Animal 19 (2025) 101323

Contents lists available at ScienceDirect

Animal

The international journal of animal biosciences

Lysine requirement of weaned piglets

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ARTICLE INFO

Article history:
Received 1 December 2023
Revised 29 August 2024
Accepted 2 September 2024
Available online 10 September 2024

Keywords:
Amino acids
CP
Dose–response studies
Feed formulation
Meta-analysis

ABSTRACT

Lysine, often referred to as the 'first limiting amino acid' in pig nutrition, plays a pivotal role in growth performance. Variability in lysine requirements arises due to factors such as age, sex and environmental conditions. Optimising pig health and production efficiency and minimising nitrogen excretion require accurate knowledge of estimated lysine requirements accounting for factors such as genetics, feeding practices, scientific advancements, and environmental considerations. This study aimed to determine standardised ileal digestible (**SID**) lysine requirements of weaned piglets (5–30 kg) based on a literature review using meta-analytical approaches. The literature review yielded 344 studies that were screened for title and abstract. In total, 41 experiments met the inclusion criteria, resulting in a dataset of 206 treatment means. Linear, quadratic and linear-plateau models were used to gain insight into the effect of SID lysine addition on average daily gain and feed efficiency for the combined dataset and separately for the individual experiments. Regression analysis showed a predominant linear increase in average daily gain and feed efficiency as an overall response to increasing lysine levels across both the combined dataset and individual experiments. Breakpoint estimation from the linear-plateau models was inconclusive, indicating that the optimal SID lysine requirement to maximise piglet growth performance likely exceeded the upper lysine levels tested in most studies, thus surpassing 1.3 g SID lysine per MJ net energy. This review indicates high values for the lysine requirement to achieve maximum growth performance. Results may suggest that piglet feed formulation should focus on an optimal dietary SID lysine to CP ratio, rather than SID lysine per kg of diet or unit of net energy. However, more research is needed to investigate this suggestion.

Implications

Adequate estimates of the lysine requirement of piglets are important, given lysine's critical role in growth performance. This literature review indicates that the lysine requirement to achieve maximal performance in weaned piglets likely exceeds 1.3 g standardised ileal digestible lysine per MJ net energy. However, using such high lysine levels for protein accretion might require a level of dietary CP, which is not commonly used in practice. This may imply that in commercial piglet feed formulation, the balance between lysine and CP content deserves attention, in addition to the commonly used lysine-to-energy ratio. This suggestion requires further study.

Introduction

Adequate estimates of amino acid (**AA**) requirements are essential when formulating pig feed. Imbalances in AA supply can have substantial consequences related to pig performance, feed costs and nitrogen excretion (Wang et al., 2018). Dietary AA levels affect feed intake, growth and feed efficiency. Optimal performance depends not only on absolute AA levels; rather, digestibility of and balance between AAs are crucial. As lysine (**Lys**) is considered the 'first limiting AA' in pig nutrition, the requirements of other essential amino acids (**EAAs**) are expressed relative to Lys (NRC, 2012). Adequate estimation of the Lys requirement is therefore crucially important, as changes in the Lys requirement also result in changes in absolute levels of other EAAs.

Empirical studies traditionally establish AA requirements based on key performance indicators such as average daily gain (**ADG**; g/d), feed efficiency (**G:F**; gain:feed ratio) or feed conversion ratio and average daily feed intake (**ADFI**; g/d). That type of study determines the optimal level of a nutrient that corresponds to the maximum observed performance, using graded levels of the nutrient of interest (NRC, 2012). For effective dose–response studies, the nutrient of interest should be the first limiting nutrient and the response in performance parameters should be directly proportional to an increase in the nutrient of interest. Here, it must be ensured that no other nutrients limit performance and any

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https://doi.org/10.1016/j.animal.2024.101323
1751-7311/

alterations in other nutrients must be minimised, both in their absolute values and in the balance between nutrients (Boisen, 2003). Average daily feed intake is a major driver of performance, as energy intake is supposed to be the first limiting factor for muscle deposition in piglets (Campbell et al., 1985). The optimum supply of AAs maximises ADG and G:F; any level below or above this optimum leads to an inefficiency of AA utilisation. Deficiency of certain EAAs means that these are not present in sufficient amounts to support maximal protein synthesis, leading to submaximal growth rates and feed efficiency. Therefore, the minimum concentration of an AA that maximises pig performance is considered to be the nutritional requirement (Pomar et al., 2003).

Reported values for the Lys requirement of weaned piglets based on dose–response studies range from 10.8 g/kg of total Lys, in this study recalculated on the basis of diet composition as 9.8 g standardised ileal digestible (**SID**) Lys/kg, to greater than 16 g/kg SID Lys (Moretto et al., 2000; Nichols et al., 2018). Also, SID Lys recommendations proposed by CVB (1996), NRC (2012), or Danish recommendations (Tybirk et al., 2021) range from 1.05 g SID Lys/MJ net energy (**NE**), to 1.22 g SID Lys/MJ NE (11–25 kg piglets), and to 1.43 g SID Lys/MJ NE (15–30 kg piglets), respectively. This variation could be attributed to animal-specific characteristics, including the pig's genotype, age or sex, as these factors determine the feed intake capacity and the genetic capacity for protein deposition (Nieto et al., 2015; Schneider et al., 2010), but they may also be attributed to some limitations of the studies. In general, the higher the protein–to–lipid deposition ratio, the higher the Lys requirement expressed both in terms of Lys per kg diet and Lys per unit of energy. However, as feed intake capacity is the most limiting factor in the nursery phase, the effects of genetic capacity and sex are mostly limited in this phase. Therefore, AA requirements are generally not significantly affected by sex and genotype in the early postweaning phases (Taylor et al., 2012, Edwards et al., 2006; Moretto et al., 2000). Other factors that could contribute to the variation in the Lys requirement of weaned piglets are sanitary conditions of the experimental environment (Williams et al., 1997; Kahindi et al., 2014), the statistical approach used for predicting the requirement (Pesti et al., 2009), the performance parameter (Baker et al., 2002; Nemechek et al., 2012; Vier et al., 2016), or differences in feed evaluation system to estimate dietary AA content and nutrient digestibility.

The large variation in Lys requirement between studies hampers optimal Lys supply in diets for weaned pigs. This variability underscores the critical need for a comprehensive analysis of existing literature to establish a more unified understanding of Lys requirements. By synthesising and rigorously analysing previously reported Lys dose–response experiments, our objective was to estimate the Lys requirement for maximal growth performance in weaned piglets and to address the multifaceted sources of variation influencing this requirement.

Material and methods

Search strategy and data collection

A dataset was compiled with experimental studies that analysed the response of weaned piglets to increasing dietary concentrations of Lys in the diet. A literature search in the 'Web of Science' and 'CAB Abstracts' was conducted in September 2021, searching relevant articles published between 1990 and 2021 that included currently used diets and genotypes. The following keywords and their combinations were used to search for relevant articles: "pig(s) or piglet(s)" and "growth or gain or performance" and "lysine" and "requirement(s) or dose–response or recommendation(s)". In addition to the results obtained from the aforementioned databases, some additional papers based on the reference list or citations of relevant papers were searched using Google Scholar. Peer-reviewed journal articles or abstracts containing detailed information fulfilling the following criteria after abstract and full-text screening were retained: (a) *in vivo* studies with piglets between 5 kg and 30 kg, (b) dose–response studies with at least four dietary levels of Lys tested, (c) (the major part of) the ingredient composition was reported and (d) at least ADG and ADFI were reported as response criteria. A flow chart of the search strategy for the papers and subsequent data selection is shown in Fig. 1.

After selection of relevant studies, the following information was retained: (a) paper characteristics (authors, publication year, country), information on animals and experimental design (age, weight range, weaning age, adaptation period, treatment duration, *ad libitum*/restricted feeding, genotype, sex, number of animals per treatment, number of animals per pen, number of pens per treatment), (b) information on experimental diets (feed ingredients, calculated and/or analysed nutrient composition, source of Lys addition: supplementation of L-Lys hydrochloride or L-Lys sulphate versus increase in protein rich feed materials, energy content in digestible energy, metabolisable energy or NE and CP content, the use of ZnO and antibiotics, the number of Lys levels tested and the tested Lys range as well as the AA profile, feed evaluation system and digestibility coefficients used), and (c) performance information as function of the tested Lys level (ADG in g/d, ADFI in g/d and G:F or feed conversion ratio) in the overall period. In two studies, three-phase feeding was applied in the nursery phase (Braga et al., 2018; Kim et al., 2011). For these studies, the weighted average ingredient composition throughout the three phases was used to investigate the performance as function of the dietary treatments. In some studies, the effect of Lys level was tested in combination with other factors such as genotype, Lys source and different energy levels (Fraga et al., 2008; Palencia et al., 2019; Urynek and Buraczewska, 2003). If performance results of all different treatments were reported, the results of the factors other than Lys level were treated as separate experiments. However, in the second experiment of the study of Urynek and Buraczewska (2003), only performance results of the main effects were reported, as no interaction was found between the two tested factors (four Lys to metabolisable energy ratio levels and two metabolisable energy levels). Therefore, for the four diets differing in Lys level, the average ingredient composition of the two energy levels was calculated and used in combination with the performance results of the main effect of dietary Lys to metabolisable energy ratio.

Data treatment

In the selected studies, dietary AA levels, AA digestibility values, and energy levels were expressed in various units based on table values from various feed evaluation systems as applied by the authors. Dietary Lys was expressed as calculated and/or analysed total dietary Lys, and as calculated SID, apparent or true ileal digestible Lys, whereas energy levels were expressed as NE, metabolisable or digestible energy. The nutrient composition of the diets in the selected studies was calculated using different feed evaluation systems such as the feed tables provided by NRC (1998, 2012), Rostagno et al. (1992, 2011), Whittemore et al. (2003) and CVB (2007). In a few studies, the digestibility coefficients of AAs used were experimentally determined. In most studies, additional crystalline AAs (apart from Lys) were supplied to meet the minimum AA ratio according to (different) ideal protein ratios suggested by Chung and Baker (1992), NRC (1998, 2012), Rostagno et al. (1992, 2011), Whittemore et al. (2003) or Gloaguen et al. (2013).

Recalculating the nutrient composition of the diets using the reported feed ingredient composition and table values from one

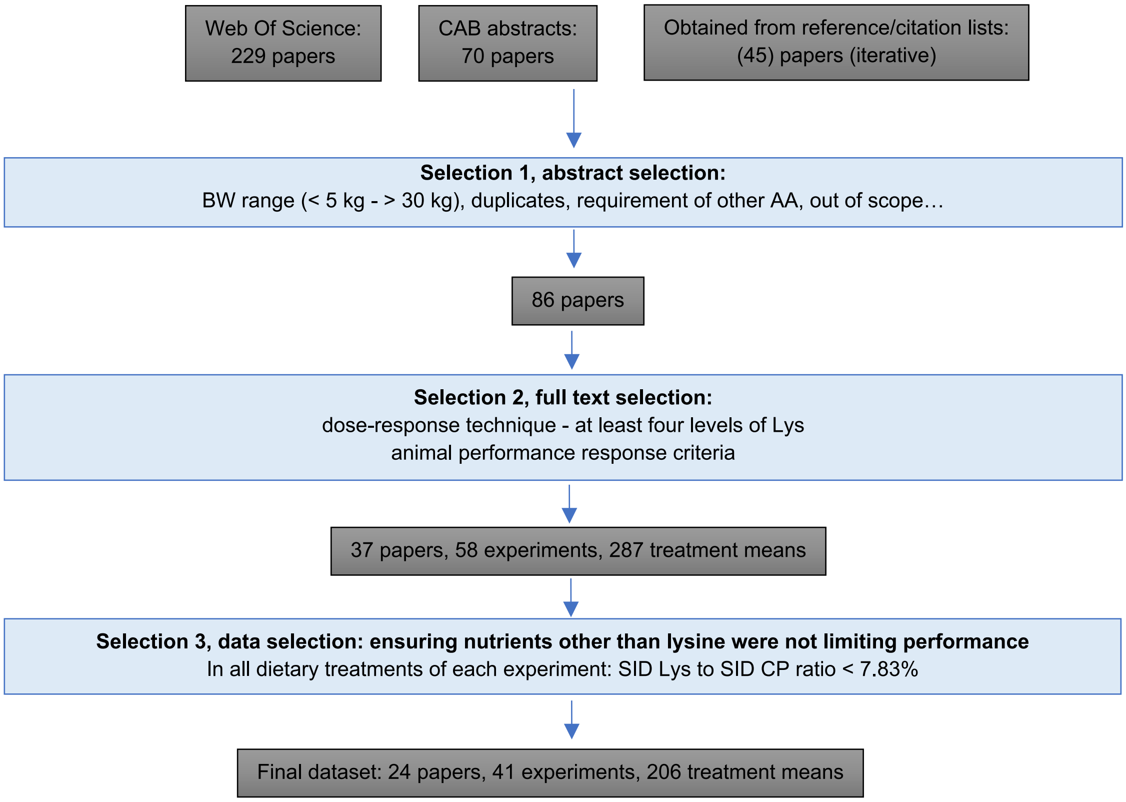


Fig. 1. Flow chart of the search strategy and data selection of dose–response studies estimating the lysine requirement in weaned piglets. AAs = amino acids; Lys = lysine; SID = standardised ileal digestible.

