Determining the optimal dietary lysine levels to maximise growth performance of boars and gilts throughout the grower/finisher stage of pig production and its impact on behaviour and welfare

by

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Abstract

With increasing slaughter weights and changing genetics, reviewing growing-finishing pigs lysine requirements is necessary, given it is usually the amino acid first-limiting in their diets. Additional aims were to determine whether requirements differ between sex, and if feeding lysine below or above requirements impacts behaviour and welfare. At approximately 36 kg, a total of 320 pigs ((Large White x Landrace) x Danish Duroc)) were allocated to mixed sex pens of 10. Pens were allocated to one of four dietary lysine treatments (eight replicates per treatment) each following a 3-phase feeding regime with isoenergetic diets and phases from d0-21, d22-49, and d50-slaughter (d64-d84). Treatments and their standardized ileal digestible lysine concentrations in each phase were as follows: Low (0.71, 0.62, 0.52 SID lysine), Med. Low (0.90, 0.76, 0.67 SID lysine), Med. High (1.09, 0.90, 0.81 SID lysine) and High (1.28, 1.09, 1.00 SID lysine). Statistical analyses were performed using linear mixed models or generalized linear models and lysine requirements for optimal average daily gain (ADG) and feed conversion ratio (FCR) estimated using linear plateau, quadratic plateau and quadratic models. Boars grew faster ($p<0.001$) than gilts but consumed similar quantities of feed ($p=0.183$) and were more feed efficient ($p<0.001$). Both sexes responded to increasing dietary lysine with improvements to FCR, ADG and end weight ($p<0.001$), but to differing extents. The boars' greater response and higher estimated lysine requirements would support split sex feeding, with potential economic and environmental benefits. Weekly behavioural observations and lesion scoring found pigs on the High treatment had fewer lesions ($p<0.001$), engaged in less fighting/aggression ($p=0.001$) and were more inactive ($p<0.001$) compared to pigs on the Low treatment. These latter pigs showed increased exploration ($p<0.001$) and damaging behaviours ($p=0.007$) alongside different feeding related behaviours. Consequently, increasing dietary lysine above recommendations could positively improve grower-finisher pigs welfare and performance.

Key words: lysine, lysine requirements, boars, gilts, behaviour

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Chapter 1. Literature review

1.1. Lysine, requirement differences between sexes, changing requirements and nitrogen excretion

In the UK pig industry, there are various challenges being faced ranging from high feed costs and reduced breeding herds to the reduced demand for pork products driven by the cost-of-living crisis (AHDB, 2023a). There are also the longer-term challenges of climate change and increasing demand, with sustainable intensification in response to these becoming increasingly important in the coming years and decades. Regardless of the nature of the challenge, reducing production costs and improving production efficiency will likely always be considered a priority. Feed is the greatest contributor to total production costs and one of the most variable costs of production (Alves et al., 2022), so one area in particular where there is potential to meet these goals is the grower-finisher stage (from approximately 30-120 kg). This typically comes at a high cost due to pigs consuming as much as 80% of the total feed used (per unit of product sold) (Cline and Richert, 2001) and pigs generally being the least efficient in this phase, a result of their higher body weights (Patience et al., 2015). Understandably this period of production has been the focus of research to better understand dietary requirements and more accurately formulate diets for maximum growth whilst keeping costs low. In this review the focus will be on the amino acid lysine, discussing how it can affect growth and behaviour and how sex may influence requirements.

The role of lysine in muscle accretion

As one of the 20 amino acids used in protein synthesis, for pigs lysine is not only essential but also the amino acid often first limiting in typical diets and it has a range of growth-related, metabolic functions (Liao et al., 2015). These include being a proteinogenic substrate for the synthesis of proteins and peptides and having a regulatory role in the metabolism of other amino acids and nutrients. For example, supplementing lysine in the diet is thought to be able to enhance the intestinal absorption of calcium and improve the retention of absorbed calcium in the kidney (Civitelli et al., 1992; Liao et al., 2015). However, the most important of these roles is protein synthesis which can be linked to muscle protein accretion. This means increasing lysine content in pig diets can improve their lean tissue deposition (i.e. muscle growth) by raising the protein synthesis rate, as opposed to lowering the rate of degradation (Roy et al., 2000). Muscle growth largely refers to skeletal muscle, which accounts for the greatest proportion of total muscle mass and is the predominant muscle of interest in livestock production, being that which most pork products are composed of. The growth of skeletal muscle, referred to as lean gain, and the efficiency of this muscle gain is typically focused on rather than overall gain of body weight (Liao et al., 2015). This is because a proportion of weight gain will be from adipose tissue (fat) deposition rather than lean tissue deposition. Genetics, amongst other things, determines the pig's potential for lean tissue and adipose tissue deposition, with the former generally being considered desirable and the latter not. Consequently, over the past few decades, improved lean gain and feed efficiency have been selected for in addition to carcasses with a reduction in fat content. Particularly backfat which is indicative of the whole-body fat content (Gozalo-Marcilla et al., 2021). Although Schumacher et al. (2022) provided evidence that too little fat in the carcass can comprise meat quality and taste.

While genetics largely dictates these traits, whether a pig performs at its genetic potential can depend on numerous things, including its health status, environment and nutrition. In terms of diet, the two most important aspects for lean growth are energy and protein (de Lange et al., 2001, p.77) both of which are also the two most expensive components (Aymerich et al., 2021). Often high levels of soya bean are used as a protein source, which has environmental implications, due to land use change and its importation from places like South America (zu Ermgassen et al., 2016). In addition to this, high dietary crude protein can lead to high levels of nitrogen excretion, a major environmental concern, due to nitrogen causing issues with eutrophication and groundwater potability, as well as contributing to ammonia emissions and associated acid rain (Lenis, 1989; Millet et al., 2018a). Therefore, to reduce these impacts (and feed costs) diets formulated to be low in crude protein but which still meet amino acid requirements are becoming common, which can also help the performance and gut health of younger pigs, post-weaning (Fang et al., 2019). To maintain performance on these diets amino acids are instead supplemented as crystalline amino acids (Rocha et al., 2022). This is often how lysine will be added to diets, but determining the correct quantities to include in feed involves understanding the impact of lysine on growth performance and hence defining the pigs lysine requirements.

Dietary lysine and growth performance

Studies into the effect of lysine on growth performance are numerous, with the benefits of increasing dietary lysine clear. In terms of general growth performance, increasing dietary lysine has been shown to increase average daily gain (ADG), improve feed efficiency (Cline et al., 2000; King et al., 2000; O'Connell et al., 2006; Main et al., 2008; Rikard-Bell et al., 2012; Soto et al., 2019; Hu et al., 2022) and increase carcass leanness (Cline et al., 2000; King et al., 2000; Main et al., 2008; Rikard-Bell et al., 2012). Conversely a deficiency of dietary lysine will negatively affect growth, reducing ADG and worsening feed efficiency (Liao et al., 2015). Oversupplying lysine isn't believed to have any toxic effects (Liao et al., 2015) and excess lysine will often be catabolized, providing some energy. However, greatly oversupplying lysine would increase feed costs and some studies have shown performance reductions at the highest levels (Edmonds and Baker, 1987; Van Lunen and Cole, 1996; Aymerich et al., 2020). While the detrimental effects from undersupplying lysine are much more of a concern, oversupplying lysine should also be avoided.

Understanding the impact of lysine and other nutrients on growth performance allows recommended dietary nutrient levels to be formulated, levels which are affected by multiple factors, e.g. genetics, sex, stage of growth, health status and environmental conditions (Cline and Richert, 2001). Nutrient recommendations for pigs need to be regularly reviewed and updated to ensure diets are meeting the requirements to support optimal growth performance. Most diets being used will likely include lysine at the NRC (2012) recommended levels, shown in Table 1.1 (adapted from NRC, 2012). But given the ever-changing and advancing genetics of modern pig breeds, how closely these recommendations match the true requirements of pigs currently being reared requires evaluation. Since this last NRC report, the average UK live weight for pigs going to slaughter has increased from approximately 100 kg in 2012 to 115 kg at the end of 2021 (AHDB, 2023b). It is therefore important to establish whether these heavier weight pigs have different nutritional requirements for optimal growth. Additionally, while differences in nutrient requirements between sexes have been acknowledged, studies investigating this aren't all in agreement, prompting the need for further clarification.

Table 1.1. Lysine requirements published by the NRC (2012) for growing pigs over different weight ranges when fed *ad libitum*[1 2]

	SID Lysine (%)			
	20-50 kg	**50-75 kg**	**75-100 kg**	**100-135 kg**
Growing pigs[3]	0.98	0.85	0.73	0.61
Boars		0.88	0.82	0.73
Gilts		0.87	0.77	0.64

SID = standardized ileal digestible

[1] Adapted from "Nutrient Requirements of Swine: Eleventh Revised Edition", by NRC. 2012, pp. 210-211 (Table 16-1A) and pp. 214-215 (Table 16-2A).

[2] Fed diets with 90% dry matter content.

[3] Includes barrows and gilts (1:1 ratio).

Sex differences in lysine requirements

Lack of castration in the UK means boars show significantly different growth to gilts, growing faster and producing leaner carcasses (Aymerich et al., 2021). Countless studies have demonstrated that boars have higher growth rates compared to gilts and are more feed efficient, (O'Connell et al., 2006; Moore et al., 2012; Rikard-Bell et al., 2012; Aymerich et al., 2021). Generally, pigs will need more lysine the higher their protein deposition rate is (de Lange et al., 2001, p.77) and since boars have a higher protein deposition potential than gilts, theoretically they will have higher lysine requirements for maximum growth (Aymerich et al., 2020).

While it is recognized that the different growth performance of boars in comparison to both gilts and barrows may drive them to have differing lysine requirements, the literature on this isn't consistent. This section will cover some of the main, relevant studies in this area (summarised in Table 1.2 at the end of the section), which focused on lysine requirement differences between boars and gilts. As expected, this is an area with numerous studies already, the first from a few decades ago. These earlier studies began to indicate that a difference in lysine requirements does occur, with Batterham et al. (1985) observing that concentration of dietary lysine affected ADG and feed conversion ratio (FCR), as well as feed intake but with differing responses depending on sex (and stage of growth). Their analyses suggested that at higher weights (75-80 kg) maximum ADG was achieved at a lower lysine concentration (5.6g lysine/kg of feed) for females than for entire males (boars, 8 g/kg). Giles et al. (1987) similarly found that increasing dietary lysine increased the ADG of boars in a curvilinear response but had no apparent effect for females. Pigs were only taken to 50 kg in this study and the boars' maximum daily rate of gain (at ~40 kg) was estimated to occur at a concentration of 12 g/kg. Both of these studies also looked at carcass composition, which was seemingly unaffected by lysine, except when pigs were restrictively fed and carcass fatness for pigs on the 12 g/kg lysine concentration treatment reached a minimum (Giles et al., 1987).

