from barrows. Conversely, backfat thickness was always greater in barrows than in gilts ($p < .015$), with the only exception at the start of the trial.

Barrows had a constantly greater feed intake than gilts ($p < .01$), with an average consumption 8.3% greater during the trial. As this superiority in feed intake was not adequately compensated by a concurrent increase in growth rate, barrows had lower feed efficiency than gilts ($p < .001$) over the whole experiment.

Feeding cost and N balance

As anticipated, feed prices increased progressively with higher SID-lysine content. Consequently, the cost of producing a finished pig was 7.5–11% lower for the

Table 5. Feeding costs and N balance of pigs[a] fed voluntarily feeds with different crude protein and SID lysine content.

	Treatments[b]				SEM[c]	Contrast (p)			Sex		SEM	p
	L	ML	MH	H		ML vs L	ML vs MH	ML vs H	Gilts	Barrows		
Feeding costs												
Early growing feed price, euro/ton	523	539	554	569	–	–	–	–	–	–	–	–
Late growing feed price, euro/ton	508	523	539	554	–	–	–	–	–	–	–	–
Finishing feed price, euro/ton	480	493	508	523	–	–	–	–	–	–	–	–
Feeding cost, euro/finished pig (A)	231	248	253	258	4.100	0.042	0.441	0.156	239	256	2.900	<0.001
Body weight gain kg/pig place/year (B)	260	303	295	299	4.700	0.003	0.269	0.528	287	292	3.300	0.296
Feeding costs, euro/kg BW gain[d]	1.770	1.630	1.710	1.730	0.015	0.003	0.021	0.013	1.670	1.750	0.011	<0.001
N balance												
Consumed, kg/finished pig	9.050	10.400	11.400	12.200	0.180	0.006	0.015	0.002	10.300	11.210	0.120	<0.001
Retained, kg/finished pig	3.150	3.770	3.690	3.790	0.067	0.003	0.405	0.902	3.590	3.610	0.047	0.757
Excreted, kg/finished pig	5.900	6.610	7.700	8.410	0.140	0.022	0.005	<0.001	6.740	7.570	0.100	<0.001
Excreted, kg/pig place/year	11.800	13.200	15.400	16.800	0.270	0.022	0.005	<0.001	13.400	15.100	0.190	<0.001
N in manure, kg/pig place/year[e]	8.500	9.500	11.100	12.100	0.190	0.022	0.005	<0.001	9.700	10.900	0.140	<0.001
N in manure, g/kg BW gain[f]	32.700	31.400	37.600	40.500	0.550	0.168	0.001	<0.001	33.800	37.200	0.390	<0.001
Pigs equivalent to 170 kg net N/ha[g]	20.300	18.100	15.500	14.200	0.320	0.008	0.005	0.001	18.000	16.000	0.230	<0.001

[a]Data are about 24 pigs/treatment.
[b]L = low dietary SID lysine content (Lys 6.9, 6.0, 4.2); ML = medium-low dietary SID lysine content (Lys 7.8, 6.9, 5.2); MH = medium-high dietary SID lysine content (Lys 8.3, 7.8, 6.0); H = high dietary SID lysine content (Lys 9.3, 8.3, 6.9).
[c]SEM = pooled standard error of the mean.
[d]Computed as A* rounds per year/B.
[e]Assuming 1.99 rounds/years.
[f]Assuming 30% of N losses in the atmosphere.
[g]The treatment × sex interaction was significant at $p = .043$.

L group compared with other treatments, whereas the feeding costs for the MH and H groups were only marginally higher than those of the ML group (Table 5). However, when expressed per unit of BW gain, ML was significantly the least expensive feeding program, with feed costs 5 to 8% lower than those of the other treatments.