feed evaluation system does not always guarantee a more correct estimation than the reported nutrient composition. Therefore, we decided to use the reported analysed or calculated nutritional values, or to use recalculated nutritional values based on the table's nutrient and digestibility values in a defined order of priority:

(i) if the calculated total Lys levels reported in the paper deviated less than 5% from the calculated total Lys levels according to the CVB (2023a) Feed Table (based on the given ingredient composition), then the dietary SID Lys content was estimated by the multiplication of the calculated total Lys content reported in the paper with the weighted average SID Lys digestibility coefficient based on CVB table values, (ii) if the paper only reported analysed instead of calculated total Lys levels, or if calculated total Lys levels reported in the paper deviated more than 5% from the total Lys levels calculated according to the CVB (2023a) Feed Table, then the reported analysed total Lys levels were multiplied by the weighted average SID Lys digestibility coefficients based on CVB table values to estimate SID Lys levels in the diets, (iii) if the paper did not report analysed total Lys levels, then the calculated SID Lys values as reported in the paper were used.

For total dietary CP level, the reported calculated total dietary CP levels were compared with the total dietary CP levels calculated according to the CVB (2023a) Feed Table. When the reported calculated total dietary CP levels deviated more than 5% from the total dietary CP levels according to the CVB (2023a) Feed Table, or when the paper did not report calculated total CP values, then reported analysed total CP levels were used. To estimate SID CP levels in the diet, the reported total CP levels were multiplied by the weighted average SID CP digestibility coefficients from the CVB (2023a) Feed Table.

To estimate the energy content of the diets, reported NE (net energy) values were used. When energy content was expressed as digestible or metabolisable energy, NE was estimated using a conversion factor of 0.74 and 0.71, respectively (Noblet et al., 2022). In the dataset, it was recorded whether the diets were isocaloric and/or isonitrogenous and if the diets were formulated with or without varying ingredient compositions.

Most studies ensured that SID Lys was the first limiting nutrient. However, in studies using a constant dietary CP level while increasing the SID Lys level, high SID Lys to total CP ratios were reached (up to 9%). This may imply that the sum of non-essential amino acids (**NEAAs**) or total nitrogen becomes limiting, resulting in an inefficient use of Lys. Therefore, it has been suggested to use a maximal dietary SID Lys:CP ratio (Millet et al., 2018; Rocha et al., 2022), although the optimal ratio is still a matter of debate. As Lys is largely used for body protein accretion, it seems reasonable to assume that Lys will only be efficiently used for protein accretion up to the ratio of Lys in body protein. A theoretical optimal SID Lys to SID CP can thus be estimated by taking into account the Lys content in deposited body protein and the maximum efficiencies of using SID CP and SID Lys. According to Van Milgen et al. (2008), body protein consists of 6.96% Lys, while the efficiency for using SID CP (kCP) and SID Lys (kLys) are 0.81 and 0.72, respectively. This leads to a theoretical optimal SID Lys to SID CP ratio of 7.83% ($6.96 \times 0.81/0.72$). If this ratio is exceeded, SID Lys might not be used for protein synthesis since a shortage of NEAAs or nitrogen may limit protein accretion. To avoid the inclusion of studies for which it cannot be excluded that NEAAs or nitrogen may have limited growth, only experiments where all dietary treatments had an SID Lys to SID CP ratio below 7.83% were retained in the final dataset.

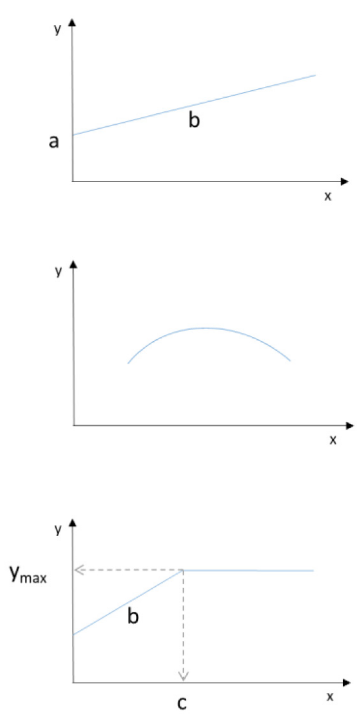
Ratios of SID methionine, methionine + cysteine, threonine, tryptophane, isoleucine, leucine and valine relative to SID Lys in all dietary treatments of the experiments were estimated from the feed ingredient composition as reported in the papers and from the AA content and AA digestibility values in the CVB (2023a) Feed

Table. Although an imbalance of AAs can impair growth performance, compliance with an ideal AA profile was not considered as a selection criterium for the dataset in the current review due to the following assumptions and uncertainties. (1) As data on total (calculated or analysed) EAAs were not always reported in the paper, it was not possible to correct for analysed values in the paper, as was done for the estimation of SID Lys in this review. (2) Most studies reported supplementation of EAA to meet the AA requirements according to the ideal AA profile, but different ideal AA profiles were used (NRC, 1998, 2012; Chung and Baker, 1992; Whittemore et al., 2003; Gloaguen et al., 2013). (3) It was not always clear if the ideal AA profile was only used in the basal diet or in all dietary treatments. However, although the estimated SID EAA:SID Lys ratios were not considered as a selection criterion for the dataset, the ratios were used to assess whether a deficiency or AA imbalance may have affected growth performance. Studies with estimated SID EAA:SID Lys ratios that were 10% lower than the recommended ideal AA profile for piglets (CVB, 2023b) were considered as 'experiments in which the first limiting nutrient may have been an EAA other than Lys in one or more dietary treatments'. The other experiments were considered as 'experiments assumed to have an ideal AA profile in all dietary treatments'. The classification of these experiments was taken into account in the interpretation of the results.

Statistical models to estimate the lysine requirement

A general overview of the dose–response experiments was obtained by the visualisation of the performance parameters (ADG, G:F and ADFI) as a function of Lys in the diet (expressed as g SID Lys/kg diet and g SID Lys/MJ NE). Then, for each experiment, it was verified whether there was a response to an increasing SID Lys concentration by linear, quadratic and linear-plateau regression models (Fig. 2). The model parameters for each model were estimated using the linear and non−linear least squares approach (function nlsfit, package easynls) in R (R Core Team, 2022). The dependent variable y is the response of the piglets (performance parameters, ADG, G:F or ADFI) and the independent variable x is the SID Lys dose (g SID Lys/kg diet or g SID Lys/MJ NE). The slope (b) in the linear and linear-plateau model represents the marginal efficiency of dietary SID Lys utilisation before ymax (which is the maximum response or plateau) is reached. The SID Lys requirement is estimated by the breakpoint of the linear-plateau model (c), which corresponds to the minimum Lys supply needed to maximise the response. To identify a breakpoint and plateau using linear-plateau models, at least two levels above the breakpoint should be tested (NRC, 2012). Therefore, in the case that a linear ascending, but no linear-plateau model can be fitted to the data, the SID Lys requirement is considered to be higher than the second highest tested SID Lys level. The regression coefficient w of the quadratic model represents the direction and the steepness of the quadratic response. Significance of the quadratic term indicates that the response on SID Lys addition slows down as the SID Lys level reaches the optimum, or it could also indicate a decline in the performance response to SID Lys levels greater than the optimum.

Linear, quadratic and linear-plateau models were used to gain insight into the response to SID Lys addition (in g SID Lys/kg diet and in g SID Lys/MJ NE) for the complete dataset and for the individual experiments. Experiments were considered to show a linear, quadratic and/or linear-plateau response if the R^2 of the corresponding models was greater than 0.70 in combination with a P-value for the slope (linear model), quadratic term (quadratic model) or breakpoint (linear-plateau model) smaller than 0.25, similar to the approach in the meta-analysis of Van Milgen et al. (2012). This higher and less stringent P-value was preferred over the more conventional P-value of 0.05 because of the low statistical power of the tests. This low statistical power is the result of the limited observations in most experiments; in most cases, only treatment means for the responses (for four − six Lys levels) were available and used in the current analysis.



$$y = a + bx \qquad \text{(i)}$$

$$y = u + vx + wx^2 \qquad \text{(ii)}$$

$$y = y_{max} + b\,(x - c)\ for\ x < c \qquad \text{(iii)}$$
$$y = y_{max}\ for\ x \geq c$$

Fig. 2. Schematic representation of the linear (i), quadratic (ii) and linear-plateau (iii) model with y representing the response of the piglets, x the lysine level, a the intercept of the linear model, b the marginal efficiency of lysine addition before the maximum response (ymax) is reached, v and w the regression coefficient of the linear and quadratic term, and c the breakpoint or the lysine level maximising the response.

When combining multiple experiments in the regression analysis, response data were standardised to deal with the wide range in magnitude of the performance parameters due to differences in characteristics like BW and genotype of the pigs. Two approaches were used to account for these scale differences: the first approach applied to all three models, while the second approach only applied to the linear and quadratic model. In the first approach, dependent variables were expressed as a percentage of the response observed at the highest level of Lys supplementation within each experiment (Van Milgen et al., 2012), followed by a regression analysis (function nlsfit, package easynls) on these standardised data. In the second approach, mixed effects regression was applied (function lmer, package lme4), including the intercept of each experiment as random factor. All statistical analyses were performed using R (R Core Team, 2022).

Results

Paper and data selection

A total of 344 articles were retrieved from the search and, after deletion of duplicates and articles not fulfilling the criteria for inclusion in the dataset, 58 experiments from 37 scientific publications (articles or abstracts) and publicly available trial reports from research institutes were included to estimate the SID Lys requirement of piglets (Fig. 1). Among the 58 experiments, 41 did not exceed the theoretical optimal SID Lys to SID CP ratio of 7.83% in any of the dietary treatments. These 41 experiments were used to estimate the optimal SID Lys content in the diet. All analyses were performed with the SID Lys content expressed per kg diet and MJ NE. However, given the minimal variation in NE content between and within experiments, only results expressed as g SID Lys/MJ NE are presented and discussed in this paper.

Both studies with a constant or varying ingredient composition (and thus CP level) were included. It was estimated that about 17 experiments had an ideal AA profile in all dietary treatments, whereas for 24 studies, it can be speculated that EAAs other than Lys could have limited performance due to an imbalance of AAs in one or more of the dietary treatments.