Unlike the previous two studies Van Lunen and Cole (1996) used both boars and barrows (castrated males) as well as gilts, up to heavier weights of 90 kg, again looking at the effect of dietary lysine on growth but using differing lysine to energy ratios (g lysine/MJ energy). This is a common way to express requirements since the utilisation of amino acids for protein deposition is energy dependent (Moore et al., 2012). They found no evidence for a difference in requirements between the three, but at the highest lysine levels ADG of the barrows and gilts didn't just plateau, as was the case in the previous studies, but began to decrease. They attributed this decrease to a reduction in energy available for growth, with it instead being directed towards deamination of excess protein, present from the increased crude protein used to achieve the high lysine levels in the diets. In agreement with this study, King et al. (2000) concluded that for optimal protein deposition (at 104 g/d), lysine requirements of finisher boars and gilts during growth from 80-120 kg did not significantly differ (a concentration of 0.39 g lysine/MJ energy (DE, digestible energy) was estimated for both sexes to achieve 95% of the maximum protein deposition). After this came three studies by O'connell et al. (2005) which looked at grower pigs from 20-68 kg and a further three studies using heavier finisher pigs from 60-100 kg (O'connell et al., 2006). For the former, although the FCR of boars was comparatively better than that of gilts, the concentrations of lysine calculated for optimal ADG and FCR for each sex were not different. The same was found in two of the finisher pig trials (O'connell et al., 2006) but the other showed males had a higher requirement of lysine for both optimal ADG and FCR. From 80-100 kg, penned in pairs and fed diets of lysine concentrations ranging from 7 to 13.5 g/kg (8 different diets), these requirements for optimal ADG and FCR were 11.8 and 11.9 g/kg respectively for the boars and 9.9 and 10.0 g/kg respectively for the gilts.

Already the discrepancies around lysine requirements and sex are evident, but the findings from studies over the past 12 years show somewhat more consistency. While they may not agree on the exact values of lysine required, it seems much more evident that a difference in requirements, whatever that may be, does occur. While not directly investigating lysine, Quiniou et al. (2010) compared the growth performance of boars, gilts and barrows and using van Milgen et al.'s (2008) InraPorc model found the simulated lysine requirements were lower for gilts and barrows than for boars. As a result of their improved efficiency for lean tissue deposition, Dunshea et al. (2013) further modelled Quiniou et al.'s data (again using InraPorc) and suggested boars have a standardized ileal digestible lysine: net energy requirement (SID Lys: NE) that is 114% that of gilts in late finishing, from 95-125 kg. This is higher than the 108% suggested for 50-95 kg, showing that at heavier body weights the differences in lysine requirements may become more pronounced, shown in Figure 1.1 (Dunshea et al., 2013, pp. 1775). Since its estimated that at around 40-70 kg is the time when boars and gilts growth performance begin to differentiate (Aymerich et al., 2020) it is reasonable to predict that requirements at the start of finishing are fairly homogenous before beginning to diverge.

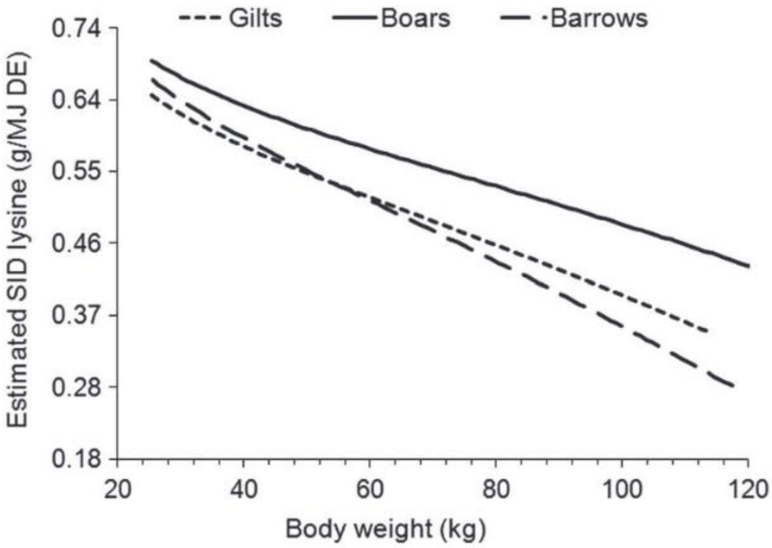

Figure 1.1. A graph illustrating the reduction in pigs' lysine requirements during growth from approximately 20 to 120 kg and the differences in requirements between gilts, boars and barrows over this time. Dunshea et al. (2013), p1775., using data from Quiniou et al. (2010).

Findings from both Moore et al. (2012) and Rikard-Bell et al. (2012) further suggest that during finishing boars have higher lysine requirements, as growth performance of boars responded to increasing lysine up to higher concentrations. In the study by Rikard-Bell et al. (2012), using finisher pigs penned individually (from 60 to 90 kg), the range of lysine concentrations used (0.40 to 0.72 g/MJ DE) was not sufficient to limit the boars performance but an estimated 0.56 g/MJ DE maximised the gilts ADG and FCR. However, when using only a slightly higher range of concentrations (0.40 to 0.80 g/MJ DE) for pigs weighing ~50-100 kg, Moore et al. (2012) were able to estimate lysine requirements for both sexes, which were substantially different for optimal FCR (reported as F: G (feed to gain ratio)). The greatest requirement difference reported in this study occurred for pigs in the weight range 80-95 kg, for which F: G (or FCR) was minimised at a concentration of 0.63 g/MJ DE for boars as opposed to 0.40 g/MJ DE for gilts. Unlike in the study by Rikard-Bell et al. (2012) pigs were penned in groups (of seven) which could partially explain the studies differing results.

In addition to these requirement differences, Moore et al. (2012) saw a negative effect on the growth performance of gilts when lysine was supplied above requirements. As previously mentioned, Van Lunen and Cole (1996) saw a similar effect of oversupplying lysine for gilts and a recent meta-analysis carried out by Aymerich et al. (2021) also highlighted this negative correlation.

They suggested it could either be a result of the redirection of energy for deamination, or a reduction in ADFI which was observed in an earlier study (Aymerich et al., 2020). This tendency was observed in the dose response trial carried out by Aymerich et al. (2020) in which both boars and gilts showed a slight decrease in ADFI as SID lysine: NE (net energy) was increased during the latter end of finishing (89-106 kg). Overall, Aymerich et al. (2020) found that in accordance with other studies boars and gilts do respond differently to increasing SID lysine: NE, estimating that the boars requirements were 117% of gilts (3.63 vs 3.10 g SID lysine/Mcal NE), with the higher protein deposition of males being used to explain why they responded to higher levels of lysine than females.

To further clarify the differing responses of boars and gilts, Aymerich et al. (2021) carried out a meta-analysis using 11 publications. The findings were as expected, boars were more feed efficient and faster growing, which they suggested must be the driving factors behind their higher lysine requirements. These were calculated from each sex's response to increasing SID lysine: NE and for finisher pigs of the weight 70-100 kg the boars dietary lysine requirement was approximated at 115% of gilts. This was higher than the 108% quoted by Dunshea et al. (2013) for 50-95 kg. The concentrations of SID lysine (%) estimated to maximise ADG and G: F (gain to feed ratio), respectively, were 1.06 and 1.11 SID lysine for boars and 0.92 and 0.95 SID lysine for gilts (Aymerich et al., 2021). They also concluded that both sexes have similar feed intakes throughout finishing, supporting some studies (O'Connell et al., 2006; Moore et al., 2012; Rikard-Bell et al., 2012) but contradicting others, which assume boars actually consume slightly less (NRC, 2012; Dunshea et al., 2013). If feed intake doesn't differ then it's likely not contributing to the different lysine requirements as was proposed (Dunshea et al., 2013). Using ADFI and the SID lysine: NE content of the diets, Aymerich et al. (2021) calculated daily SID lysine intake. These values could then be used to estimate efficiency of lysine use (per kg of gain) for each sex, finding that boars and gilts used lysine with similar efficiencies, suggesting this also isn't behind the differing requirements. Instead, they concluded requirement differences are more likely to be driven by the different feed efficiencies and performances of each sex, with the boars improved efficiency a result of their higher growth rates and greater proportion of growth from protein deposition (Aymerich et al., 2021).

Although there is evidence in the literature on boars and gilts having different lysine requirements, the variations in experimental design and different methods of analyses, which have led to inconsistent results, mean this is still an area requiring research if definitive requirements are to be identified and used in the formulation of diets. Over the years these different studies have used pigs with differing genetics, start and end weights and used different housing conditions (see Table 1.2), trial lengths and diet formulations i.e. how dietary lysine was altered (Aymerich et al., 2021). In terms of housing, a number of studies penned pigs individually or in pairs (King et al., 2000; O'Connell et al., 2005; O'Connell et al., 2006; Rikard-Bell et al., 2012) which doesn't replicate commercial conditions where pigs are usually in groups. This may have influenced the observed feed intakes, as boars individually penned will consume more than they would in typical commercial conditions (Dunshea et al., 2005; Dunshea et al., 2013). Furthermore, in some of the studies where pigs were in groups, these were likely single sex pens, given that measurements were taken on a pen basis (Moore et al., 2012; Aymerich et al., 2020), with the performance of each sex in mixed sex pens not necessarily being studied as often. These factors can't with certainty be held accountable for the varying results but contribute towards the justification of further study in this area.

Table 1.2. Summary of the studies reviewed which looked at differences in lysine requirements between boars and gilts