The N intake was significantly greater for pigs on the ML diet than for those on L ($p = .006$), whereas MH and H groups evidenced progressively and significantly greater N intake ($p = .05$ and $p < .001$, respectively), mainly due to differences in the crude protein content of the feeds they consumed. Similarly, the average estimated N retention was greater for ML pigs than for L pigs ($p = .003$) but equal to MH and H treatments. The estimated N excretion per pig finished and per pig-place in a year progressively increased with the increase in lysine content of the dietary group (ML vs L, $p = .022$), but differences were much greater when the ML group was compared with the MH ($p = .005$), or H group than with the L group ($p < .001$).

The net N remaining in manure, computed by the total N excreted in a year and accounting for 30% atmospheric losses, ranged from 8.5 to 12.1 kg per pig place, with ML showing a greater value compared to L ($p = .022$) and lower values when compared to MH ($p = .005$) and H ($p < .001$). This corresponded to pig-place equivalents per 170 kg N/ha net N load, ranging from 14.2 for the H diet to 20.3 for the L diet, with the ML diet being significantly different from all other treatments ($p < .001$). However, N production in manure per kg of BW gain did not differ between the L and ML diets ($p = .17$). Concerning the sex effect, gilts had lower production costs than barrows ($p < .001$), both per pig produced (−6.7%) and per unit of BW gain (−4%). Similarly, gilts had nearly 10% lower N excretion than barrows both per pig finished and per kg BW gain, because of their lower N intake. This resulted in a nearly 2 greater pig load equivalents to 170 kg net N/ha ($p < .001$).

Discussion

Voluntary feed intake and growth performance

Understanding feed intake dynamics is crucial for optimising pig production, as it directly impacts growth performance, feed efficiency, and economic sustainability. Feed intake is a critical determinant of pig growth performance and feed efficiency, and its variability is strongly influenced by production conditions (Whittemore et al. 2001). Although predicting voluntary feed intake for specific pig populations remains challenging, understanding voluntary feed intake is essential to formulating precise diets that ensure adequate nutrient intake and may optimise feed efficiency and growth performance without over- or underfeeding (Baker 1986). The primary determinant of voluntary feed intake is the demand for energy and nutrients, guided by the principle of the first limiting nutrient (Kyriazakis and Whittemore 2006; Black 2009). However, positive or negative factors such as dietary nutrient balance, climate, health, housing, environment and social interactions can cause deviations from optimal intake (Black 2009).

In this study, voluntary feed intake increased throughout the trial, peaking at over 3.3 kg/d between 133 and 160 days of age (90–130 kg BW), before declining slightly to around 3.0 kg/d by 217–251 d (average BW 180 kg). These patterns were consistent with observations in purebred Goland C21 pigs (Schiavon et al. 2022) but exceeded NRC (2012) predictions when the intake was expressed in terms of metabolisable energy (ME) intake (Figure 1). Growth performance was remarkable, with a peak average daily gain of 1178 g/d between 74 and 107 kg BW and an overall average of 946 g/d across the growing period (45–190 kg BW). These growth rates exceed most values reported in the literature for similar body weight intervals (NRC 2012; Becker et al. 2022; Figueroa-Velasco et al. 2022; Song et al. 2022; Tolosa et al. 2022). These growth rates are consistent with studies reporting ADG greater than 1100 g/d (Remus et al. 2020; Camp Montoro et al. 2022). Assuming a protein content of 0.16 in body weight gain (De Lange et al. 2003; Noblet 2005), protein retention may have peaked between 177 and 196 g/d, with an overall average of 137–158 g/d across the growing period. These values match or exceed those reported for modern pig genotypes (Wecke and Liebert 2009; NRC 2012; Remus et al. 2020) and findings for pigs with a similar genetic background reported by Schiavon et al. (2025).