The selected experiments, reported between 1992 and 2020, used piglets between 6 and 31 kg fed *ad libitum* (n = 38) or restrictedly (n = 3). The described dose–response studies with at least four SID Lys levels used different levels of L-Lys hydrochloride (n = 37), L-Lys sulphate (n = 3), soybean meal (n = 1), or a combination of protein–rich feed ingredients and the addition of crystalline Lys sources. Twenty-two studies originated from the USA, six from Brazil, seven from Europe, four from Canada and two from Asia. Mostly mixed-sex groups were used (n = 29), but some studies used only barrows (n = 8) or gilts (n = 2), or compared both sexes (n = 2). Ten dose–response studies used six levels of Lys, 22 experiments used five levels, and nine studies used four Lys levels. More detailed information on the study design of each study including the number of Lys levels and Lys source, number of animals and experimental units and the use of ZnO, copper or antibiotics in the diets is presented in Supplementary Table S1.

Recalculated nutritional values and descriptive statistics

In general, the SID Lys values estimated on the CVB (2023a) Feed Table showed very good agreement with the reported SID Lys values, but were consistently slightly higher (estimated Lys (g SID Lys/kg diet) = 0.9947 reported Lys (g SID Lys/kg diet) + 0.2613; R^2 = 0.9754, residual standard deviation = 0.29 g SID Lys/kg diet). Among the 41 experiments, eight focused on the initial postweaning period, involving piglets with a BW ranging between 5 and 12 kg. Another eight experiments focused on piglets at a later stage in the nursery period with a BW ranging from 12 to 31 kg. The remaining 25 experiments covered the overall period, including piglets with a BW ranging from 5 to 31 kg (Fig. 3). The estimated SID Lys levels ranged from 0.59 to 1.63 g SID Lys/MJ NE. Most dose–response experiments with lighter (younger) piglets used a higher range of dietary SID Lys levels, whereas in the experiments with heavier (older) piglets, usually lower dietary Lys levels were tested. The overall mean performance parameters were 494 ± 134 g/d for ADG, 0.67 ± 0.08 g/g for G:F and 746 ± 268 g/d for ADFI (Table 1). More detailed information on the BW range, the range of dietary treatments (g SID Lys/kg diet, g SID Lys/MJ NE, CP and NE content) and performance results for each study is presented in Supplementary Table S2.

Regression analysis for combined experiments and overall response of the individual experiments

The responses to Lys addition varied from virtually no response to linear or quadratic responses with and without plateau values being reached. Based on visual interpretation of the performance parameters (ADG, G:F and ADFI) as a function of the dietary SID Lys level, the regression equations for the combined experiments and the number of individual studies showing a linear, quadratic or linear-plateau response, the conclusion was made that the

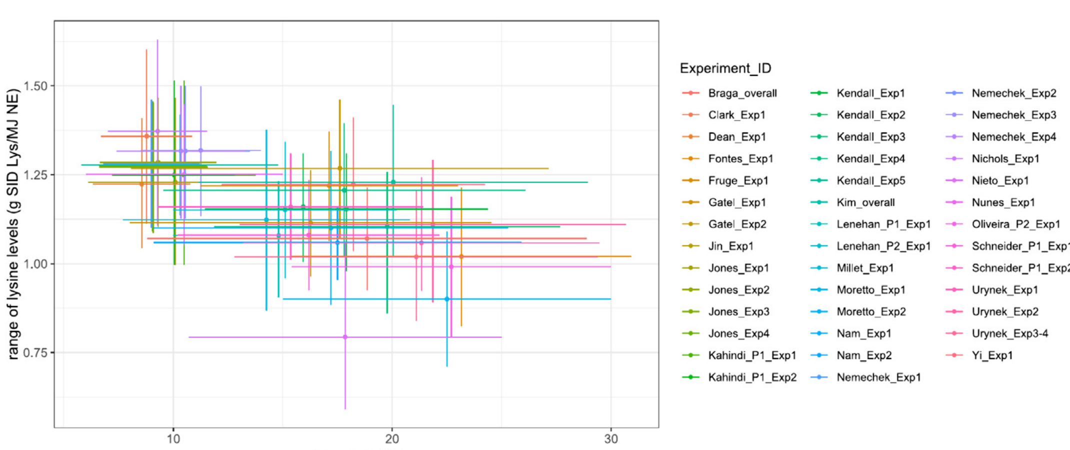


Fig. 3. BW range (horizontal line) and range of tested standardised ileal digestible lysine (SID Lys) levels (vertical line) of the 41 experiments, each represented by a cross, used to estimate the SID Lys requirement in piglets. Lys = lysine; SID = standardised ileal digestible; NE = net energy.

Table 1
Descriptive statistics of the performance parameters, the average BW of the piglets during the experiments and the BW at the start and end of the experiments (n = 206 treatments means from 41 experiments).

Item	Average	SD	min	max	Q1	Q3
ADG (g/d)	494	134	228	847	376	581
G:F (g/g)	0.67	0.08	0.45	0.86	0.61	0.74
ADFI (g/d)	746	268	336	1 544	494	886
Average BW (kg)	15.0	5.0	6.6	23.2	10.1	18.1
BW at start (kg)	9.5	2.9	5.8	15.4	7.1	11.4
BW at end (kg)	20.7	7.2	10.8	30.9	13.6	26.9

ADG = average daily gain; G:F = gain to feed; ADFI = average daily feed intake; min = minimum; max = maximum; Q1 = first quartile, the value under which 25% of data points are found when they are arranged in increasing order; Q3 = third quartile: the value under which 75% of data points are found when arranged in increasing order.

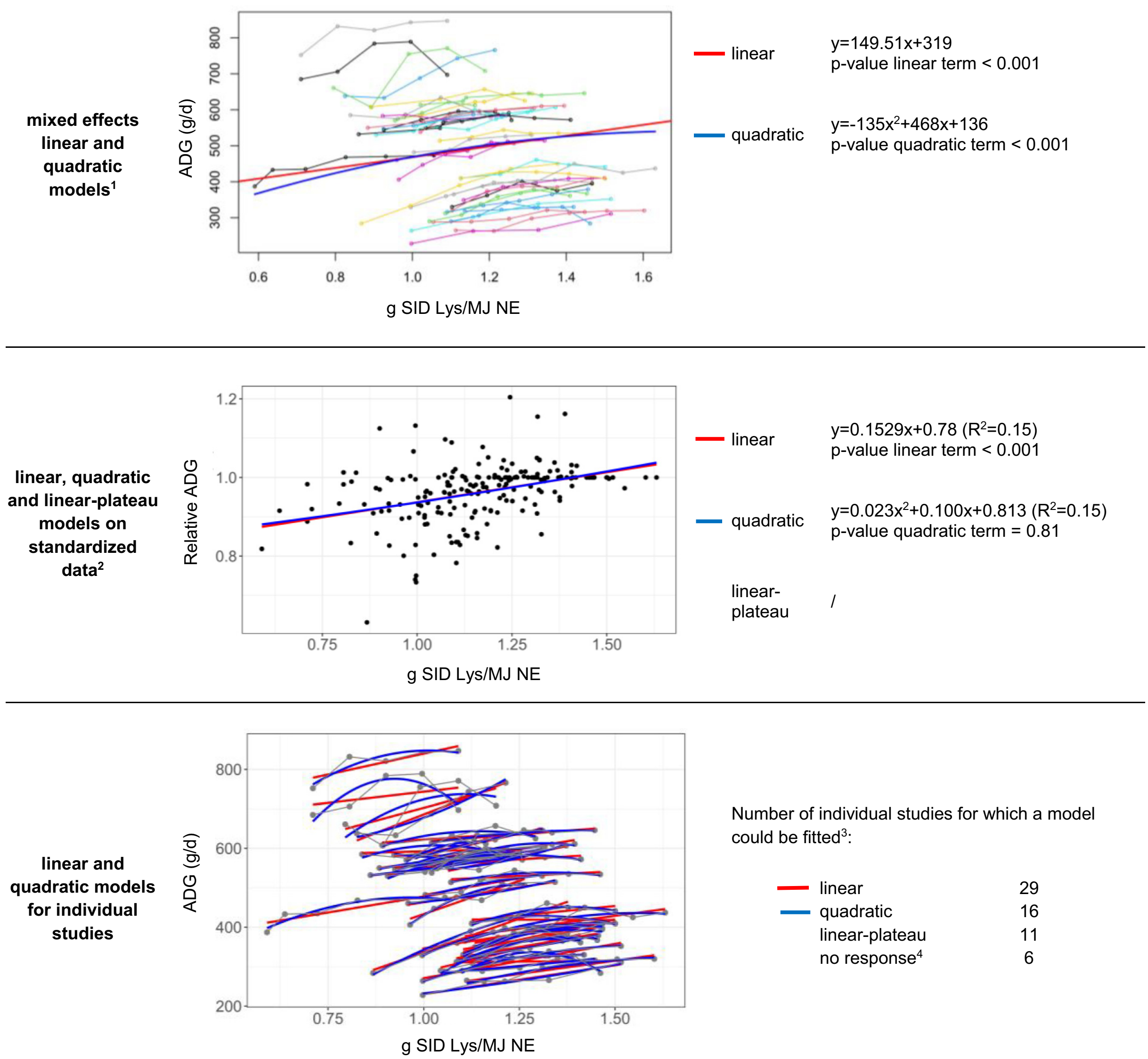


Fig. 4. Absolute and standardised average daily gain of piglets (ADG; g/kg) as a function of dietary standardised ileal digestible lysine (expressed as g SID Lys/MJ NE) for the dataset (n = 41 dose–response studies with 4, 5 or 6 lysine levels tested). Linear, quadratic and linear-plateau models were fitted for the complete dataset and for the individual studies. For the complete dataset, both mixed effects regression models and regression on standardised data were applied to account for scale differences between experiments. For individual studies, the number of experiments showing a linear, quadratic or linear-plateau response was indicated.

response in ADG and G:F was predominantly characterised by a linear increase (Figs. 4 and 5). ADFI was hardly affected by the dietary Lys content (Supplementary Figure S1). For more than half of the studies with ADFI as a response parameter, no statistically significant linear, quadratic or linear-plateau model could be fitted (Supplementary Tables S3 and S4).

For ADG and G:F, linear and quadratic models could be fitted using both mixed effects regression models and regression models on standardised data (Figs. 4 and 5). Visualisation of the different model plots indicates that the regression lines for the linear and quadratic models were very similar within the range of most data points. Especially within the range of the dataset, the response