Study	Sex	Feeding Strategy	Housing	Weight range (kg)	Lysine range	Estimated lysine concentration for optimal performance	Performance measure	Sex diff? Y/N
Batterham et al. (1985)	Boars & Gilts	*Ad libitum*	N/S	20-85	7-10 g/kg	Boars (80 kg)- 8 g/kg; Gilts (75 kg) - 5.6 g/kg	ADG	**Y**
Giles et al. (1987)	Boars & Gilts	*Ad libitum*	N/S	20-50	7-14 g/kg	Boars (40.3 kg) - 12 g/kg; Gilts - No effect of Lys	ADG	**Y**
	Boars & Gilts	Restricted	N/S	20-50	7-14 g/kg	Boars (50 kg) - 11.2 g/kg; Gilts (50 kg) - 13.1 g/kg	ADG	**Y**
Van Lunen and Cole (1996)	Boars, Gilts & Barrows	*Ad libitum*	N/S	25-90	0·4 to 1·4 g/MJ	Boars, Gilts & Barrows - 0·95 to 1·0 g/MJ	N/S	N
King et al. (2000)	Boars & Gilts	*Ad libitum*	Individually	80-120	4.8-9.7 g/kg	Boars & Gilts - 0.35 g available Lys/MJ DE	Growth rate & FCR	N
						Boars & Gilts - 0.39 g available Lys/ MJ DE	Protein deposition	
O'connell et al. (2005) - **1.**	Boars & Gilts	N/S	Pairs	20-41	9.7-14.4 g/kg	Boars & Gilts - 13.1 g/kg; 14.6 g/kg	ADG, FCR	N
O'connell et al. (2005) - **2.**	Boars & Gilts	N/S	Pairs	40-68	9.0-14.1 g/kg	Boars & Gilts - 12.7 g/kg; 12.2 g/kg	ADG, FCR	N
O'connell et al. (2005) - **3.**	Boars & Gilts	N/S	Groups (14)	40-62	9.0-14.1 g/kg	Boars & Gilts - 12.7 g/kg	FCR	N
O'connell et al. (2006) - **1.**	Boars & Gilts	N/S	Pairs	60-90	7.9-12.5 g/kg	Boars & Gilts - 10.8 g/kg; 10.9 g/kg	ADG, FCR	N
O'connell et al. (2006) - **2.**	Boars & Gilts	N/S	Pairs	80-100	7.0-13.5 g/kg	Boars - 11.8 & 11.9 g/kg; Gilts - 9.9 &10.0 g/kg	ADG, FCR	**Y**
O'connell et al. (2006) - **3.**	Boars & Gilts	N/S	Groups (13)	80-100	7.0-11.7 g/kg	Boars & Gilts - 9.3 g/kg; 9.6 g/kg	ADG, FCR	N
Moore et al. (2012) - **1.**	Boars & Gilts	*Ad libitum*	Groups (7)	22-53	0.6-1.0 g Lys/ MJ DE	(20-35 kg) Boars - 1.00 & 1.00 g/ MJ DE; Gilts - 0.90 & 0.86 g/MJ DE	ADG, F:G	**Y**
						(35-50 kg) Boars - 0.87 & 0.87 g/MJ DE; Gilts - 0.84 & 0.85 g/ MJ DE	ADG, F:G	
Moore et al. (2012) - **2.**	Boars & Gilts	*Ad libitum*	Groups (7)	50-103	0.4-0.8 g Lys/ MJ DE	(50-65 kg) Boars - 0.72 & 0.80 g/ MJ DE; Gilts - 0.67 & 0.64 g/ MJ DE	ADG, F:G	**Y**
						(65-80 kg) Boars - 0.67 & 0.69 g/ MJ DE; Gilts - 0.63 & 0.66 g/ MJ DE	ADG, F:G	
						(80-95kg) Boars - 0.63 & 0.63 g/ MJ DE; Gilts - 0.58 & 0.40 g/ MJ DE	ADG, F:G	
Rikard-Bell et al. (2012)	Boars & Gilts	N/S	Individually	60-90	0.40-0.72 g/MJ DE	Boars - NA (diets did not limit performance); Gilts - 0.56 g/ MJ DE	ADG, FCR, carcass wgt.	**Y**
Aymerich et al. (2020). **Period 1.**	Boars & Gilts	*Ad libitum*	Groups (13)	70-89	0.63-1.00 g/MJ	Boars - 3.71 to 4.05 g/ Mcal NE; Gilts - 3.13 g/ Mcal NE	ADG	**Y**
Aymerich et al. (2020). **Overall**	Boars & Gilts	*Ad libitum*	Groups (13)	70- 106	0.63-1.00 g/MJ	Boars - 3.63 to 4.01 g/ Mcal NE; Gilts - 3.10 g/ Mcal NE	ADG	**Y**
Aymerich et al. (2021). **Meta-analysis**	Boars & Gilts	N/A	N/A	av. 70–100	0.38-1.23 g/MJ	Quadratic models: Boars - 1.01 g/ MJ NE; Gilts - 0.88 g/ MJ NE	ADG	**Y**
						Quadratic models: Boars - 1.06 g/ MJ NE; Gilts - 0.91 g/ MJ NE	G:F	
						Quadratic Plateau models: Boars - 0.926 g/ MJ NE; Gilts - 0.872 g/ MJ NE	ADG	

Nitrogen excretion and phase feeding

Although oversupplying lysine is not likely to have a serious detrimental effect on the growth or health of the pigs (with only slight reductions in performance observed by Van Lunen and Cole (1996), Moore et al. (2012) and Aymerich et al. (2020)), it will increase production costs and nutrient wastage. The main concern with this is in regard to nitrogen, which is either present in the atmosphere in its molecular form (N_2) or in multiple different forms (e.g. NH_3 (ammonia) or NO_3^- (nitrate)) known as fixed or reactive nitrogen (Leip et al., 2013). Living organisms all require nitrogen, as it is an essential component of all proteins and other important biomolecules, but only the fixed forms of nitrogen are accessible to plants and animals. So rather than nitrogen itself being included in diets, pigs are instead supplied with amino acids and protein, which already contain nitrogen (Lautrou et al., 2022). Only a proportion of the ingested amino acids will be absorbed (in the small intestine) and made available for use in the body, known as bioavailability. This and the inability of amino acids to be stored to any substantial extent means that a significant proportion of the nitrogen will be excreted (mostly via faeces and urine). From rearing a piglet to finisher weight (~110 kg), Millet et al. (2018a) estimated this amount of excreted nitrogen to be approximately 54% (of the total amount used throughout the pigs lifetime). Although much higher values of around 60-70% were suggested in earlier studies (Canh, 1998; Dourmad et al., 1999). Nitrogen containing manure (both urine and faeces) may end up being used as fertilizer, allowing some of the nitrogen to be reincorporated into plants (Millet et al., 2018a). But as a source of ammonia (NH_3), nitrate ions (NO_3^-) and nitrogen oxides (NO_x), nitrogen in manure may also be lost to the environment as a pollutant. For example, roughly 30% of excreted nitrogen may be lost via the release of ammonia (gas) which is converted from ammonium ions in the manure at pHs above 7 (Canh, 1998). Other losses may occur once manure is applied to agricultural land, such as the movement of nitrate into surface waters and groundwater by runoff and leaching (Leip et al., 2013). This causes problems with water potability and eutrophication, whilst the main concerns with ammonia are linked to the acidification of environments (soils and water bodies) and acid rain (Lenis, 1989). N_2O (nitrous oxide) is also contributing to greenhouse gas emissions. These impacts demonstrate why from an environmental perspective, reducing nitrogen excretion has long been one of the main objectives in pig production.

Advancements have been made towards this goal in the past few decades, targeting both diet and management. Management strategies include things such as genetic selection for pigs which show improved protein efficiency (or a lower residual feed intake), the rearing of leaner more efficient boars as opposed to barrows and slaughtering pigs at slightly lighter weights (Millet et al., 2018a). Despite the potential for some of these methods to reduce nitrogen excretion, their employment is not as simple as that of diet/nutritional strategies, which can also have the biggest influence. Nitrogen ingested, the proportion able to be absorbed, the balance of dietary amino acids and the individuals' requirements for these amino acids all determine how much nitrogen is excreted (Millet et al., 2018a). Therefore, better meeting nutritional requirements as they change throughout growth can limit the amount of protein/amino acids being ingested in excess and so reduce nitrogen excretion. Phase feeding is one of the ways to do this, with various studies confirming that this feeding strategy is one way to reduce nitrogen excretion in growing pigs (Lee et al., 2000; Andretta et al., 2016b; Monteiro et al., 2016).

Phase feeding involves feeding pigs two or more differently formulated diets over a period of growth to meet their requirements more closely over this time (Pomar et al., 2021). Common practise is to feed pigs in groups of similarly aged individuals with a diet formulated to meet the average requirements of these individuals over a certain weight range. When production systems use one feed for a long period of time (e.g. over the whole finishing period) the group's nutrient requirements will be changing and so for a large proportion of time pigs are either receiving nutrients in excess or below what they require. Phase feeding minimises this by using multiple diets, fed over a smaller weight/age range and formulated to meet the corresponding requirements at these times, so in theory pigs spend less time consuming feed above or below requirements. The earliest studies began to show that nitrogen excretion can be reduced by using phase feeding, e.g. Lee et al. (2000) saw a 12% reduction when finisher pigs were fed three or four diets rather than one. A greater number of phases is proposed to improve this further (Pomar et al., 2021), which was indeed the case in a study by Andretta et al. (2016b) where pigs fed individually tailored diets on a daily basis excreted around 30% less nitrogen than those fed on a group phase feeding regime (with three phases). Despite these benefits, high facility costs and the practicalities of storing and using multiple feeds on farm (Han et al., 2000; Pomar et al., 2021) mean this precision feeding strategy may not be a viable option for many farmers. Nevertheless, if phase feeding continues to become more widespread, more accurately outlining nutrient requirements (including that of lysine) over specific weight/age ranges will be necessary.

Another strategy used is to decrease crude protein content of diets and instead meet amino acid requirements using crystalline amino acids (Wang et al., 2018). Typically, increased lysine levels in feed, in order to meet requirements of this first limiting amino acid, have been achieved by raising crude protein levels. However, this means many of the other amino acids are provided in excess and their deamination and excretion will consequently contribute to higher levels of nitrogen excretion. Using the results of seven published studies, Wang et al. (2018) estimated that the emissions of ammonia can be reduced by 8-10% for every 10 g/kg decrease in crude protein. Amino acids instead being provided in the diets to their individual requirement levels. These levels and the balance between different amino acids must be clearly defined as the deficiency of one amino acid can impact the utilization of others (Millet et al., 2018a). This in turn could increase nitrogen excretion, providing another incentive for the lysine requirements of boars and gilts to be accurately defined and updated. It should also be noted that because lysine is generally first limiting, it is typical for the other dietary amino acids to be included in diets at ratios relative to lysine, this concept is that of ideal protein (Boisen, 2003) and is conventionally used when formulating swine diets.

Future prospects

Although the NRC (2012) did publish specific nutrient requirements for boars and gilts (see Table 1.1), genetics have undoubtedly changed since this report was published more than a decade ago. Performance measures such as rate of gain (ADG) and feed efficiency have been improved as a result of these genetic improvements (van der Peet-Schwering and Bikker, 2018) and it can be expected that amino acid requirements, particularly lysine, have altered in response due to their role in protein deposition. This change in requirements has been evident in studies where lysine requirements have been reported higher than those recommended (Aymerich et al., 2021). Current diets should therefore be tested against those with higher levels of lysine to ascertain whether requirements have increased along with improvements in performance, nutrition, management and genetics. It should also be assessed whether changing genetics are shifting the requirements of both boars and gilts equally, or perhaps making them differ more significantly. If the latter is the case and diets were to be fed to both sexes with increased lysine levels to meet the higher requirements of boars, then the gilts production cost would increase (Aymerich et al., 2020) along with the environmental impacts associated with their production (as they would likely excrete more nitrogen). These economic and environmental considerations must therefore be taken into account if recommendations are to change.