Gain-to-feed ratio (G:F) values in this study were lower compared to those reported in the literature for other pig genotypes. For instance, Remus et al. (2020) reported a gain:feed ratio of 0.43 between 70 and 100 kg BW, and Camp Montoro et al. (2022) observed a G:F ratio of 0.45 between 60 and 112 kg. Besides the impact of heavier BW, the higher voluntary feed intakes and the lower feed efficiency of the pigs of the current research could also be attributed to a greater lipid deposition, reflecting the genetic selection in Goland-C21 pigs for increased fat cover and marbling desired for pigs used in dry-cured ham production systems (Cecchinato et al. 2008). Indeed, Knap (2009) demonstrated that, during the early 1980s, voluntary feed intake declined by approximately 30 g/d annually, driven by genetic selection for reduced body fatness and enhanced feed efficiency. Conversely, the pigs studied in the present research, which were derived from Goland-C21 sires, underwent selective breeding aimed at maintaining or increasing fat cover depth and marbling in the thighs, thereby favouring fat deposition (Malgwi et al. 2021). This selection was intended to enhance the fatness status of the pigs, which contributes to the improved seasoning characteristics of the thighs for dry-cured ham production (Carcò et al. 2019). Consequently, the pronounced appetite observed in the pigs from the current study, along with their reduced feed efficiency, likely reflects a genetic predisposition for protein and fat accretion.

Barrows typically consume more feed and exhibit greater fat deposition than gilts (Wagner et al. 1999). However, under traditional feed-restricted systems in Italian heavy pig production, these differences are often minimised, thus reducing the exploitation of sexual dimorphism (Gallo et al. 2014). The higher feed intake observed in barrows, particularly during the mid-growth phase, can be attributed to their greater propensity for fat accretion relative to gilts (Wagner et al. 1999). There is limited literature on the performance differences between gilts and barrows fed ad libitum at body weights exceeding 140–150 kg (Wagner et al. 1999; NRC 2012). However, data from the present study suggest that the difference in performance between barrows and gilts would be attenuated as BW or age increases. Nonetheless, irrespective of sex, the response of pigs to different dietary SID lysine content in terms of feed intake and growth rate was similar.

Effect of dietary SID lysine content

Optimal nutrient allowances depend on age, sex, weight, genetics, physiological state, and housing environment (Song et al. 2022). Insufficient amino acid levels reduce protein retention, increase fat deposition, and impair growth performance and feed efficiency (Van Milgen and Dourmad 2015). On the other hand, excess amino acid (protein) increases N excretion, posing environmental concerns (Schiavon et al. 2018). Lysine, the first limiting amino acid in cereal grain and soybean meal-based diets, is a key determinant of feeding costs (van Milgen and Dourmad 2015). Therefore, studies suggest that the growth performance of pigs can be taken as a criterion for assessing adequate dietary lysine supply (Baker 1986; Soto et al. 2019).

There are conflicting findings in existing literature data regarding the influence of dietary SID lysine content on feed intake (Baker 1986; Song et al. 2022). Lysine restriction below the requirement negatively impacts growth rate and feed efficiency (Shelton et al. 2011; Ma et al. 2015; Song et al. 2022). According to the theory that feed intake is regulated by the first limiting nutrient (Kyriazakis and Whittemore 2006), a moderate reduction in dietary amino acid levels below the animal's requirements is expected to stimulate increased feed intake to offset the deficiency (Baker 1986). A hypothesis supported by the study of Schiavon et al. (2018). Conversely, Ferguson and Gous (1997) argued that pigs provided with insufficient dietary protein initially increase feed intake to sustain their genetic potential for protein deposition; however, once the compensatory capacity is exceeded, feed intake eventually declines. In the present study, pigs fed the L diet consumed approximately 4% less feed than those on the ML treatment, even though this difference was not statistically significant.