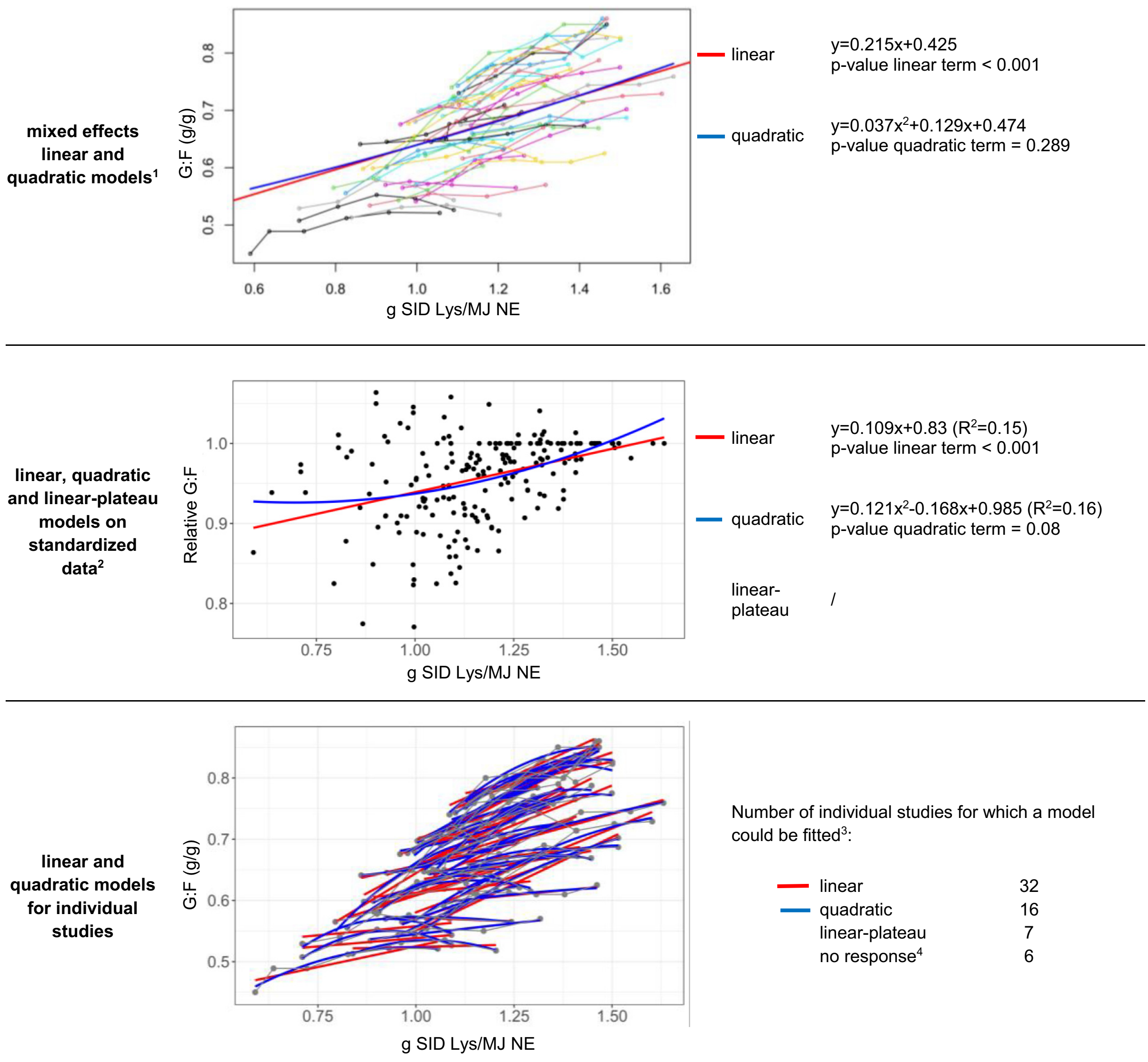


Fig. 5. Absolute and standardised feed efficiency of piglets (G:F; gain to feed ratio) responses as a function of dietary standardised ileal digestible lysine per MJ net energy (expressed as g SID Lys/MJ NE) for the dataset (n = 41 dose–response studies with 4, 5 or 6 lysine levels tested). Linear, quadratic and linear-plateau models were fitted for the complete dataset and for the individual studies. For the complete dataset, both mixed effects regression models and regression on standardised data were applied to account for scale differences between experiments. For individual studies, the number of experiments showing a linear, quadratic or linear-plateau response was indicated.

seemed predominantly linear. After the exclusion of the experiments with a potential imbalance in AAs in one or more dietary treatments, the combined analysis of the 17 remaining experiments also resulted in a predominant linear response, without reaching maximal growth performance (data not shown).

Regression analysis for individual experiments

As no optimal SID Lys level could be estimated using regression analysis for the combined dataset, we verified for the individual experiments whether linear and/or quadratic and/or linear-plateau models could be fitted for ADG and G:F as a function of the dietary SID Lys level per MJ NE (Tables 2 and 3). More detailed tables including model parameters, *P*-values and R^2 for the models for ADG, G:F and ADFI as a function of SID Lys level in g SID Lys/kg diet and in g SID Lys/MJ NE are available in Supplementary Tables S3 and S4 for ADFI; Tables S5 and S6 for ADG, and Tables S7 and S8 for G:F.

For ADG as a function of SID Lys per MJ NE, 29 experiments showed a linear response, including 18 studies with only a linear response, one study with both a linear and a quadratic response, one study with both a linear and linear-plateau but no quadratic response, and nine studies with both a linear, quadratic and linear-plateau response. Six studies showed only a quadratic response, and for five studies, none of the three models could be fitted to the response data (Fig. 4 and Table 2). For G:F as a function of SID Lys level per MJ NE, 32 studies showed a linear response, including 19 studies with only a linear response, six studies with both a linear and a quadratic response, and seven studies with both a linear, quadratic and linear-plateau response. Three studies showed only a quadratic response, and for six studies, none of the three models could be fitted to the response data (Fig. 5 and Table 3). These numbers indicate that the database contained more studies with a continuous linear increase in ADG and G:F than studies reaching a plateau or optimum within the tested SID Lys range. In experiments for which both linear and quadratic but no

Table 2
Range of dietary treatments, fit to linear, quadratic or linear-plateau models, and estimation of the SID Lys requirement in weaned piglets with ADG as a response parameter upon a dietary increase in Lys expressed as g SID Lys/MJ NE (for experiments with SID Lys to SID CP ratios below 7.83%, n = 41 dose–response studies with 4, 5 or 6 Lys levels tested).

Reference[1,2]	BW range (kg)	Dietary ranges			Average ADG (g/d)	Response[3]	g SID Lys/MJ NE at the quadratic function's maximum[4]	Estimated Lys requirement[5] (g SID Lys/MJ NE)
		g SID Lys/MJ NE	total CP % in diet	NE MJ/kg diet				
Nieto_Exp1_2015	10.7–25	0.59–1.06	16.3–16.7	10.2–10.7	444	lin&quad&linp	0.967	0.811
Moretto_Exp1_2000	15–30	0.71–1.09	17.7–17.7	10.6–10.6	819	-&-&linp		0.925
Braga_overall_2018	8.8–28.9	0.93–1.22	19.2–19.7	10.3–10.3	577	lin&quad&linp	1.183	1.102
Gatel_Exp1_1992	8–24.5	0.96–1.26	16–22.9	9.7–9.8	472	lin&quad&linp	1.257	1.175
Jin_Exp1_1998	6.1–14.1	1–1.47	18.3–21.8	10.4–10.5	380	lin&quad&linp	1.354	1.226
Kendall_Exp4_2008	9.5–26.1	1.02–1.39	21.2–22	10.6–10.6	591	lin&quad&linp	1.315	1.228
Kendall_Exp5_2008	11.1–29	1.02–1.45	21.2–22	10.6–10.6	634	lin&quad&linp	1.427	1.246
Dean_Exp1_2007*	6.3–10.8	1.04–1.41	24.4–24.4	10.6–10.6	339	lin&quad&linp	1.347	1.261
Jones_Exp3_2014*	6.6–11.6	1.09–1.45	22–22.8	10.9–10.9	353	lin&quad&linp	1.375	1.303
Nemechek_Exp3_2012	8.5–14	1.13–1.5	22.6–23.5	10.7–10.7	390	lin&quad&linp	1.457	1.354
Jones_Exp2_2014*	6.7–12	1.1–1.47	25.3–25.8	11–11	375	lin&-&linp		1.425
Nam_Exp2_1994	9.1–25.9	0.95–1.16	18.6–19	9.9–9.9	599	lin&-&-		>1.094
Fontes_Exp1_2005	15.4–30.9	0.82–1.21	19–19	10.3–10.3	694	lin&-&-		>1.117
Schneider_P1_Exp1_2010	10.2–22.2	0.93–1.24	19.8–19.9	10.9–10.9	570	lin&-&-		>1.158
Lenehan_P1_Exp1_2004	10–19.6	0.91–1.23	18.5–18.5	10.4–10.4	566	lin&-&-		>1.162
Nam_Exp1_1994*	9.1–25.3	0.88–1.32	18.6–18.6	9.4–9.4	579	lin&-&-		>1.172
Schneider_P1_Exp2_2010	9.3–21.4	1.01–1.31	21.6–21.7	11–11	577	lin&-&-		>1.235
Kendall_Exp2_2008	11.9–20	1–1.31	21.2–21.9	10.6–10.6	509	lin&-&-		>1.242
Lenehan_P2_Exp1_2003	10–20.2	0.96–1.34	20–20	10.4–10.4	486	lin&-&-		>1.247
Kendall_Exp3_2008	11.9–27.7	0.86–1.26	21.2–21.9	10.6–10.6	561	lin&-&-		>1.251
Millet_Exp1_2020*	7.7–20.8	0.87–1.38	20.1–21	9.8–9.8	379	lin&quad&-	1.612[†]	>1.255
Kendall_Exp1_2008*	11.4–24.4	0.98–1.31	20.3–21.6	10.6–10.6	616	lin&-&-		>1.262
Kim_overall_2011*	5.8–14.8	1.1–1.38	20.9–22.7	10.7–10.7	325	lin&-&-		>1.29
Fruge_Exp1_2017	11.2–23	1.06–1.37	16.8–21.1	10.4–10.4	574	lin&-&-		>1.299
Kahindi_P1_Exp1_2014*	7.2–13.8	1–1.52	22.4–22.8	9.6–9.6	314	lin&-&-		>1.327
Kahindi_P1_Exp2_2014*	7.3–12.8	1–1.52	22.4–22.8	9.6–9.6	267	lin&-&-		>1.327
Nunes_Exp1_2008*	6–15	1.05–1.45	21.6–21.6	10.4–10.4	302	lin&-&-		>1.35
Jones_Exp4_2014*	6.6–11.5	1.09–1.46	17.7–23.9	10.9–10.9	348	lin&-&-		>1.363
Clark_Exp1_2017*	6.7–10.9	1.11–1.6	19.3–24.7	10.1–10.3	296	lin&-&-		>1.506
Nichols_Exp1_2018*	7–11.6	1.11–1.63	19.3–24.7	10.1–10.2	412	lin&-&-		>1.547
Gatel_Exp2_1992	8.1–27.1	1.07–1.46	19.7–20.3	9.8–9.9	531	-&quad&-	1.329	–
Moretto_Exp2_2000	15–30	0.71–1.09	17.7–17.7	10.6–10.6	732	-&quad&-	0.924	–
Nemechek_Exp1_2012*	6.8–11.2	1.1–1.46	19.3–23.8	10.5–10.5	313	-&quad&-	1.285	–
Nemechek_Exp2_2012	7.6–13.5	1.13–1.5	22.6–23.3	10.7–10.7	436	-&quad&-	1.385	–
Nemechek_Exp4_2012	7.4–13.3	1.13–1.5	22.6–23.3	10.7–10.7	419	-&quad&-	1.309	–
Yi_Exp1_2006	12.2–24.2	1.03–1.41	22–22	10.6–10.6	570	-&quad&-	1.271	–
Jones_Exp1_2014*	6.7–11.9	1.1–1.47	25.3–25.8	11–11	373	-&-&-		–
Oliveira_P2_Exp1_2006*	15.4–30	0.79–1.19	17.8–24.4	10.3–10.4	700	-&-&-		–
Urynek_Exp1_2003*	13.2–29.5	0.92–1.24	20.8–21.6	10–10	581	-&-&-		–
Urynek_Exp2_2003	13–30.7	0.89–1.29	21.2–22.4	10.7–10.7	630	-&-&-		–
Urynek_Exp3-4_2003	12.8–29.4	0.84–1.2	21–22	10.4–10.4	593	-&-&-		–

ADG = average daily gain; SID = standardised ileal digestible; Lys = lysine; NE = net energy.
[1] References are indicated by the name of the first author, the code attributed to each experiment with P_i representing the paper of the first author (in case of multiple papers) and Exp_i representing the number of the experiment published in the corresponding paper, followed by the year in which the paper was published.
[2] References with an asterisk were classified as 'experiments assumed to have an ideal amino acid profile in all dietary treatments', whereas other studies were considered as 'experiments with a potential imbalance in amino acids in one or more dietary treatments'.
[3] Experiments were considered to show a linear (lin), quadratic (quad) and/or linear-plateau (linp) response if the coefficient of determination (R^2) of the corresponding models was greater than 0.70 in addition with a P-value for the slope (linear model), quadratic term (quadratic model) or breakpoint (linear-plateau model) smaller than 0.25.
[4] The level of lysine (g SID Lys/MJ NE) at which the quadratic model reaches its maximum value. Values with daggers indicate that the maximum of the quadratic model was reached outside the tested range lysine.
[5] The lysine requirement for each experiment was estimated from the linear-plateau and the linear statistical model with the assumption that lysine is the first limiting nutrient in the entire experiment.

linear-plateau models could be fitted, the Lys levels corresponding to the maximum of the quadratic model were found to exceed the tested Lys ranges (Tables 2 and 3). This suggests that there is an ascending but flattening curve within the tested range of these experiments. The estimated plateau values obtained with the linear-plateau model ranged from 370 to 845 g/d for ADG, and 0.52–0.83 for G:F. Estimates for the breakpoint ranged between 0.81 and 1.43 g SID Lys/MJ NE.