However, one way to avoid this would be by splitting pens by sex, which would enable boars and gilts to be fed more tailored diets to meet their requirements. This may potentially maximise the performance of both sexes, improve efficiency and reduce nutrient output. All of which are important goals for the pig industry in terms of production costs and environmental impacts. However, in single sex pens a reduction in welfare is thought to occur for boars, attributed predominantly to their tendency to engage more frequently in aggressive behaviours and sexual behaviours like mounting. Both of these can result in scratches and bruising, with mounting in particular being linked to leg related injuries and lameness (Li et al., 2019). Some studies suggest that aggressive behaviours and mounting performed by boars are reduced when they are in mixed sex pens, with Björklund and Boyle (2006) observing a decrease in mounting over time for those in mixed pens, whilst levels were maintained in all male pens. But Rydhmer et al. (2006) found males did not behave significantly differently when in single sex pens versus mixed ones, performing the same behaviours to pen mates seemingly regardless of sex. If further research confirms this is the case, or a way to avoid this reduction in welfare is proposed, then splitting pens by sex would be beneficial. Also, because it is thought to improve the welfare of gilts, with less mounting carried out in female only pens (Björklund and Boyle, 2006). The trend for increasing slaughter weight that has been observed over the last few decades and was exacerbated during the coronavirus pandemic (and Brexit), is another reason why splitting pens by sex has gained interest. There are welfare concerns around housing these heavier weight pigs which have reached sexual maturity, due to pigs at these weights performing more mounting and so inflicting more injuries and from an increase in the proportion of gilts pregnant at slaughter (More et al., 2017). If pigs continue to be reared to such weights, single sex housing may be necessary, facilitating split sex feeding. Alternatively, precision feeding would again enable boars and gilts to receive sex specific diets but also individually tailored diets (Pomar et al., 2021) whilst remaining in the same pen and thus avoiding this welfare issue.

1.2. Lysine and behaviour

Most studies involving lysine and pig production investigate how it can affect growth performance with significantly fewer considering the possible behavioural effects of differing lysine levels, despite behaviour itself impacting performance as well as welfare. Fornós et al. (2022) reviewed how feeding related behaviours can affect both carcass quality and performance of grower-finisher pigs, exploring a series of factors which may influence these behaviours including sex, diet composition and environmental conditions. These feeding related behaviours and the factors affecting them will be discussed to determine whether varying dietary lysine could also influence these behaviours and what that could mean in terms of performance.

Feeding related behaviours

Some of the main behaviours of interest in relation to production and growth performance are the feeding related behaviours of pigs. This includes things such as feed intake, the number of meals a pig chooses to consume a day, size of these meals and the rate of consumption of feed (amongst other similar measures). With *ad libitum* access to feed, pigs will tend to eat at discrete intervals (Chassé et al., 2021) primarily throughout the day and with two peaks in feeding (Simonsen, 1990), often showing variation in the amount of feed they eat in a day (ADFI – average daily feed intake). ADFI is perhaps the most commonly looked at feeding related behaviour and can be influenced by a number of factors, both internal and external (such as age, health status, environmental conditions, diet composition, sex and genotype (Boumans et al., 2015)), making it a very complex measure to predict (Fornós et al., 2022). But while ADFI does vary between individuals, often as a result of these factors, the variation in other feeding related behaviours (i.e. how the daily feed intake is met) is much greater (Boumans et al., 2015). Aside from the amount and times at which pigs eat, individuals can vary the means by which they consume feed in numerous ways, with some pigs choosing to consume fewer larger meals and others tending to have more frequent smaller meals (Fornós et al., 2022). Pigs also show variation in the rate at which they consume feed, with distinct slow and fast eaters due to different "preferred feeding rates" (Nielsen, 1995; Nielsen, 1999).

Some of the inter-individual variation observed in feeding related behaviours may be explained genetically (Remus et al., 2020), but studies have also found that changes to these behaviours can be driven by age, social, environmental and dietary factors. Firstly, in regard to age, both consumption rate and average daily feed intake (ADFI) increase as pigs age (Fornós et al., 2022), which is thought to be linked to their greater physical capacity (e.g., stomach and mouth size) to consume food as they grow (Nielsen, 1999). Some studies have also found that these changes as pigs age coincide with a reduction in the number of feeder visits and thus meals (Fornós et al., 2022), with pigs moving away from frequent smaller meals to instead have fewer larger meals.

Aside from consumption rate tending to increase with body weight and pigs showing individual variation in their "preferred feeding rates", pigs may alter their consumption rate and other related behaviours in response to social and dietary constraints. For example, group-housed pigs tend to eat at a faster rate than those housed alone, likely due to stronger competition for access to the feeder (Young and Lawrence, 1994). They will also consume feed in fewer but larger meals which could have consequences for nutrient digestibility. Similarly, numerous studies have observed an increase in consumption rate when group size is increased (Nielsen et al., 1995; Hyun and Ellis, 2001; Hyun and Ellis, 2002) which Fornos et al. (2022) attributed to the reduction in pig to feeder ratio and floor space rather than the number of pigs itself. Additionally, despite the higher consumption rate that may be seen for the pigs in larger groups, Nielsen (1999) reported no difference in ADFI between these pigs and those in smaller groups. Hyun and Ellis (2002) found similar results in their study when finisher pig group size was increased from 2 to 12, as no change in ADFI, ADG and feed efficiency were found between groups of differing size, despite consumption rate increasing along with meal size in the larger groups. These changes to consumption rate and other feeding related behaviours may therefore be seen as mechanisms by which pigs can maintain feed intake and thus performance in environments with increased feeder access competition (Hyun and Ellis, 2002).

Diet composition and preferences may also play a part in a pig's feeding related behaviour. Pigs have been found to show a preference for certain diets (or diet components) when given a choice (Solà-Oriol et al., 2011). These preferred feeds may thus be consumed at a faster rate (Remus et al., 2020). A pigs consumption rate may also increase in response to its feeding motivation (Carcò et al., 2018), something which has been observed when nutritionally restricted diets are fed. For example, those on a diet below requirements may be expected to consume feed faster due to their motivation to try ensure requirements are still met. This will allow them to consume more feed and indeed there are examples of pigs increasing feed intake of a diet low in energy (Smit et al., 2021) or low in amino acids (Schiavon et al., 2018) to ensure the requirements of these respective diet components are met. Pichler et al. (2020) also reported pigs taking more frequent visits to a feeder and spending longer feeding when fed a diet composed with a low density of nutrients. For lysine specifically there have been few studies but one by Hyun et al. (1997) contradicts this somewhat as it found that pigs increased their feed intake, spending longer at the feeders and consuming larger meals, when dietary lysine was increased rather than restricted. Increasing lysine increased the pigs growth rates, which although not discussed could have been accompanied by an increase in body weight which may have driven some of these changes to feed intake and feeding behaviours. Furthermore, when similar feeding-related behaviours were looked at by Andretta et al. (2016a), diet composition (again in the form of diets with different lysine concentrations) was found to have no effect on these behaviours, illustrating the dissimilarities between findings.

Feeding related behaviours - growth performance effects

Having looked at these differences in feeding related behaviours, it is important to establish why they are important in regard to their impacts on growth performance. Of the behaviours aforementioned, the consumption rate (feeding rate/rate of feed intake) is one of those most strongly linked to growth performance (Andretta et al., 2016a; de Haer et al., 1993; Fornós et al., 2022) along with meal size (how much feed is eaten per discrete meal). Studies have found that the pigs which eat faster (i.e. have a higher consumption rate) typically grow faster (with higher ADGs) and have higher end weights (Carcò et al., 2018). These pigs may also have higher feed intakes which could contribute to the improvements in performance (Rauw et al., 2006, Carcò et al., 2018). But although pigs may show improved growth, a faster rate of consumption can increase carcass fatness and reduce leanness (Carcò et al., 2018: de Haer et al., 1993). Furthermore, Andretta et al. (2016a) found a slight negative correlation between consumption rate and pigs' feed efficiency.

Another important aspect to consider is nutrient digestibility, which relates primarily to meal size (the second feeding related behaviour most strongly linked to performance) and number of meals (Chassé et al., 2021). Gastrointestinal tract retention time is shortened when a large meal is consumed, which means digesta has less time in contact with the digestive enzymes, potentially decreasing digestibility and nutrient utilisation. A study by de Haer et al. (1993) acknowledged the potential for consumption rate as well as meal size to impact digestibility, via both a faster rate of passage and a change to the performance of digestive enzymes. The latter was observed by Botermans et al. (2000) when pigs fed more frequent smaller meals (as opposed to one larger meal) showed increased secretion of some endogenous enzymes. These changes to digestibility and nutrient utilisation were proposed to explain the reduction in feed efficiency seen by Andretta et al. (2016a) when meal size and consumption rate were increased. Additionally, de Haer et al. (1993) found that while pigs which ate smaller meals (with a slower consumption rate) tended to have leaner carcasses, they were also the pigs which grew slower (with lower ADGs). This may also be seen for pigs which spend a longer time eating, as ADG, end live weight and feed efficiency all show a negative correlation with total time spent eating (per day) (Carcò et al., 2018).

Lysine and feed intake

Returning the focus to lysine, only the feeding related behaviour of feed intake has received significant attention, due to its close alignment with performance. This is through its linear relationship with the deposition of protein, where increasing ADFI will increase protein growth up until the upper limit (maximum protein deposition or PD_{max}) is reached and deposition will not increase further (Patience et al., 2015). In agreement with Hyun et al. (1997), Soto et al. (2019) saw a quadratic increase in ADFI (average daily feed intake) as SID lysine increased, but there have also been numerous studies where lysine levels have no apparent effect on feed intake/ADFI (Campbell and Taverner, 1988; Witte et al., 2000; Jin et al., 2010). There is also the previously mentioned indication that at the highest lysine levels a negative correlation with ADFI (average daily feed intake) may occur (Aymerich et al., 2020; Aymerich et al., 2021). Additionally, some studies have suggested that when lysine is restricted pigs will subsequently increase feed intake, as with low energy diets (Menegat et al., 2020). Yin et al. (2017) found that piglets showed a preference for a lysine restricted diet and had a higher feed intake, which they attributed to them having lower levels of the satiety hormones leptin and CCK (than piglets on the control diet did) which usually control feed intake by inhibiting hunger. However, Rodríguez-Sánchez et al. (2011) found that ADFI of finisher pigs was decreased as dietary lysine was reduced, indicating a negative impact of lysine restriction on feed intake. Whether dietary lysine has an effect on the other feeding related behaviours remains relatively unexplored.

Foraging and damaging behaviours

Aside from the feeding-related behaviours, those known as abnormal or damaging behaviours can also have an impact on growth performance and importantly the pigs' welfare. These are behaviours which pigs would not naturally perform in unrestricted conditions similar to that of their wild ancestors (Brunberg et al., 2016) and instead occur in restricted environments where the full range of their behaviours (for survival or reproduction) are unable to properly be expressed (Garner, 2005). For example, in an indoor environment without appropriate materials to root in and forage, pigs still show a motivation to perform exploratory behaviours, which could instead be directed to parts of the pen and provided enrichment but also towards other individuals. In accordance with this, studies have shown pigs to increase fighting, aggression and biting when they have a lack of enrichment and material to root in (Mkwanazi et al., 2019). It is these abnormal behaviours directed towards other pen mates that are the most problematic, with biting/chewing of the tails, ears and flanks of other pigs being seen most often, along with belly nosing (Brunberg et al., 2016). These undesirable behaviours often lead to lesions, which negatively impact both health and welfare. Various factors can influence or increase the likelihood of damaging behaviours occurring, such as sex and genotype, temperature, health, housing conditions (floor space, enrichment, feeder access) and diet (Boyle et al., 2022). For this study, it is diet which is of particular interest.