For the majority of the traits considered, the L pigs differed from the ML ones. However, ML did not significantly differ from pigs fed MH and H diets, which were fed diets having greater SID lysine content. Therefore, our findings suggest that the dietary SID lysine content of the L treatment was inadequate for the genetic line and the BW interval considered in this study, despite their similar feed intake compared to the other groups. On the contrary, increasing the SID lysine content over the level of the ML group had no impact on growth rate and feed efficiency, but increased the feeding costs and the N excretion per unit of BW gain. A greater SID lysine content was recommended by NRC (2012) 9.1, 7.8, and 6.5 g/kg for BW ranges of 50–75, 75–100, and 100–135 kg, respectively, when targeting high protein deposition. Similarly, other authors (De Blas et al. 2013; Song et al. 2022; Tsuchino et al. 2024), have proposed greater dietary SID lysine content for lean pig genotypes; however, the feed intakes reported in these studies were notably lower than those observed in the current experiment. When expressed as absolute daily intakes (Figure 2), SID lysine in the ML group slightly exceeded NRC (2012) recommendations but closely matched values reported for *ad libitum*-fed purebred Goland-C21 barrows and gilts reported by Schiavon et al. (2022, 2025).

Implications

Increasing dietary SID lysine, primarily achieved by replacing barley with soybean meal, raised feed costs from €480 to €569 per ton. Because lysine content did not affect voluntary feed intake, the cost to finish a pig increased by 15% with higher SID lysine levels. However, the L diet negatively affected growth rates, resulting in one of the highest costs per unit of BW gain (€1.74/kg), whereas the ML diet minimised this cost (€1.60/kg). Further increases in soybean meal increased the cost per unit of BW gain. Notably, a €0.10/kg BW gain difference translates to an additional €30 income per pig place, assuming a BW production of 300 kg/pig place/year.

The study also assessed the environmental impact of dietary SID lysine and crude protein on nitrogen excretion in manure. Under European nitrate vulnerable area regulations, a maximum load of 170 kg N/ha must be applied to comply with the Nitrate Directive (European Commission 1991). This normative N load depends on dietary crude protein intake, N retention, atmospheric N losses, and the number of production cycles completed per pig place per year. Under such pig production systems, limiting excess dietary protein reduces N excretion, thereby increasing admissible pig density per hectare (Schiavon et al. 2012). Historical data showed that lean pigs growing from 25 to 105 kg produce approximately 10.1 kg N/pig place annually (Ketelaars and der Meer 1999), consistent with later surveys reporting approximately 9.8 kg N/pig place/year under traditional Italian systems by Xiccato et al. (2005). These values underpin the current Italian manure regulations, which assume 17 pig places/ha (MIPAAF 2006). In the present study, heavy pigs fed *ad libitum* on ML diets produced 9.5 kg N/pig place/year, potentially allowing a density of 18.1 pig places/ha.

Finally, *ad libitum* feeding contributed to observed sex differences between gilts and Barrows. Barrows consumed 8% more feed, had 6% greater backfat depth, incurred 4.2% higher feeding costs, and produced 12.4% more N in manure than gilts. These findings suggest potential advantages of separate rearing and management practices for pigs under specific production conditions.

Conclusion

This study determined the dietary SID lysine allowances that optimise growth performance, feed efficiency, and minimise both feeding costs and N excretion in barrows and gilts reared for traditional dry-cured ham production. These pigs exhibited remarkable voluntary feed intake and growth rates even at greater BW, highlighting the considerable growth potential of this population. The dietary SID lysine contents that maximised growth, feed efficiency, and minimised N excretion were 7.8, 6.9, and 5.2 g/kg of feed for the age intervals 90–118, 119–146, and 147–251 days, respectively. Although these values are lower than literature recommendations for lean pig genotypes, they closely align with established recommendations when expressed as absolute daily intakes. This discrepancy reflects the genetic predisposition of the pigs for high voluntary feed intake, which enables enhanced lipid deposition, a critical trait for high-quality dry-cured ham production.

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Ethical approval

The experiment was approved by the Animal Ethics Committee of the University of Padova (document #37/2023) and complied with the European Union Directive on animal experimentation (European Union 2010).

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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