For the majority of the experiments with an ideal AA profile, the second highest tested SID Lys level was in the range of 1.3 – 1.4 g SID Lys/MJ NE (nine out of 17 experiments). For ADG, a breakpoint was obtained for three of nine (33%) studies within the tested SID Lys range using a linear-plateau model, with breakpoints at 1.26, 1.30, and 1.43 g SID Lys/MJ NE. For four of nine (44%) studies, it could only be concluded that the optimal SID Lys level was higher than 1.3 g SID Lys/MJ NE, and for the other two experiments, no linear nor linear-plateau model could be fitted (Supplementary Figure S2). For G:F, for one out of nine (11%) studies, a breakpoint of 1.37 g SID Lys/MJ NE was obtained using a linear-plateau model. For seven out of nine (78%) studies, it could only be concluded that the optimal SID Lys level was higher than 1.3 g SID Lys/MJ NE, and for one experiment, no linear nor linear-plateau model could be fitted (Supplementary Figure S3). Only two (out of the 17) experiments had a second−highest Lys level greater than 1.4 g SID Lys/

Table 3
Range of dietary treatments, fit to linear, quadratic or linear-plateau models, and estimation of the SID Lys requirement in weaned piglets with G:F as a response parameter upon a dietary increase in SID Lys expressed as g SID Lys/MJ NE (for experiments with SID Lys to SID CP ratios below 7.83%, n = 41 dose–response studies with 4, 5 or 6 Lys levels tested).

Reference[1,2]	BW range (kg)	Dietary ranges			Average G:F (g/g)	Response[3]	g SID Lys/MJ NE at the quadratic function's maximum[4]	Estimated Lys requirement[5] (g SID Lys/MJ NE)
		g SID Lys/MJ NE	total CP % in diet	NE MJ/kg diet				
Nieto_Exp1_2015	10.7–25	0.59–1.06	16.3–16.7	10.2–10.7	0.497	lin&quad&linp	0.981	0.861
Fontes_Exp1_2005	15.4–30.9	0.82–1.21	19–19	10.3–10.3	0.612	lin&quad&linp	1.134	1.048
Lenehan_P1_Exp1_2004	10–19.6	0.91–1.23	18.5–18.5	10.4–10.4	0.628	lin&quad&linp	1.194	1.108
Kendall_Exp5_2008	11.1–29	1.02–1.45	21.2–22	10.6–10.6	0.657	lin&quad&linp	1.335	1.197
Nemechek_Exp3_2012	8.5–14	1.13–1.5	22.6–23.5	10.7–10.7	0.741	lin&quad&linp	1.457	1.342
Nunes_Exp1_2008*	6–15	1.05–1.45	21.6–21.6	10.4–10.4	0.736	lin&quad&linp	1.412	1.370
Nemechek_Exp4_2012	7.4–13.3	1.13–1.5	22.6–23.3	10.7–10.7	0.803	lin&quad&linp	1.470	1.389
Oliveira_P2_Exp1_2006*	15.4–30	0.79–1.19	17.8–24.4	10.3–10.4	0.641	lin&-&-		>1.091
Nam_Exp2_1994	9.1–25.9	0.95–1.16	18.6–19	9.9–9.9	0.574	lin&-&-		>1.094
Braga_overall_2018	8.8–28.9	0.93–1.22	19.2–19.7	10.3–10.3	0.674	lin&-&-		>1.119
Schneider_P1_Exp1_2010	10.2–22.2	0.93–1.24	19.8–19.9	10.9–10.9	0.636	lin&quad&-	1.271†	>1.158
Nam_Exp1_1994*	9.1–25.3	0.88–1.32	18.6–18.6	9.4–9.4	0.552	lin&-&-		>1.172
Gatel_Exp1_1992	8–24.5	0.96–1.26	16–22.9	9.7–9.8	0.594	lin&-&-		>1.205
Schneider_P1_Exp2_2010	9.3–21.4	1.01–1.31	21.6–21.7	11–11	0.734	lin&-&-		>1.235
Kendall_Exp2_2008	11.9–20	1–1.31	21.2–21.9	10.6–10.6	0.744	lin&-&-		>1.242
Lenehan_P2_Exp1_2003	10–20.2	0.96–1.34	20–20	10.4–10.4	0.714	lin&-&-		>1.247
Kendall_Exp3_2008	11.9–27.7	0.86–1.26	21.2–21.9	10.6–10.6	0.671	lin&-&-		>1.251
Millet_Exp1_2020*	7.7–20.8	0.87–1.38	20.1–21	9.8–9.8	0.697	lin&quad&-	1.575†	>1.255
Kendall_Exp1_2008*	11.4–24.4	0.98–1.31	20.3–21.6	10.6–10.6	0.72	lin&-&-		>1.262
Fruge_Exp1_2017	11.2–23	1.06–1.37	16.8–21.1	10.4–10.4	0.738	lin&-&-		>1.299
Yi_Exp1_2006	12.2–24.2	1.03–1.41	22–22	10.6–10.6	0.66	lin&-&-		>1.317
Kahindi_P1_Exp2_2014*	7.3–12.8	1–1.52	22.4–22.8	9.6–9.6	0.627	lin&quad&-	1.887†	>1.327
Kahindi_P1_Exp1_2014*	7.2–13.8	1–1.52	22.4–22.8	9.6–9.6	0.64	lin&-&-		>1.327
Kendall_Exp4_2008	9.5–26.1	1.02–1.39	21.2–22	10.6–10.6	0.697	lin&quad&-	1.408†	>1.336
Jones_Exp3_2014*	6.6–11.6	1.09–1.45	22–22.8	10.9–10.9	0.81	lin&-&-		>1.362
Jones_Exp4_2014*	6.6–11.5	1.09–1.46	17.7–23.9	10.9–10.9	0.786	lin&-&-		>1.363
Jin_Exp1_1998	6.1–14.1	1–1.47	18.3–21.8	10.4–10.5	0.765	lin&quad&-	1.619†	>1.37
Jones_Exp1_2014*	6.7–11.9	1.1–1.47	25.3–25.8	11–11	0.788	lin&-&-		>1.376
Jones_Exp2_2014*	6.7–12	1.1–1.47	25.3–25.8	11–11	0.79	lin&-&-		>1.376
Nemechek_Exp1_2012*	6.8–11.2	1.1–1.46	19.3–23.8	10.5–10.5	0.802	lin&quad&-	1.608†	>1.39
Clark_Exp1_2017*	6.7–10.9	1.11–1.6	19.3–24.7	10.1–10.3	0.681	lin&-&-		>1.506
Nichols_Exp1_2018*	7–11.6	1.11–1.63	19.3–24.7	10.1–10.2	0.718	lin&-&-		>1.547
Moretto_Exp1_2000	15–30	0.71–1.09	17.7–17.7	10.6–10.6	0.552	-&quad&-	0.932	–
Moretto_Exp2_2000	15–30	0.71–1.09	17.7–17.7	10.6–10.6	0.533	-&quad&-	0.931	–
Urynek_Exp3-4_2003	12.8–29.4	0.84–1.2	21–22	10.4–10.4	0.524	-&quad&-	1.034	–
Dean_Exp1_2007*	6.3–10.8	1.04–1.41	24.4–24.4	10.6–10.6	0.688	-&-&-		–
Gatel_Exp2_1992	8.1–27.1	1.07–1.46	19.7–20.3	9.8–9.9	0.61	-&-&-		–
Kim_overall_2011*	5.8–14.8	1.1–1.38	20.9–22.7	10.7–10.7	0.675	-&-&-		–
Nemechek_Exp2_2012	7.6–13.5	1.13–1.5	22.6–23.3	10.7–10.7	0.801	-&-&-		–
Urynek_Exp1_2003*	13.2–29.5	0.92–1.24	20.8–21.6	10–10	0.57	-&-&-		–
Urynek_Exp2_2003	13–30.7	0.89–1.29	21.2–22.4	10.7–10.7	0.62	-&-&-		–

G:F = feed efficiency (gain to feed ratio); SID = standardised ileal digestible; Lys = lysine; NE = net energy.
[1] References are indicated by the name of the first author, the code attributed to each experiment with P_i representing the paper of the first author (in case of multiple papers) and Exp_i representing the number of the experiment published in the corresponding paper, followed by the year in which the paper was published.
[2] References with an asterisk were classified as 'experiments assumed to have an ideal amino acid profile in all dietary treatments', whereas other studies were considered as 'experiments with a potential imbalance in amino acids in one or more dietary treatments'.
[3] Experiments were considered to show a linear (lin), quadratic (quad) and/or linear-plateau (linp) response if the coefficient of determination (R^2) of the corresponding models was greater than 0.70 in addition with a P-value for the slope (linear model), quadratic term (quadratic model) or breakpoint (linear-plateau model) smaller than 0.25.
[4] The level of lysine (g SID Lys/MJ NE) at which the quadratic model reaches its maximum value. Values with daggers indicate that the maximum of the quadratic model was reached outside the tested range lysine.
[5] The lysine requirement for each experiment was estimated from the linear-plateau and the linear statistical model with the assumption that lysine is the first limiting nutrient in the entire experiment.

MJ NE. For both response parameters, only a linear model could be fitted. These two studies (with second highest Lys levels of 1.51 and 1.55 g SID Lys/MJ NE) indicate that the optimal SID Lys level was higher than 1.5 g SID Lys/MJ NE.

The average of the slope of linear models and the linear ascending portion of the linear-plateau models (194 ± 87 for ADG and 0.285 ± 0.081 for G:F) indicate an average increase of 19.4 ± 8.7 g ADG for each additional 0.1 g SID Lys/MJ NE, and approximately 28.5 ± 8.1 g gain/kg feed intake for each additional 0.1 g SID Lys/MJ NE for G:F until the estimated requirement of the piglets was reached. No correlations were found between the slopes of the models and the average BW, nor between the slopes and the average ADG or G:F in the studies.

Discussion

The aim of this study was to evaluate the Lys requirement of weaned piglets and the sources of variation in the requirement using meta-analytical approaches. The response to an increase in SID Lys in the dose–response studies ranged from virtually no response to linear and quadratic responses with and without achievement of plateau values. Analyses of both the combined and individual experiments showed a predominant linear increase without reaching a plateau or maximum response level for ADG and G:F within the tested SID Lys range, whereas ADFI was hardly affected by the dietary SID Lys content. The linear response without plateau suggests that most authors anticipated a lower SID

Lys requirement than their data showed since the requirement was likely higher than the range of values tested.

Influence of study design on nutrient ratio shifts in dose–response studies

Most of the originally selected studies (44 of 58 studies) used a basal diet and increased the SID Lys content in the dietary treatments by adding graded levels of crystalline Lys, in combination or not with the supplementation of constant or graded levels of other (one or multiple) crystalline AAs to meet recommended SID EAA:SID Lys ratios. A minority of studies (14 of 58 studies) increased the SID Lys content in the dietary treatments via the increase in protein–rich feed materials at the expense of other low–protein feed ingredients, with or without the combination of supplementation of crystalline Lys and either constant or graded levels of other EAAs. In the first type of study, as only SID Lys was increased, the SID Lys:SID CP ratio increased, whereas the SID EAA: SID Lys ratios decreased (except for a few studies where most of the other EAAs were gradually supplemented). In the second type of study, the SID Lys to SID CP ratio remained similar and differences in SID EAA:SID Lys ratios were less pronounced.