Jensen et al. (1993) stated that pigs fed diets formulated below nutritional requirements may show an increase in foraging behaviours, carried out in an attempt to meet nutritional demands. In indoor commercial environments with minimal enrichment, such diets could lead to an increase in damaging behaviours (e.g. ear or tail biting). Certain diet ingredients (e.g. wheat and whey) have also been identified to influence abnormal behaviours, particularly tail biting, with Kallio et al. (2018) finding the risk of tail biting increased when weaner pigs were fed diets with these components. Other studies exploring diet composition and these behaviours have mostly focused on crude protein levels, with van der Meer et al. (2017) finding greater occurrences of aggression and oral manipulation when grower-finisher pigs were on a low crude protein diet. The effect of individual amino acids, like lysine, haven't been assessed but with advancing genetics and differences between sexes even if diets are being formulated with SID lysine at suggested levels (NRC, 2012) some pigs may actually be receiving lysine below what they require for optimal growth performance. These pigs may consequently show differing behaviours, both aggressive and exploratory, to those which have sufficient lysine or those which are receiving lysine in excess of requirements.

Behavioural observations and lesion scoring can be used to assess the extent to which abnormal and damaging behaviours are occurring and whether they are affected by dietary lysine. Lesions, which can be used to assess welfare (De Luca et al., 2021) arise from either fighting/aggression or abnormal behaviours like tail biting. While fighting is not strictly an abnormal behaviour (Mkwanazi et al., 2019) it remains undesirable due to its similar negative effects on performance and welfare. The literature specifically on lysine and behaviour is scarce but similar studies looking at either crude protein or diet compositions below requirements provide sufficient rationale for further research into the effects of dietary lysine on behaviour.

1.3. Aims and hypotheses

- **Aim One -** To improve our understanding of the response of finisher pigs to increasing dietary lysine, particularly at heavier weights.
- **Aim Two** - To investigate how these responses differ between sexes.
- **Aim Three** - To determine if feeding lysine above or below requirements alters finisher pig behaviour, particularly that of exploration and aggression and consequently if it has any effect on the number and severity of lesions.

Hypotheses

1. Increasing dietary lysine (SID lysine %) will improve the growth performance of pigs (rate of gain and feed efficiency), until a concentration where a plateau in performance is reached.
2. Boars will grow faster and more efficiently than gilts because of their greater genetic potential for protein deposition.
3. These differences in growth will affect the concentration of lysine required by each sex to maximise growth performance, with the boars lysine requirements expected to be higher.
4. Feeding lysine below requirements will increase the occurrence of undesirable behaviours such as fighting and oral manipulation, increasing the number of lesions.

Chapter 2. Materials and methods

This experiment was conducted at the National Pig Centre, a commercial pig farm from January 2023 to April 2023. The protocol used for the experiment was reviewed and approved by the University of Leeds Animal Welfare and Ethical Review Body.

Animals

At approximately 36 kg, a total of 320 pigs ((Large White x Landrace) x Danish Duroc)) were allocated to mixed sex finisher pens measuring 2.6 m by 3.5 m and accommodating 10 pigs per pen. Pens were allocated to one of four dietary lysine treatments giving 8 replicates (pens of 10) per treatment. These replicates were balanced for group size, group total weight, gender profile and sow. Live weight variation within and between pen groups (and across replicates) was minimized where possible. Treatment pens were also rotated within the grower/finisher accommodation to remove any confounding environmental effects. Pigs were housed in the finisher accommodation at the National Pig Centre and remained on trial until slaughter at an average live weight of 110 kg. Pigs went to the abattoir in four batches over three weeks, the first batch leaving at the end of week nine of the experiment and the last leaving at the end of week twelve. Pens were fully slatted with room temperature and ventilation controlled for the duration of the experiment. All pigs had *ad libitum* access to both feed and water throughout the experiment, with feed provided by the Pig Performance Nedap ProSense system in each pen.

With the exception of the dietary treatments, pigs were subject to all normal husbandries, management and veterinary procedures deemed necessary by the management of the farm and/or their nominated veterinary consultant. No antibiotic treatments were included in either the diet or water during this experiment. A total of 14 pigs were taken off trial for differing health reasons (5 from the Low treatment, 5 from the Med. Low treatment, 2 from the Med. High treatment and 2 from the High treatment).

Diet

From approximately 36 kg pigs were randomly allocated to one of four dietary lysine treatments: Low, Med. Low, Med. High or High. A 3-phase feeding regime was used from 36 kg to slaughter meaning each of these treatments consisted of three different diets of differing lysine concentrations (see Table 2.1) and each treatment diet was kept the same for the duration of each phase (i.e. one diet per treatment per phase). Diets were formulated by commercial nutritionists, with the two intermediate diets (Med. Low and Med. High) representing two commercially available diets, one at the lower end of requirements and one slightly above requirements. Both of these met minimum nutrient requirements of NRC (2012) and/or the BSAS (Whittemore et al., 2003) for the age and stage of production. The two intermediate diets, Med. Low and Med. High were blended from the Low and High diets as shown in Table 2.2, with the diet compositions of the Low and High diets in Table 2.3.

Phases fed as follows:

Phase 1 - From the start of the experiment to the end of week three, d0-21 (~36-53 kg)

Phase 2 - Week four to the end of week seven, d22-49 (~53-83 kg)

Phase 3 - Week eight to the end of week nine minimum/to the end of week twelve maximum, d50 to slaughter (d64-d84) (~83-110 kg)

Table 2.1. Dietary lysine concentrations (SID lysine %) of each treatment diet in each phase

	SID lysine (%)			
	Low	**Med. Low**	**Med. High**	**High**
Phase 1	0.71	0.90	1.09	1.28
Phase 2	0.62	0.76	0.90	1.09
Phase 3	0.52	0.67	0.81	1.00

SID = standardized ileal digestible

Table 2.2. Percentages of the Low and High lysine diets blended to make the Med. Low and Med. High diets in each phase and the resulting lysine concentrations of these diets (SID Lys %)

	% of Low	**% of High**	**Resulting SID Lys (%)**
Med. Low diet			
Phase 1	67.10	32.90	0.90
Phase 2	70.00	30.00	0.76
Phase 3	68.90	31.10	0.67
Med. High diet			
Phase 1	33.70	66.30	1.09
Phase 2	40.60	59.40	0.90
Phase 3	39.40	60.60	0.81

SID = standardized ileal digestible

Table 2.3. Ingredient and nutritional composition of the Low and High treatment diets in each phase

Item	Phase One		Phase Two		Phase Three	
	Low	High	Low	High	Low	High
Ingredient %						
Barley	30	30.06	30	30.00	30	30.36
Wheat	33.15	17.88	30.90	11.12	32.43	25.49
Maize	0	0	0	14.07	0	0
Wheatfeed	7.84	0	4.91	5.29	12.58	0
Maize germ	10.05	12.5	10.8	5.19	9.36	12.5
Bakery meal	0	0	0	3.68	0	0
Soya bean meal	0	21.45	0	12.99	0	5.96
Rapeseed extract	15	15	14	14	12.5	12.5
Sunflower meal	0.72	0	6.56	0	0	10.05
Pig finisher premix	0.25	0.25	0.25	0.25	0.25	0.25
L-Lysine (Liquid Base)	0.51	0.73	0.26	0.76	0.17	0.75
DL-Methionine	0.01	0.13	0	0.10	0	0.03
Threonine	0.08	0.20	0	0.19	0	0.14
L-Tryptophan	0.002	0.032	0	0.038	0	0.019
L-Valine	0	0.014	0	0.022	0	0
Quantum Blue Phytase [1]	0.01	0.01	0.01	0.01	0.01	0.01
Belfeed Xylanase [2]	0.01	0.01	0.01	0.01	0.01	0.01
Limestone (coarse)	0.79	0.66	0.76	1.09	1.06	0.64
Salt	0.33	0.35	0.33	0.34	0.33	0.33
Sodium Bicarbonate	0.75	0	0.51	0.15	0.60	0.28
Fat spray (veg)	0.5	0.72	0.7	0.7	0.7	0.7
Energy and nutrient content [3 4]						
Dry matter (%)	87.07	87.61	87.36	87.51	87.13	87.49
NE (MJ/kg)	9.52	9.57	9.47	9.59	9.54	9.45
Protein (%)	13.90	21.35	14.89	17.96	13.08	17.77
Total Lys (%)	0.83	1.45	0.74	1.23	0.63	1.14
Fibre (%)	5.20	4.92	5.64	5.02	5.15	5.69
Salt (%)	0.47	0.47	0.47	0.47	0.47	0.47
Ca (%)	0.53	0.53	0.53	0.68	0.62	0.50
P (%)	0.42	0.46	0.46	0.43	0.41	0.48
Na (%)	0.35	0.16	0.28	0.20	0.31	0.22
SID Lys (%)	0.71	1.28	0.61	1.09	0.52	1.00
SID Lys/MJ DE	0.54	0.93	0.47	0.81	0.40	0.74
Dry matter (%) (analysed)[5]	85.5	85.9	86.2	86.1	86.2	86
Protein (%) (analysed)	14.9	20.8	14.1	18.2	12.8	17
Lys (%) (analysed)[6]	0.83	1.41	0.73	1.17	0.45	1.02

[1] Phytase (500 FTU/kg).

[2] Xylanase (IU).

[3] SID = standardized ileal digestible; NE = net energy; DE = digestible energy.

[4] Unless stated otherwise values are ID = ileal digestible.

[5] Analysis performed by DM Scientific, Thirsk, Uk.

[6] Analysed values from P1, P2 and P3 were 0.95, 0.77 and 0.74 % for Med. Low; 1.13, 0.91 and 0.91 % for Med. High.

Measurements

Pig growth performance

Daily feed intake, and daily weight measurements of each individual pig were determined throughout the experiment using the Pig Performance Nedap ProSense system. This system allowed pigs on the four different treatments to receive the appropriate diets on a pen basis from individual electronic feeders (one per pen). A weighted trough measured feed intake and on the base of the feeder a scale measured the pigs weight. Allowing individuals average daily gain (ADG) and feed conversion ratio (FCR) to be calculated throughout the experiment. Individual information on feeding related behaviours was also collected. This included the number of feeder visits per day and the total time pigs spent in the feeder each day, which could be used to calculate their average consumption rate. Automated or mechanical equipment was inspected at least once a day to check there were no defects in it and feed was sampled weekly for analysis.

Faecal scores and pig health were recorded daily in accordance with established protocol at the trial site (Table 2.4). Pigs showing signs of ill health were treated individually with antibiotics or taken off trial following consultation and inspection by the study leader. All antibiotic treatments were recorded, along with the dose and reason for administration. The number of mortalities and pigs taken off trial were also recorded per treatment, dietary period and overall.

Table 2.4. Point scale scoring systems used to measure daily faecal, health and cleanliness scores

Score	Faecal score	Health score	Cleanliness score
1	Firm	No signs of poor health	Clean
2	Soft, spreads easily	Some signs of poor health	Some indication of faecal contamination
3	Very soft (mild diarrhoea)	Clear signs of poor health	Contaminated with faecal material
4	Watery liquid (diarrhoea)*	Serious signs of poor health	Heavily contaminated with faecal material

Lesion scoring

Lesion scoring was carried out weekly for the duration of the experiment, as well as before it started and the day after pigs were assigned pens and mixed. Lesion scoring was done on an individual basis, assessing both severity and location of every lesion, as detailed in Table 2.5 and Figure 2.1. The three locations, front, middle and rear, shown in Figure 2.1 are based on the regions used by Turner et al. (2006). The front third comprising the head, neck and front legs up to and including the shoulders, the middle third the back, sides and belly and the rear third the rump, tail and back legs of the pig.

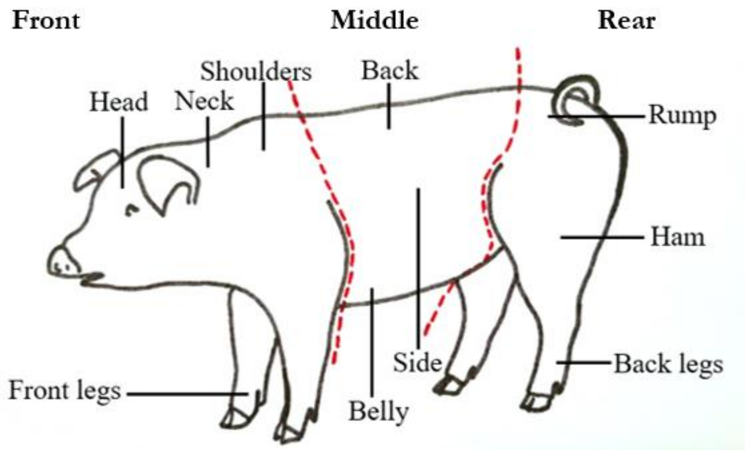

Figure 2.1. Diagram illustrating the three location categories given to separately record lesions on the front, middle and rear of each pig.

Table 2.5. The scoring scale used to assess and grade the severity of each lesion. Adapted from Aaslyng et al. (2013) and Carroll et al. (2018)

Score	Description
1	**Minor lesion** – superficial pink/red lesion small in length or shallow. Alternatively, a small lesion which has broken the skin but is <4 cm in diameter.
2	**Moderate lesion** – slightly larger superficial lesion >8 cm or a deeper red lesion, which has broken the skin and is >4 cm. Alternatively a cluster of minor lesions (>5).
3	**Severe lesion** – very deep/large, open lesion or a collection of moderate lesions (>5) covering a larger area >10 cm.

Behavioural observations

Behaviour was observed weekly (same day every week) for a total of four hours, split into two sessions, between 09:00-11:00 and 12:00-14:00. This was to capture at least one of the bimodal peaks in feeding activity that pigs typically display throughout the day (Simonsen, 1990). Limited by the need to carry out observations in person the afternoon session likely represented a period of lower activity. But given that pigs spend the majority of their time inactive (O'Malley et al., 2021), this would have helped avoid overestimating the frequency of active behaviours, which can occur when pigs are only observed during the most active time periods (Wilder et al., 2021). During these sessions, scan sampling at 15-minute intervals was used to assess how many individuals in each pen were carrying out the behaviours of interest, outlined in Table 2.6. Individual pigs weren't identified but the sex of the pig being observed was determined, allowing the behaviour of boars and gilts to be recorded separately (except for the first weeks recording which didn't account for sex). Observations had to be carried out in person and the observer was positioned outside of the pen and where possible out of view of the pigs being recorded (by standing back from the pen or beside/behind the feed system). On the occasions where a pig became aware of the observer (made eye contact, approached the pen side or performed a warning vocalization) and altered their behaviour, the behaviour they were performing prior to disruption was recorded where possible and any performed after disregarded. These occurrences of disruption decreased throughout the experiment.

Table 2.6. Ethogram of behaviours of interest

Behaviour	Description
Drinking	Manipulating drinker with mouth/ mouth around drinker
Mounting	Pig has front legs raised onto the body of another pig whilst standing on its hind legs
Aggresion/Fighting	Aggressively engaging with another pig/pigs through head-knocks, biting, pushing and other agonistic behaviour
Oral manipulation of pen mate	Pig is sucking, chewing or biting the tail/ear/body part of another pig
Exploration	Pig is chewing, licking, nosing or sniffing the surroundings (walls/floor) or enrichment objects provided
Inactive	Lying, sitting or standing immobile
Other	Performing none of the above behaviours

Faecal sampling /environmental considerations

Faecal samples from each pen (3-4 samples from each) were collected on three consecutive days during the last week of each phase. These samples will be used for future nitrogen output analysis, as analysis wasn't possible given the time constraints of this experiment. To still give some consideration to the potential environmental impacts of these differing lysine diets, the calculated carbon dioxide equivalent values (CO_2e) of the four lysine treatments were compared for each phase and over the experiment as a whole. For each treatment these values were a product of the pigs average feed intake over the course of the experiment/each phase and the CO_2e values (in kg) from the formulated diets.

Carcass data

Pigs were sent to slaughter at a commercial abattoir at approximately 110 kg, during a period of approximately 3 weeks. All pigs received an individual slap number for identification at the abattoir so that hot weight, cold weight, killing out percentage (KO%), lean meat percentage (LM%) and P2 (a measure of backfat) could be recorded.

Statistical analysis

Linear mixed models using IBM SPSS Version 28 (IBM Corp, 2021) were run to analyse performance data from each phase separately, overall performance, the feeding related behaviours and carcass data. Linear mixed models were also used to carry out an economical evaluation using the slaughter data and feed costs of the differing diets. Carbon dioxide equivalents (CO_2e) associated with the different diets were estimated for each treatment (in kg per pig) and a comparison of these values was also carried out. Analysis by linear mixed models enabled the effect of both lysine and sex to be looked at and any interaction between the two. Analyses accounted for the pigs being housed in groups and those in a pen fed the same by nesting pen within lysine. The slightly differing start weights of boars and gilts were also accounted for by including start weight as a covariate. For the carcass data, end live weight was adjusted for the number of days taken to reach slaughter and the carcass cold weight, KO%, LM% and P2 thickness (mm) were adjusted for end live weight.

Modelling was also carried out to look at the growth response of pigs to increasing dietary lysine in each phase of the phase-feeding regime. These regression models looked at the response of the boars and gilts' ADG and FCR (response variables) to SID (standardized ileal digestible) lysine concentration (predictor variable). RStudio 2023 (Version 4.2.3; R Core Team, 2023) was used to fit quadratic models and two broken line models (a linear plateau model and a quadratic plateau model) following Millet et al. (2018b). SID lysine concentrations required by boars and gilts to maximise ADG and minimise FCR could then be estimated in each phase. Estimated requirements were taken as the lysine concentration at which the breakpoint occurred in the broken line models or the lysine concentration at the maximum point of the quadratic regression in the quadratic models. To obtain this maximum, the quadratic regression equation was differentiated and solved for $y' = 0$. An estimation was also taken at 90% of this maximum. All three models weren't always able to be fitted to the data (indicated by the absent values (-) in Table 3.12) but where applicable model comparisons were carried out using Akaike information criterion (AIC), Bayesian information criterion (BIC) and R^2 values (see Tables A1, A2, A3 and A4 in the Appendix). A better fit was determined when either AIC or BIC values from the different models had a difference of more than two (with a lower value being better).

Behavioural observations were used to calculate activity time budgets on a pen and sex basis over each two-hour session (i.e. a single two-hour recording would give average values (as a % of the total time) for the time spent performing each recorded behaviour and for boars and gilts separately in each pen). It is these percentages of time which were then compared between lysine treatments and sex. Statistical analyses were run in SPSS (Version 28; IBM Corp, 2021) using generalized linear models (GLMs) to analyse behaviour in each phase separately and then overall, looking for lysine, sex and lysine*sex effects for each behaviour. Pen was nested within lysine treatment and recording number (week of experiment) included as a factor. When analysing the behaviour data over the whole finishing period, phase was included as a factor rather than recording number.

Given the low occurrence of severe lesions (severity score 3) throughout the experiment, the number of moderate and severe lesions (scored 2 and 3) were combined into one measure for the analysis of the lesion scores. The total number of lesions, the number of lesions in each of the three locations (front, middle and rear), the number of mild lesions and the number of moderate/severe lesions were all analysed using generalized linear models in SPSS (Version 28; IBM Corp, 2021). For these models a Poisson distribution was selected and a log link function. Recording number was included as a factor in the phase separate analyses and phase as a factor in the overall analysis.

Chapter 3. Results

3.1. Growth performance

Phase One (day 0-21)

For Phase One no significant interactive effects were found between sex and lysine for any of the performance measures looked at. At the start of the experiment boars were already heavier than females (p = 0.013), a difference which became more pronounced by the end of Phase One (p = 0.002), with boars on average 1.03 ± 0.33 kg heavier than gilts. Boars were also faster growing and more feed efficient, with a higher mean ADG and lower FCR (p = 0.002 and p <0.001; Table 3.1) but no difference in average daily feed intake (ADFI) was seen between sexes (p = 0.611).

There was a strong lysine effect seen for ADG, FCR and Phase One end weight (all p <0.001, Table 3.1), as ADG, end weight and FCR were all improved for pigs on the higher two

Table 3.1. Performance of grower-finisher pigs (boars and gilts) throughout the first three weeks of finishing (~35-53 kg) fed diets of differing SID lysine concentrations [1 2 3]

Measure	Sex	SID Lysine concentration (%)					*P*-value		
		0.71	0.90	1.09	1.28	SE	Lysine	Sex	Lysine*Sex
Start weight (kg)	**Mixed**	36.43	36.42	36.50	36.48	0.26	0.995	**0.013**	0.938
	Boar	36.75	36.64	36.95	36.80	0.37			
	Gilt	36.11	36.20	36.04	36.17	0.36			
End weight (kg)	**Mixed**	51.09^{a}	51.95^{a}	55.53^{b}	54.60^{b}	0.33	**<0.001**	**0.002**	0.156
	Boar	51.55	52.11	55.84	55.74	0.47			
	Gilt	50.64	51.80	55.23	53.46	0.46			
ADG (kg)	**Mixed**	0.666^{a}	0.705^{a}	0.868^{b}	0.826^{b}	0.01	**<0.001**	**0.002**	0.156
	Boar	0.687	0.712	0.882	0.878	0.02			
	Gilt	0.646	0.698	0.854	0.774	0.02			
ADFI (kg/day)	**Mixed**	1.629^{a}	1.579^{ab}	1.645^{a}	1.532^{b}	0.02	**<0.001**	0.611	0.409
	Boar	1.630	1.565	1.616	1.553	0.03			
	Gilt	1.629	1.593	1.674	1.512	0.03			
FCR	**Mixed**	2.52^{a}	2.28^{b}	1.91^{c}	1.91^{c}	0.03	**<0.001**	**<0.001**	0.451
	Boar	2.40	2.22	1.84	1.80	0.05			
	Gilt	2.64	2.33	1.97	2.01	0.04			

[1] Different superscript letters indicating significantly different means (p < 0.05).
[2] ADG = average daily gain; ADFI = average daily feed intake; FCR = feed conversion ratio.
[3] End Weight (kg), ADG (kg), ADFI (kg/day) and FCR adjusted for start weight = 36.44 kg.

lysine treatments (1.09 and 1.28 SID Lys) as opposed to those on the lower two lysine treatments (0.71 and 0.90 SID Lys). For FCR and ADG values improved by roughly 24% when comparing pigs on the Low and High lysine treatments. However, differences in these measures were not seen between the Med. High and High lysine treatments (p = 0.263, p = 0.263 and p = 1.000 for ADG, end weight and FCR respectively) as well as between the Low and Med. Low treatments for end weight and ADG (p = 0.388). During Phase One ADFI did vary between lysine treatments

($p<0.001$) and was significantly higher for pigs on the Low and Med. High treatments when compared to those on the High lysine diet, who ate significantly less (approximately 100g less when compared to both the Low treatment ($p = 0.008$) and the Med. High treatment ($p = 0.001$)).