Especially in the first type of study and in diets with high SID Lys to SID CP ratios, it is possible that SID Lys was not the first limiting AA, but that other EAAs or NEAAs were limiting optimal performance at the highest levels of Lys inclusion, although the linear response and absence of breakpoints suggest this was not the case in most studies. Still, AA imbalances may explain some of the observed effects (or absence thereof). For example, in the dose–response experiments of Moretto et al. (2000), where only Lys but no other EAAs were added to the basal diet, the ratio of SID methionine + cysteine to SID Lys, SID threonine to SID Lys and SID tryptophan to SID Lys was estimated at 47.6, 50 and 14.2%, respectively, for the diet with the highest Lys content. This is considerably lower than the recommended AA profile (CVB, 2023b), which may explain the lack of an increase in growth performance in this particular Lys dose–response experiment.

As such, it cannot be excluded that the deficiency of SID EAAs other than SID Lys has limited performance in most of the experiments showing a linear-plateau response. Only the experiments of Dean et al. (2007), Jones et al. (2014, experiments 2 and 3) and Nunes et al. (2008) supplied the ideal AA profile in all treatment groups. They reported levels for optimal performance at 1.26, 1.30, 1.43 and 1.37 g SID Lys/MJ NE, respectively.

Experiments showing only a continuous linear increase or a linear increase in combination with a quadratic response curve indicate that the optimal SID Lys level to maximise ADG or G:F was outside the tested range or at the highest level. For those studies, it can be concluded that the optimal SID Lys level to maximise ADG or G:F is higher than the second highest tested SID Lys level in the experiment. In case of a deficiency of a certain EAA other than Lys, a continuous linear increase could also result from the gradual addition of a deficient EAA instead of a response on SID Lys addition, although this seemed unlikely from the used AA patterns. From the studies using a high SID Lys range (with the second highest Lys level between 1.3 and 1.4 g SID Lys/MJ NE), 44% of the studies showed a linear increase in ADG and 78% showed a linear increase in G:F. Two studies performed a dose–response study with the second highest levels above 1.5 g SID Lys/MJ NE, but even in these two studies, no plateau in performance was observed, suggesting that the SID Lys requirement in these two studies was higher than 1.5 g SID Lys/MJ NE. It was thus not possible to derive one exact SID Lys requirement level for piglets based on the current analysis. Rather, the results indicate that the SID Lys requirement is at least higher than 1.3 g SID Lys/MJ NE.

It should be mentioned that most studies only tested 4–6 levels of SID Lys and that fitting a linear-plateau model should contain both a linear increase and a plateau (requiring at least two levels above the breakpoint). The small number and range of SID Lys levels tested is a limitation of the dose–response studies found in the literature. Using only the treatment means in the analysis of the individual studies in this review (and the concomitant lower statistical power) additionally limits the potential of fitting linear-plateau models. Applying a meta-analysis approach, combining data from multiple studies should enlarge the number of tested Lys levels and widen the range of Lys levels tested. However, both the results of the individual studies (based on results reported in the paper and analysis in this study) and the combined analysis show a linear increase within the tested range. In future Lys dose–response studies, it is advisable to include more Lys levels and a broader range of Lys.

Most dose–response studies also express the optimal Lys requirement on a g/day and g/kg BW gain basis by multiplying the estimated Lys requirement with the corresponding growth performance parameters. Studies reporting Lys requirement for piglets on this basis obtained Lys requirement values of 17–19 g SID Lys/kg BW gain (Nemechek et al., 2012), 16.8 g SID Lys/kg BW gain (Kahindi et al., 2017) and 19.0–20.7 g SID Lys/kg BW gain (Kendall et al., 2008). However, as no accurate value for the SID Lys requirement for maximal growth response could be established, expressing the SID Lys requirement per day or kg BW gain is not possible based on the data of this study.

For some studies, no statistically significant linear nor linear-plateau model could be fitted (n = 11 for ADG and n = 9 for G:F, see Tables 2 and 3). This means that the response showed another shape (quadratic or irregular), or that growth performance was not affected by the dietary treatments in the experiment. A lack of response would indicate that SID Lys was not limiting performance and that the SID Lys requirement was theoretically below the SID Lys level of the basal diet in these studies. For the studies with an (assumed) ideal AA profile in all dietary treatments, it is not clear why a quadratic, irregular, or lack of response was observed for ADG or G:F (first experiment of Nemechek et al. (2012), first experiment of Jones et al. (2014), Oliveira et al. (2006), first experiment of Urynek and Buraczewska (2003), first experiment of Dean et al. (2007) and Kim et al. (2011)). This is potentially related to (i) a less appropriate experimental design like individual housing and restricted feeding (Urynek and Buraczewska, 2003), or (ii) the availability of only treatment means in this analysis or a limited sample size used in the experiments. For example, for the first experiment of Jones et al. (2014), a linear plateau model could be fitted (with a breakpoint at 1.38 g SID Lys/MJ NE), but the R^2 of the model was below 0.70. In that paper, a slightly different outcome was reported (linear-plateau model with R^2 = 0.81 and breakpoint at 14 g SID Lys/kg diet, or 1.32 g SID Lys/MJ NE), potentially as a result of the use of pen as experimental unit and use of a different statistical model (NLIN procedure of SAS). For the studies of Oliveira et al. (2006) and Urynek and Buraczewska (2003), experiments 1 and 2), a low sample size was used with five and six replicates per dietary treatment, respectively, and two and one animals per experimental unit, respectively, which could have resulted in a low power of the experiment.

Factors influencing the estimated lysine requirement

Influence of response variable

Many factors can contribute to the variation in estimated SID Lys requirements, including the choice of the response variable, dietary factors such as digestibility coefficients, the use of antimicrobial growth promotors, and animal characteristics such as BW, age, gender, genotype, and disease status or sanitary conditions.

The current review was unable to confirm the notion of higher SID Lys requirements for maximum G:F than for ADG as suggested by others (Nemechek et al., 2012; Vier et al., 2016; Graham et al., 2017, Kahindi et al., 2017). This was due to the absence of sufficient breakpoint estimates in the linear-plateau models, both in the combined analysis and in the analysis of the individual studies. The overall observation that ADFI was unaffected by the dietary SID Lys level in the current review is in agreement with multiple other studies (Kendall et al., 2008; Jones et al., 2014). However, some studies showed a quadratic effect (Kahindi et al., 2017), a linear increase (Millet et al., 2020), or a linear decrease in ADFI (experiment 4, Nemechek et al., 2012) when dietary Lys was increased. This difference in response in ADFI may be related to AA (im)balances, as it was demonstrated that ADFI can be depressed both by AA deficiencies and by an excessive supply of some AAs (Harper et al., 1970; Li and Patience, 2017). In addition, ADFI directly influences ADG and G:F. Therefore, it should be considered whether the response in ADG or G:F is directly due to a change in Lys versus a change in ADFI related to an imbalance of other AAs.

Influence of digestibility coefficients and lysine source

In the current review, dietary SID CP and SID Lys contents were estimated using SID Lys and SID CP coefficients of feedstuffs for growing pigs listed in the CVB (2023a) Feed Table. The choice of feed evaluation system used to estimate the AA digestibility can result in different SID Lys estimates between studies. In the current review, recalculating the SID Lys contents in the diets resulted in marginally higher estimates of dietary SID Lys compared to the values reported in the respective papers. A more general question arises, namely: To what extent might the use of digestibility coefficients of growing pigs impact the estimated SID Lys requirement for piglets? Although no table with SID AA or SID CP coefficients specific to piglets has been published (due to lack of data), digestibility coefficients obtained in experiments with growing pigs may overestimate the AA digestibility in weaned piglets. Especially during the 1st 2 weeks after weaning, lower digestibility is to be expected (Engelsmann et al., 2022; Pedersen et al., 2016). For example, the current review used an SID coefficient of 92.4% for CP in soybean meal based on CVB (2023a), whereas in the study of Engelsmann et al. (2022), SID CP digestibility coefficient values of 15–81% were reported for piglets at 7 and 28 days after weaning, respectively. Furthermore, the digestibility (and the potential degree of overestimation) might also depend on the source of the nutrients, as free AAs have a higher digestibility compared to the nutrients in the major feed ingredients (Nørgaard et al., 2016).

Influence of antimicrobial growth promotors and sanitary conditions

The dataset in the current review did not allow for a comparison of SID Lys requirements for piglet–fed diets with or without antimicrobial growth promoters versus antibiotic-free diets. Literature on the Lys requirement of piglets fed antibiotic-free diets is scarce. Because Lys is mainly required for protein accretion and is less involved in the immune response, a lower SID Lys requirement could be expected in piglets fed antibiotic-free diets as performance might be lower without growth promoters. In contrast, the higher intestinal microbial load in antibiotic-free fed piglets could utilise dietary Lys differently, leading to a higher SID Lys requirement in these piglets. A comparison between growing pigs fed diets with and without antimicrobial growth promoters resulted in a 6% increase in Lys requirements for the pigs fed antibiotic-free diets (Bikker et al., 2006). To investigate the effect of the immune response on the Lys requirement of piglets fed antibiotic-free diets, Kahindi et al. (2014) conducted a Lys dose–response study in clean and unclean sanitary conditions. Unfortunately, due to a lack of plateau in ADG and G:F, no Lys requirement and no difference in requirement between the two conditions could be established. Based on the SID Lys range tested, it could only be concluded that the SID Lys requirement was higher than the second-highest tested level (12.5 g SID Lys/kg diet). Nevertheless, results showed that unclean conditions reduced ADG and ADFI, but had no effect on G:F. These observations indicate that the efficiency of Lys utilisation for protein accretion was unaffected by the sanitary conditions. This would be consistent with the assumption that Lys is not involved in the immune response of piglets.

Influence of animal-related factors

The current review covers a range of studies that investigate the SID Lys requirements in weaned piglets. However, due to the lack of precise values for the estimated SID Lys requirements, it is not possible to conduct a comprehensive examination of how factors such as genotype, sex, age, or BW range affect these requirements. Examination of the limited number of studies that investigate these factors did not indicate any substantial differences in SID Lys requirement between weaned piglets from different genotypes (Taylor et al., 2012) or sexes (Moretto et al., 2000). Some national guidelines provide separate SID Lys recommendations for different BW or age categories for weaned piglets. However, in the current review, it was not possible to derive SID Lys requirement estimates for the different weight categories, and no correlations were found between the slopes of the linear or linear-plateau models and the average BW, or between the slopes and the ADG or G:F in the studies. This suggests that the marginal effect of an increase in dietary SID Lys is valid in the range studied (BW between 5 and 31 kg). Furthermore, dose–response studies to determine the SID Lys requirement of piglets directly after weaning pose challenges due to the varying experimental conditions used across studies, such as weaning age and the use of an adaptation period before the experimental treatments. Additionally, the response of piglets to dietary Lys levels might be confounded by weaning stress symptoms such as reduced ADFI, which could affect growth performance (Park and Kim, 2015; Kahindi et al., 2017).

The estimated lysine requirement compared with national recommendations

The results of this review indicate that the SID Lys requirement of piglets is considerably higher than recommendations proposed by the UK (Whittemore et al., 2003) and previous CVB recommendations (1996), and more in line or slightly higher than the Danish, Brazilian and NRC guidelines (Tybirk et al., 2021; Rostagno et al., 2017; NRC, 2012; Table 4). However, it is not always clear how these recommendations were determined and which studies were used as references. The differences between the current observations and the national recommendations could be related to the factors elaborated above, including the approach to determine the Lys requirements, the increased feed intake or lean gain potential of modern pig genetics, the use of antimicrobial growth promoters and the potential inclusion of dose–response studies where other nutrients than Lys were first limiting. Furthermore, national recommendations do not necessarily envision maximal growth response as the most important criterion for the Lys recommendation. Other factors such as economic optimisation, safety margins, and legislation might also play a role.

Practical consequences for diet formulation

The SID Lys requirement of the piglets appeared to be higher than most researchers anticipated and was also higher than used in most commercial diets. It remains unclear whether increasing

Table 4
National recommendations for lysine requirements for piglets.

Reference National recommendations	Country	Lysine recommendations
CVB (1996)	The Netherlands	1.05 g SID Lys/MJ NE
NRC (2012)	United States	7–11 kg: 1.32 g SID Lys/MJ NE 11–25 kg: 1.22 g SID Lys/MJ NE
Rostagno et al. (2017)	Brazil	28–35 d: 13.5 g SID Lys/kg diet 35–49 d: 12.5 g SID Lys/kg diet 49–63 d: 11.3 g SID Lys/kg diet
Whittemore et al. (2003)	United Kingdom	11.2 g SID Lys/kg diet
Tybirk et al. (2021)	Denmark	6–9; 6–15 kg: 1.31 g SID Lys/ MJ NE 9–15 kg: 1.30 g SID Lys/MJ NE 15–30 kg: 1.43 g SID Lys/MJ NE

SID Lys = standardised ileal digestible lysine; NE = net energy.

Table 5
Different scenarios for the optimal dietary SID Lys level for piglets in relation to a given dietary CP content, with varying SIDC values for CP. Values in this table are based on the assumption of a theoretical optimal SID Lys to SID CP ratio of 7.83%[1].

	SIDC CP=90%		SIDC CP=85%		SIDC CP=80%	
g CP/kg diet	g SID CP/kg diet	g SID Lys/kg diet[2]	g SID CP/kg diet	g SID Lys/kg diet[2]	g SID CP/kg diet	g SID Lys/kg diet[2]
160	144	11.3*	136	10.6*	128	10.0*
170	153	12.0*	145	11.3*	136	10.6*
180	162	12.7*	153	12.0*	144	11.3*
190	171	13.4	162	12.6*	152	11.9*
200	180	14.1	170	13.3	160	12.5*
210	189	14.8	179	14.0	168	13.2
220	198	15.5	187	14.6	176	13.8

Lys = lysine; SID = standardised ileal digestible; SIDC = standardised ileal digestibility coefficient.
[1] The ratio of 7.83% was calculated based on the assumptions of a body protein content of 6.96% Lys, and maximum efficiencies of 81% and 72% for using SID CP and SID Lys, respectively, for body protein deposition.
[2] Lys values with an asterisk are below the estimated Lys requirement of piglets, under the assumption of a Lys requirement of 1.3 g SID Lys/MJ net energy and 10 MJ net energy/kg diet. At these levels, optimal performance is probably not reached in piglets.

dietary Lys levels is beneficial when the CP level is kept at a constant (low) level. To eliminate experiments for which it cannot be excluded that other AAs or nitrogen−limited growth, a theoretical upper limit for the SID Lys to SID CP ratio of 7.83% was used in this study. The ratio of 7.83% was based on the assumptions described above but these should be considered carefully and should be backed up with empirical data. Several studies have demonstrated empirically that minimum dietary CP levels are necessary to optimise pig performance (Millet et al., 2018; Millet et al., 2020, Rocha et al., 2022). In these studies, dietary Lys to CP ratios are mostly expressed as SID Lys on total CP since both nutrients are commonly used in feed formulation and because information on CP digestibility is not always available. In the current review, the theoretical SID Lys to SID CP ratio of 7.83% corresponds with 7.07% SID Lys to total CP, assuming an average SID CP coefficient of 90 or 6.29%, assuming an average SID CP coefficient of 80%. Millet et al. (2018) studied the interaction between dietary Lys and CP levels using a 2 × 6 factorial design with two Lys levels and six CP levels. Increasing levels of dietary Lys and CP improved performance, but the effect of increasing CP depended on the SID Lys level. The observed interaction between Lys and CP levels on growth performance and the lower breakpoint in the dose–response of CP for pigs receiving the lower compared to the higher Lys level was in agreement with the hypothesis that at a low CP level, protein rather than Lys limits performance. The study also analysed serum urea levels as an indicator of excess AAs. Minimal serum urea levels, indicating the ratio where CP and not Lys would limit protein accretion, were reached at a ratio of 6.4% SID Lys to total CP ratio based on a linear-plateau model, independent on the Lys level. This value is close to the optimal SID Lys to total CP ratio of 6.6% obtained in the meta-analysis of Rocha et al. (2022). Further empirical studies to verify this number are needed.

Assuming an SID Lys requirement higher than 1.3 g SID Lys/MJ NE, an optimal ratio of SID Lys to SID CP of 7.83%, an SID digestibility coefficient for dietary CP of 85%, and an energy content of 10 MJ NE/kg diet, piglet feed should contain a CP level of at least 195 g CP/kg feed for an optimal usage of SID Lys. In practice, this high dietary level of CP is not often applied due to the high risk of post-weaning diarrhoea, and for environmental and economic reasons. Instead of focusing on an ideal ratio of SID Lys to energy, it may be more pertinent to formulate piglet feed based on the optimal SID Lys content relative to the dietary CP content. Therefore, the optimal dietary SID Lys level can be influenced by the maximum acceptable CP level in the diet, which may vary according to specific farm circumstances, as suggested by Millet and Everaert (2022). In cases of optimal health conditions, elevating dietary CP and AA levels can enhance piglet performance. However, to mitigate the risk of diarrhoea, nutritionists commonly choose to reduce dietary CP levels, thereby accepting suboptimal growth performance. Consequently, feed costs may be reduced by adapting the dietary SID Lys level to this lower CP level. Taking into account the same assumptions (a theoretical optimal ratio of SID Lys to SID CP of 7.83%, a SID digestibility coefficient for CP of 85%, and a dietary energy content of 10 MJ NE/kg diet), a piglet diet with 170 g CP/kg diet should contain 11.3 g SID Lys/kg diet. Different scenarios for the optimal dietary SID Lys level in relation to a given dietary CP content are given in Table 5. However, the assumptions made to construct this table should be carefully considered and further studied.

Conclusion

The analysis of published dose–response studies showed a predominant continuous linear increase in ADG and G:F within the tested Lys range suggesting that the SID Lys requirement is higher than what most researchers expected. A minimum of 1.3 g SID Lys/MJ NE was derived, but application of this high Lys level might require a relatively high minimum level of dietary CP. It seems reasonable to assume that the maximum performance in piglets is rarely achieved in practice due to the reluctance to use high CP diets and that piglets are probably fed below the AA and CP requirement for maximum performance. Consequently, it may be preferred for practical application to regard dietary SID Lys levels in piglet diets as a function of the CP level rather than the energy level.

Supplementary material

Supplementary material to this article can be found online at https://doi.org/10.1016/j.animal.2024.101323.

Ethics approval

Not applicable.

Data and model availability statement

Data or models are not deposited in an official repository but are available from the authors upon reasonable request.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) did not use any AI and AI-assisted technologies.

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Declaration of interest

The authors declare that there is no conflict of interest for this manuscript.

Acknowledgements

The authors acknowledge the members of the *ad hoc* group (J. Fledderus, M. van Erp and N. G. Cespedes) that participated in the project by discussing the conceptualisation, methodology and results. The authors also thank Miriam Levenson (ILVO) for English language editing.

Financial support statement

This project was funded by the foundation CVB and the Dutch Ministry of Agriculture, Nature and Food Quality as part of the Public Private Partnership "Voeding op Maat" (grant number LWV20.189). The manuscript was published with support from the University Foundation of Belgium (grant number WA-0479).

References

Baker, D.H., Batal, A.B., Parr, T.M., Augspurger, N.R., Parsons, C.M., 2002. Ideal ratio (relative to lysine) of tryptophan, threonine, isoleucine, and valine for chicks during the second and third weeks posthatch. Poultry Science 81, 485–494.
Bikker, P., Fledderus, J., Le Bellego, L., Rovers, M., 2006. AGP ban effects on amino acid requirements. Feed Mix 14, 22–24.
Boisen, S., 2003. Ideal dietary amino acid profiles for pigs. In: D'Mello, J.P.F. (Ed.), Amino Acids in Animal Nutrition. CABI Publishing, Wallingford, UK, pp. 157–168.
Braga, D.D.Á.M., Donzele, J.L., de Oliveira Donzele, R.F.M., de Sousa, M.F., Cardoso, E. F., de Freitas Donzeles, I., de Oliveira, J.P., Furtado, J.M.S., 2018. Evaluation of the standardized ileal digestible lysine requirement of nursery pigs from 28 to 63 d of age in a three-phase feeding program. Semina: Ciências Agrárias 39, 719–730.
Campbell, R.G., Taverner, M.R., Curic, D.M., 1985. Effects of sex and energy intake between 48 and 90 kg live weight on protein deposition in growing pigs. Animal Science 40, 497–503.
Chung, T.K., Baker, D.H., 1992. Ideal amino acid pattern for 10-kilogram pigs. Journal of Animal Science 70, 3102–3111.
Clark, A.B., Tokach, M.D., DeRouchey, J.M., Dritz, S.S., Goodband, R.D., Woodworth, J. C., Touchette, K.J., Bello, N.M., 2017. Modelling the effects of standardized ileal digestible valine to lysine ratio on growth performance of nursery pigs. Translational Animal Science 1, 448–457.
CVB, 1996. Aminozuurbehoefte van biggen en vleesvarkens. CVB documentatierapport nr. 14. Foundation CVB, Lelystad, The Netherlands.
CVB, 2007. CVB table pigs: chemical composition and nutritional values of feedstuffs, and feeding standards. Product Board Animal Feed, The Hague, The Netherlands.
CVB, 2023a. Feed Table. Chemical composition and nutritional values of feedstuffs. Foundation CVB, Lelystad, The Netherlands.
CVB, 2023b. Booklet Feeding of Pigs. Foundation CVB, Lelystad, The Netherlands.
Dean, D.W., Southern, L.L., Kerr, B.J., Bidner, T.D., 2007. The lysine and total sulfur amino acid requirements of six-to twelve-kilogram pigs. The Professional Animal Scientist 23, 527–535.
Edwards, D.B., Tempelman, R.J., Bates, R.O., 2006. Evaluation of Duroc-vs. Pietrain-sired pigs for growth and composition. Journal of Animal Science 84, 266–275.
Engelsmann, M.N., Jensen, L.D., van der Heide, M.E., Hedemann, M.S., Nielsen, T.S., Nørgaard, J.V., 2022. Age-dependent development in protein digestibility and intestinal morphology in weaned pigs fed different protein sources. Animal 16, 100439.
Fontes, D.D.O., Donzele, J.L., Oliveira, R.F.M.D., Silva, F.C.D.O., Lopes, D.C., 2005. Lysine levels for gilts with high genetic potential for lean gain from 15 to 30 kg. Revista Brasileira De Zootecnia 34, 90–97.
Fraga, A.L., Moreira, I., Furlan, A.C., Bastos, A.O., Oliveira, R.P.D., Murakami, A.E., 2008. Lysine requirement of starting barrows from two genetic groups fed on low crude protein diets. Brazilian Archives of Biology and Technology 51, 49–56.
Fruge, E.D., Gerhart, A.J., Hansen, E.L., Hansen, S.A., Coble, K.F., 2017. Effects of increasing standardized ileal digestible (SID) lysine on performance of 11 to 23 kg nursery pigs. Journal of Animal Science 95, 102–103.
Gatel, F., Buron, G., Fekete, J., 1992. Total amino acid requirements of weaned piglets 8 to 25 kg live weight given diets based on wheat and soya-bean meal fortified with free amino acids. Animal Science 54, 281–287.
Gloaguen, M., Le Floc'H, N., van Milgen, J., 2013. Couverture des besoins en acides aminés chez le porcelet alimenté avec des régimes à basse teneur en protéines. INRA Productions Animales 26, 277–288.
Graham, A., Knopf, B., Greiner, L., Gonçalves, M.A.D., Orlando, U.A.D., Connor, J., 2017. Evaluation of the lysine requirement of eleven-to twenty-three-kilogram nursery pigs. Journal of Animal Science 95, 146.
Harper, A.E., Benevenga, N.J., Wohlhueter, R.M., 1970. Effects of ingestion of disproportionate amounts of amino acids. Physiological Reviews 50 (3), 428–558.
Jin, C.F., Kim, J.H., Cho, W.T., Kwon, K., Han, I.K., 1998. Lysine requirement of piglets. Asian-Australasian Journal of Animal Sciences 11, 89–96.
Jones, C.K., Tokach, M.D., Usry, J.L., Neill, C.R., Patience, J.F., 2014. Evaluating lysine requirements of nursery pigs fed low protein diets with different sources of nonessential amino acids. Journal of Animal Science 92, 3460–3470.
Kahindi, R.K., Htoo, J.K., Nyachoti, C.M., 2014. Effect of dietary lysine content and sanitation conditions on performance of weaned pigs fed antibiotic-free diets. Canadian Journal of Animal Science 94, 115–118.