Phase Two (day 22-49)

In Phase Two a significant interaction between lysine and sex was found for the end weight of pigs ($p = 0.025$, Table 3.2). The end weight of both sexes increased with increasing dietary lysine, up until the Med. High treatment (0.90 SID Lys) after which they did not significantly change ($p = 0.307$ for boars and $p = 1.000$ for gilts). Boars however, were significantly heavier than gilts on the highest lysine treatment (1.09 SID Lys, $p <0.001$), with an average weight of 87.19 ± 0.86 kg for gilts as opposed to 93.06 ± 0.89 kg for boars. On the lower three treatments (0.62, 0.76 and 0.90 SID Lys) boars and gilts had similar end weights ($p >0.05$).

Throughout Phase Two boars were again faster growing (higher ADGs, $p <0.001$), gaining 10% more weight than gilts did (per day) on the High treatment, were more feed efficient (lower FCR, $p <0.001$), but did not consume more feed than gilts (ADFI, $p = 0.957$), see Table 3.2. Increasing dietary lysine increased both the boars and gilts ADG ($p <0.001$) and improved their feed efficiency ($p <0.001$) up to and including at the highest lysine concentration, where the mean ADG was over 50% higher than that on the Low lysine treatment. ADFI was also affected by lysine ($p <0.001$) with those on the higher two lysine treatments consuming more than those on the lower two treatments ($p <0.001$). For ADG the trend for a lysine*sex interaction ($p <0.1$; Table 3.2) indicates there was a tendency for boars to respond to higher lysine levels than gilts (Figure 3.1), something which wasn't observed for FCR (Table 3.2).

Table 3.2. Performance of finisher pigs (boars and gilts) from week four of finishing to week seven (~53-83 kg) fed diets of differing SID lysine concentrations [1 2 3]

Measure	Sex	SID Lysine concentration (%)					*P*-value		
		0.62	0.76	0.90	1.09	SE	Lysine	Sex	Lysine*Sex
End weight (kg)	**Mixed**	74.45^{a}	80.28^{b}	89.50^{c}	90.12^{c}	0.61	**<0.001**	**<0.001**	**0.025**
	Boar	75.17^{a}	80.84^{b}	90.65^{cd}	93.06^{d}	0.89			
	Gilt	73.73^{a}	79.71^{b}	88.35^{c}	87.19^{c}	0.86			
ADG (kg)	**Mixed**	0.843^{a}	1.027^{b}	1.226^{c}	1.284^{d}	0.01	**<0.001**	**<0.001**	0.072
	Boar	0.862	1.046	1.257	1.349	0.02			
	Gilt	0.825	1.007	1.196	1.219	0.02			
ADFI (kg/day)	**Mixed**	2.309^{a}	2.392^{a}	2.593^{b}	2.578^{b}	0.03	**<0.001**	0.957	0.630
	Boar	2.290	2.381	2.596	2.609	0.04			
	Gilt	2.328	2.403	2.591	2.548	0.04			
FCR	**Mixed**	2.79^{a}	2.35^{b}	2.13^{c}	2.02^{d}	0.02	**<0.001**	**<0.001**	0.455
	Boar	2.70	2.29	2.08	1.94	0.03			
	Gilt	2.88	2.40	2.18	2.09	0.03			

[1] Different superscript letters indicating significantly different means ($p < 0.05$).
[2] ADG = average daily gain; ADFI = average daily feed intake; FCR = feed conversion ratio.
[3] End Weight (kg), ADG (kg), ADFI (kg/day) and FCR adjusted for P1 start weight = 36.43 kg.

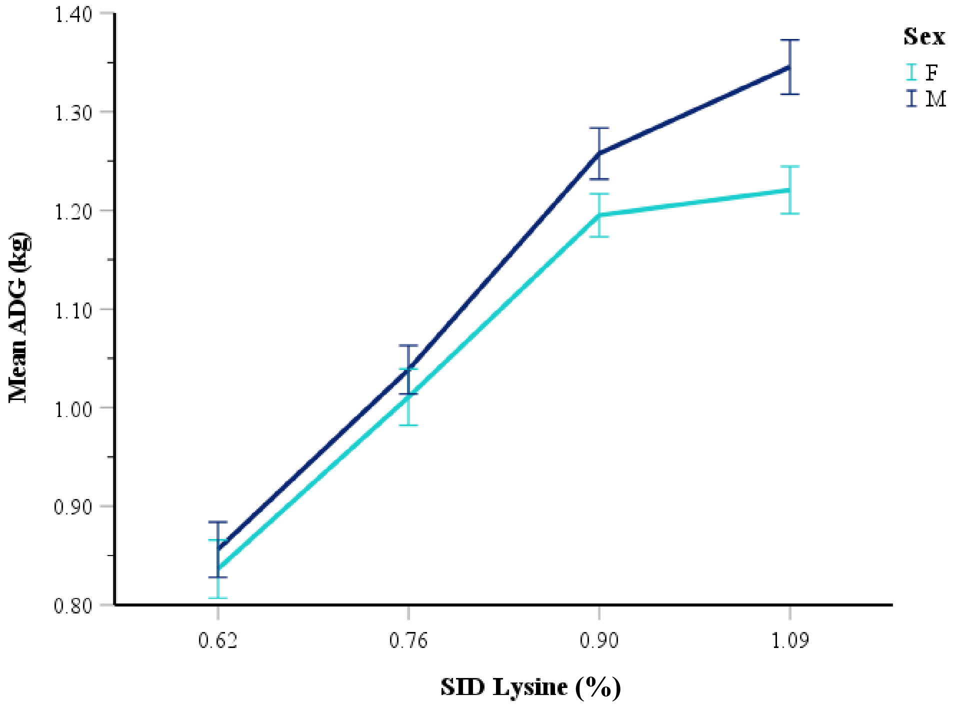

Figure 3.1. Mean ADG (average daily gain, kg) of finisher pigs (boars and gilts) from week four of finishing to week seven (~53-83 kg) fed diets of differing dietary SID lysine concentrations (%). Error bars showing standard error.

Phase Three to endpoint (day 50-64)

When the first batch of pigs went to slaughter (endpoint), there remained a significant interaction between lysine and sex on the pigs end weight (p = 0.006; Table 3.3). Boars were progressively heavier on the increasing dietary lysine treatments, with the greatest sex difference nearing 9 kg on the High treatment. Gilts on the higher two treatments (0.81 and 1.00 SID Lys) however, showed no difference in end weight (p = 1.000). In this phase a lysine*sex interaction was also seen for ADG (p = 0.001). Both boars and gilts showed an increase in ADG as lysine increased and both responded to the highest lysine level. However, ADG was similar for boars and gilts on the Low lysine diet (0.52 SID Lys, p = 0.991), but significantly higher for boars when fed the other lysine diets (0.67, 0.81 and 1.00 SID Lys; p = 0.015, p <0.001 and p <0.001; Figure 3.2). The differing response of boars and gilts to increasing dietary lysine meant boars on the High lysine treatment showed an 80% improvement in ADG (when compared to the mean ADG of pigs on the Low lysine treatment) whereas gilts showed only a 50% improvement in ADG from the Low to High lysine treatment (see Table 3.3).

Despite the ADG of both sexes increasing at the highest lysine level, there was a tendency for boars and gilts to differ in their response in regard to FCR (p = 0.091). This was perhaps a result of an apparent improvement in the boars mean FCR from the Med High to the High treatment, whereas the gilts mean FCR was 2.37 ± 0.13 on the 0.81 SID Lys diet and 2.62 ± 0.13 on the 1.00 SID Lys diet (Table 3.3). Increasing dietary lysine increased ADFI (p <0.001) with pigs on the higher two treatments consuming significantly more than those on the lower two treatments (all p <0.001 except between Med. Low and Med. High p = 0.006). Boars were not more feed efficient than gilts in this phase (p = 0.376) and did not eat significantly more (p = 0.162).

Table 3.3. Performance of finisher pigs (boars and gilts) from week eight of finishing to the end of week nine (~83-100 kg) fed diets of differing SID lysine concentrations [1 2 3]

Measure	Sex	SID Lysine concentration (%)					*P*-value		
		0.52	0.67	0.81	1.00	SE	Lysine	Sex	Lysine*Sex
End weight (kg)	**Mixed**	86.04^{a}	94.47^{b}	106.92^{c}	109.24^{c}	0.78	**<0.001**	**<0.001**	**0.006**
	Boar	86.79^{a}	95.68^{b}	109.29^{d}	113.59^{e}	1.14			
	Gilt	85.30^{a}	93.26^{b}	104.55^{c}	104.89^{c}	1.07			
ADG (kg)	**Mixed**	0.852^{a}	1.020^{b}	1.254^{c}	1.409^{d}	0.02	**<0.001**	**<0.001**	**0.001**
	Boar	0.851^{a}	1.073^{b}	1.325^{c}	1.530^{d}	0.03			
	Gilt	0.852^{a}	0.967^{e}	1.183^{f}	1.288^{g}	0.03			
ADFI (kg/day)	**Mixed**	2.876^{a}	3.108^{b}	3.309^{c}	3.392^{c}	0.04	**<0.001**	0.162	0.313
	Boar	2.837	3.146	3.371	3.453	0.06			
	Gilt	2.915	3.069	3.247	3.330	0.06			
FCR	**Mixed**	3.56^{a}	3.09^{b}	2.51^{c}	2.44^{c}	0.10	**<0.001**	0.376	0.091
	Boar	3.55	2.97	2.65	2.27	0.14			
	Gilt	3.58	3.22	2.37	2.62	0.13			

[1] Different superscript letters indicating significantly different means (p < 0.05).
[2] ADG = average daily gain; ADFI = average daily feed intake; FCR = feed conversion ratio.
[3] End Weight (kg) and ADFI (kg/day) adjusted for P1 start weight = 36.42 kg; ADG (kg) and FCR adjusted for P1 start weight = 36.39 kg.