Kahindi, R.K., Htoo, J.K., Nyachoti, C.M., 2017. Dietary lysine requirement for 7–16 kg pigs fed wheat–corn–soybean meal-based diets. Journal of Animal Physiology and Animal Nutrition 101, 22–29.
Kendall, D.C., Gaines, A.M., Allee, G.L., Usry, J.L., 2008. Commercial validation of the true ileal digestible lysine requirement for eleven-to twenty-seven-kilogram pigs. Journal of Animal Science 86, 324–332.
Kim, Y.W., Ingale, S.L., Kim, J.S., Kim, K.H., Chae, B.J., 2011. Effects of dietary lysine and energy levels on growth performance and apparent total tract digestibility of nutrients in weanling pigs. Asian-Australasian Journal of Animal Sciences 24, 1256–1267.
Lenehan, N.A., Tokach, M.D., Goodband, R.D., Nelssen, J.L., Dritz, S.S., DeRouchey, J. M., Usry, J.L., Hastad, C.W., Barker, M.R., Frantz, N.Z., Groesbeck, C.N., James, B. W., Keegan, T.P., Lawrence, K.R., Young, M.G., 2003. The optimal true ileal digestible lysine and threonine requirement for nursery pigs between 25 and 55 lb. Kansas Agricultural Experiment Station Research Reports, 61–66.
Lenehan, N.A., Tokach, M.D., Dritz, S.S., Usry, J.L., Goodband, R.D., DeRouchey, J.M., Nelssen, J.L., Hastad, C.W., 2004. Evaluation of the optimal true-ileal-digestible lysine and threonine requirement for nursery pigs. Kansas Agricultural Experiment Station Research Reports, 68–77.
Li, Q., Patience, J.F., 2017. Factors involved in the regulation of feed and energy intake of pigs. Animal Feed Science and Technology 233, 22–33.
Millet, S., Everaert, N., 2022. Managing feed to optimize pig health. In: Maes, D., Segalés, J. (Eds.), Optimising Pig Herd Health and Production. Burleigh Dodds Science Publishing, Cambridge, UK, pp. 301–332.
Millet, S., Aluwé, M., De Boever, J., De Witte, B., Douidah, L., Van den Broeke, A., Leen, F., De Cuyper, C., Ampe, B., De Campeneere, S., 2018. The effect of crude protein reduction on performance and nitrogen metabolism in piglets (four to nine weeks of age) fed two dietary lysine levels. Journal of Animal Science 96, 3824–3836.
Millet, S., Minussi, I., Lambert, W., Aluwé, M., Ampe, B., De Sutter, J., De Campeneere, S., 2020. Standardized ileal digestible lysine and valine-to-lysine requirements for optimal performance of 4 to 9-week-old Piétrain cross piglets. Livestock Science 241, 104263.
Moretto, V., Donzele, J.L., Oliveira, R.F.M.D., Fontes, D.D.O., 2000. Níveis dietéticos de lisina para suínos da raça Landrace dos 15 aos 30 kg. Revista Brasileira De Zootecnia 29, 803–809.
Nam, D.S., Aherne, F.X., 1994. The effects of lysine: energy ratio on the performance of weanling pigs. Journal of Animal Science 72, 1247–1256.
National Research Council (NRC), 1998. Nutrient requirements of swine, 10th edition. National Academy Press, Washington, DC, USA.
National Research Council (NRC), 2012. Nutrient requirements of swine, 11th edition. National Academic Press, Washington, DC, USA.
Nemechek, J.E., Gaines, A.M., Tokach, M.D., Allee, G.L., Goodband, R.D., DeRouchey, J. M., Nelssen, J.L., Usry, J.L., Gourley, G., Dritz, S.S., 2012. Evaluation of standardized ileal digestible lysine requirement of nursery pigs from seven to fourteen kilograms. Journal of Animal Science 90, 4380–4390.
Nichols, G.E., Vier, C.M., Lerner, A.B., Menegat, M.B., Cemin, H.S., Jones, C.K., DeRouchey, J.M., Tokach, M.D., Goodband, B.D., Woodworth, J.C., Dritz, S.S., 2018. Effects of Standardized Ileal Digestible Lysine on 7–15 Kg Nursery Pigs Growth Performance. Journal of Animal Science 96, 258–259.
Nieto, R., Barea, R., Lara, L., Palma-Granados, P., Aguilera, J.F., 2015. Lysine requirement relative to total dietary protein for optimum performance and carcass protein deposition of Iberian piglets. Animal Feed Science and Technology 206, 48–56.
Noblet, J., Wu, S.B., Choct, M., 2022. Methodologies for energy evaluation of pig and poultry feeds: a review. Animal Nutrition 8, 185–203.
Nørgaard, J.V., Buxant, L., Clausen, D., Sharma, N., Sørensen, P., 2016. Utilization of crystalline and protein-bound amino acids by growing-finishing pigs. Journal of Animal Science 94, 246–248.
Nunes, C.G.V., Oliveira, R.F.M.D., Donzele, J.L., Siqueira, J.C.D., Pereira, A.A., Silva, B.A. N., 2008. Níveis de lisina digestível para leitões dos 6 aos 15 kg. Revista Brasileira De Zootecnia 37, 84–88.
Oliveira, A.L.S.D., Donzele, J.L., Oliveira, R.F.M.D., Abreu, M.L.T.D., Ferreira, A.S., Silva, F.C.D.O., Haese, D., 2006. Dietary digestible lysine requirement of barrows with high genetic potential for lean gain in the carcass from 15 to 30 kg. Revista Brasileira De Zootecnia 35, 2338–2343.
Palencia, J.Y., Resende, M., Lemes, M.A., Mendes, M.F., Silva, S.R., Otani, L., Schinckel, A.P., Abreu, M.L.T., Cantarelli, V.S., 2019. Relative bioavailability of L-lysine sulfate is equivalent to that of L-lysine HCl for nursery piglets. Journal of Animal Science 97, 269–278.
Park, C.S., Kim, B.G., 2015. Standardized ileal digestible lysine requirement of 6-to 10-kg weanling pigs. American Journal of Animal and Veterinary Sciences 10, 150–155.
Pedersen, C., Almeida, J.S., Stein, H.H., 2016. Analysis of published data for standardized ileal digestibility of protein and amino acids in soy proteins fed to pigs. Journal of Animal Science 94, 340–343.
Pesti, G.M., Vedenov, D., Cason, J.A., Billard, L., 2009. A comparison of methods to estimate nutritional requirements from experimental data. British Poultry Science 50, 16–32.
Pomar, C., Kyriazakis, I., Emmans, G.C., Knap, P.W., 2003. Modelling stochasticity: dealing with populations rather than individual pigs. Journal of Animal Science 81, 178–186.
R Core Team, 2022. R: A language and environment for statistical computing (Version 4.2.1), Vienna, Austria. Available at: https://www.R-project.org/.
Rocha, G.C., Duarte, M.E., Kim, S.W., 2022. Advances, implications, and limitations of low-crude-protein diets in pig production. Animals 12, 3478.
Rostagno, H.S., Silva, D.J., Costa, P.M.A., Fonseca, P. M. A., Soares, J. B., Pereira, J. A. A., Silva, M. A., 1992. Composição de alimentos e exigências nutricionais de aves e suínos (tabelas brasileiras). Universidade Federal de Viçosa – Departamento de Zootecnia, Viçosa, Minas Gerais, Brazil.
Rostagno, H. S., Albino, L. F. T., Donzele, J. L., Gomes, P. C., Oliveira, R. D., Lopes, D. C., Ferreira, A. S.; Barreto, S. L. T., Euclides, R. F., 2011. Tabelas brasileiras para aves e suínos: composição de alimentos e exigências nutricionais. 3ª Edição. Universidade Federal de Viçosa – Departamento de Zootecnia, Viçosa, Minas Gerais, Brazil.
Rostagno, H. S., Albino, L. F. T., Hannas, M. I., Donzele, J. L., Sakomura, N. K., Perazzo, F. G., Saraiva, A., Teixeira, M. L., Rodrigues, P. B., Oliveira, R. F., Barreto, S. L. T., Brito, C. O., 2017. Tabelas brasileiras para aves e suínos: composiçao de alimentos e exigências nutricionais. 4ª Edição. Universidade Federal de Viçosa – Departamento de Zootecnia, Viçosa, Minas Gerais, Brazil.
Schneider, J.D., Tokach, M.D., Dritz, S.S., Nelssen, J.L., DeRouchey, J.M., Goodband, R. D., 2010. Determining the effect of lysine: calorie ratio on growth performance of ten-to twenty-kilogram of body weight nursery pigs of two different genotypes. Journal of Animal Science 88, 137–146.
Taylor, A.E., Toplis, P., Wellock, I.J., Miller, H.M., 2012. The effects of genotype and dietary lysine concentration on the production of weaner pigs. Livestock Science 149, 180–184.
Tybirk, P., Sloth, N.M., Kjeldsen. M., Blaabjerg, K., 2021. Danish nutrient standards. 32nd edition. SEGES, Videncenter for Svineproduktion. Denmark. Retrieved on 10 December 2022 from: https://pigresearchcentre.dk/Nutrient-standards.
Urynek, W., Buraczewska, L., 2003. Effect of dietary energy concentration and apparent ileal digestible lysine: metabolizable energy ratio on nitrogen balance and growth performance of young pigs. Journal of Animal Science 81, 1227–1236.
van Milgen, J., Valancogne, A., Dubois, S., Dourmad, J.Y., Sève, B., Noblet, J., 2008. InraPorc: a model and decision support tool for the nutrition of growing pigs. Animal Feed Science and Technology 143, 387–405.
van Milgen, J., Gloaguen, M., Le Floc'H, N., Brossard, L., Primot, Y., Corrent, E., 2012. Meta-analysis of the response of growing pigs to the isoleucine concentration in the diet. Animal 6, 1601–1608.
Vier, C.M., De Souza, I.B., De Jong, J.A., Gonçalves, M.A.D., Jones, A.M., Goodband, R. D., Tokach, M.D., DeRouchey, J.M., Woodworth, J.C., Dritz, S.S., 2016. Determining the standardized ileal digestible lysine requirement of 6.8 to 15.9 kg pigs. Journal of Animal Science 94, 191.
Wang, Y., Zhou, J., Wang, G., Cai, S., Zeng, X., Qiao, S., 2018. Advances in low-protein diets for swine. Journal of Animal Science and Biotechnology 9, 1–14.
Whittemore, C.T., Hazzledine, M.J., Close, W.H., 2003. Nutrient requirements standards for pigs. British Society of Animal Science, Penicuik, UK.
Williams, N.H., Stahly, T.S., Zimmerman, D.R., 1997. Effect of chronic immune system activation on body nitrogen retention, partial efficiency of lysine utilization, and lysine needs of pigs. Journal of Animal Science 75, 2472–2480.
Yi, G.F., Gaines, A.M., Ratliff, B.W., Srichana, P., Allee, G.L., Perryman, K.R., Knight, C. D., 2006. Estimation of the true ileal digestible lysine and sulfur amino acid requirement and comparison of the bioefficacy of 2-hydroxy-4-(methylthio) butanoic acid and DL-methionine in eleven-to twenty-six-kilogram nursery pigs. Journal of Animal Science 84, 1709–1721.