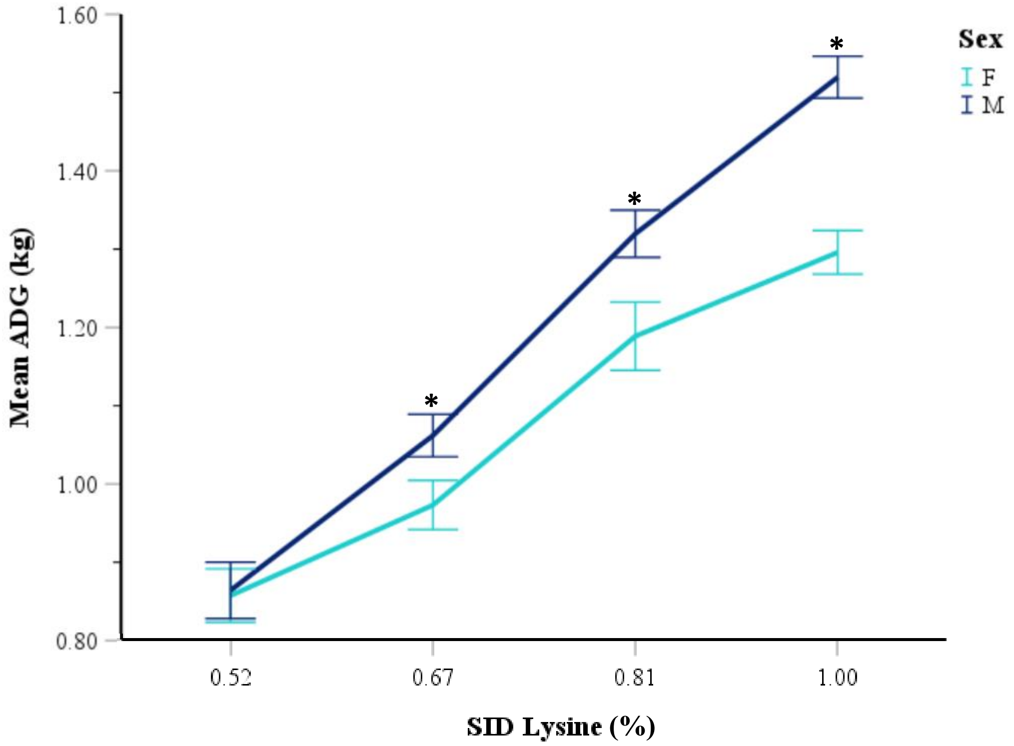

Figure 3.2. Mean ADG (average daily gain, kg) of finisher pigs (boars and gilts) from week eight of finishing to the end of week nine (~83-100 kg) fed diets of differing dietary SID lysine concentrations (%). Error bars showing standard error. Significantly different means (p < 0.05) between sex indicated by *.

Phase Three to slaughter (day 50 - slaughter)

Pigs went to the abattoir over four consecutive weeks when they reached approximately 110 kg, meaning the last batch left three weeks after the first with the first batch marking the endpoint of the experiment. Here the performance of individuals is looked at up until their departure from the farm for slaughter. Increasing dietary lysine increased ADG, but the ADG of boars and gilts became increasingly different at the higher lysine levels (0.81 and 1.00 SID Lys) shown by the lysine*sex interaction ($p = 0.003$; Table 3.4; Figure 3.3). The ADG of boars improved from the Med. High to the High lysine treatment ($p < 0.001$) but the ADG of gilts on the Med. High and High lysine treatments were similar ($p = 1.000$) albeit 8 and 15% lower than the boars corresponding ADGs on these treatments (Med. High, $p = 0.005$ and High, $p < 0.001$). However, both sexes had similar ADGs on the Low and Med. Low lysine treatments ($p = 0.185$ and $p = 0.120$). During this stage of finishing a lysine*sex interaction was also observed for FCR ($p = 0.048$; Table 3.4) with boars more feed efficient than gilts on all lysine treatments ($p < 0.001$) except the Med. Low for which they only had a tendency to be more feed efficient ($p = 0.051$). The FCR of boars improved up to and including at the highest lysine level, whereas the gilts FCR was similar on the intermediate treatments ($p = 1.000$) and on the Med. High and High lysine treatments ($p = 0.114$). Boars also showed the greatest improvement in feed efficiency as their mean FCR was reduced (i.e. improved) by almost a third, from 3.33 ± 0.05 on the Low lysine treatment to 2.25 ± 0.05 on the High lysine treatment.

Boars were heavier than gilts at final slaughter weight (approximately 2.29 ± 0.67 kg heavier, $p < 0.001$) and although there was no longer a lysine*sex interaction for end weight ($p = 0.135$) a lysine effect was still observed ($p < 0.001$). Despite pigs being retained for longer to reach slaughter weight those on the Low and the Med. Low lysine treatments (0.52 and 0.67 SID Lys) were significantly lighter than those on the Med. High and High lysine treatments ($p < 0.001$), with a 13 kg difference between the Low and High treatments' average end weights However, there was no significant difference in end weight for those pigs fed the higher two lysine treatments ($p = 1.000$). Pigs on the Low lysine treatment also ate significantly less than pigs on the other three treatments did (Med. Low, $p = 0.003$; Med. High and High, $p < 0.001$).

Table 3.4. Performance of finisher pigs (boars and gilts) from week eight of finishing to slaughter (~83-110 kg) fed diets of differing SID lysine concentrations [1 2 3]

Measure	Sex	SID Lysine concentration (%)					*P*-value		
		0.52	0.67	0.81	1.00	SE	Lysine	Sex	Lysine*Sex
End weight (kg)	**Mixed**	101.69^{a}	110.07^{b}	115.04^{c}	115.67^{c}	0.67	**<0.001**	**<0.001**	0.135
	Boar	102.95	109.94	116.42	117.72	0.99			
	Gilt	100.44	110.19	113.65	113.62	0.92			
ADG (kg)	**Mixed**	0.929^{a}	1.152^{b}	1.262^{c}	1.372^{d}	0.02	**<0.001**	**<0.001**	**0.003**
	Boar	0.954^{a}	1.181^{b}	1.315^{d}	1.485^{e}	0.03			
	Gilt	0.903^{a}	1.123^{b}	1.210^{bc}	1.259^{c}	0.03			
ADFI (kg/day)	**Mixed**	3.002^{a}	3.190^{b}	3.287^{b}	3.297^{b}	0.04	**<0.001**	0.827	0.936
	Boar	2.988	3.194	3.269	3.309	0.06			
	Gilt	3.016	3.187	3.305	3.286	0.05			
FCR	**Mixed**	3.44^{a}	2.79^{b}	2.65^{c}	2.44^{d}	0.03	**<0.001**	**<0.001**	**0.048**
	Boar	3.33^{a}	2.72^{b}	2.51^{c}	2.25^{d}	0.05			
	Gilt	3.55^{e}	2.85^{b}	2.78^{bf}	2.64^{f}	0.05			

[1] Different superscript letters indicating significantly different means ($p < 0.05$).
[2] ADG = average daily gain; ADFI = average daily feed intake; FCR = feed conversion ratio.
[3] End weight (kg) and ADFI adjusted for P1 start weight = 36.39 kg; ADG (kg) and FCR adjusted for P1 start weight = 36.36 kg.

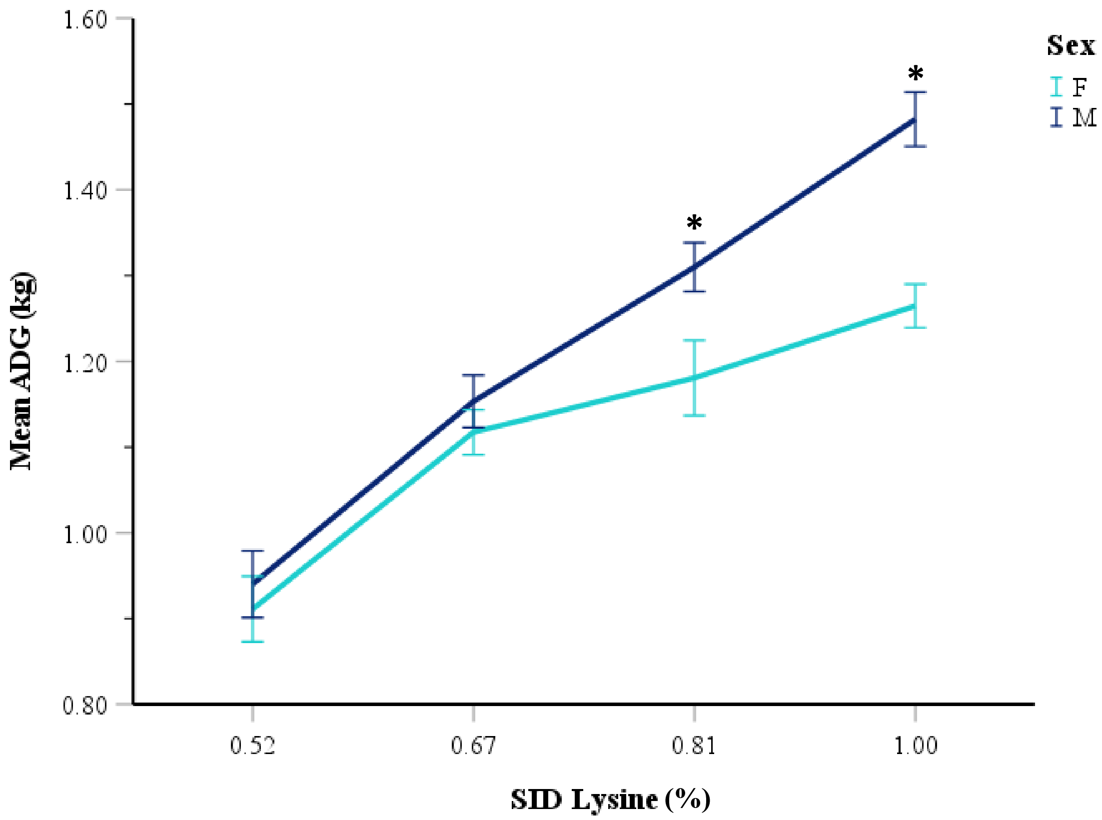

Figure 3.3. Mean ADG (average daily gain, kg) of finisher pigs (boars and gilts) from 83 kg-slaughter fed diets of differing dietary SID lysine concentrations (%). Error bars showing standard error. Significantly different means ($p < 0.05$) between sex indicated by *.

Overall Performance

Analysing the performance data over the whole finishing period, showed there was a lysine*sex interaction for ADG (p = 0.010; Table 3.5) and FCR (p = 0.025). Boars and gilts on the lower two lysine treatments had similar ADGs, but increasing lysine past this point increased the ADG of boars significantly more than it increased the ADG of gilts (see Table 3.5). There was also a trend for boars on the High lysine treatment to have higher ADGs than boars on the Med. High treatment (p = 0.082), whereas gilts on these two treatments had similar ADGs (p = 1.000). In regard to FCR, boars were more feed efficient than gilts on each dietary lysine treatment, but to the greatest extent (~ 10% lower) on the High lysine treatment (Figure 3.4). Boars also responded to the highest lysine level (p <0.001 between Med. High and High), whereas gilts on the High lysine treatment only showed a trend for improved FCR when compared to gilts on the Med. High treatment (p = 0.076).

Boars were heavier than gilts at the end of the experiment (p <0.001) and pigs had heavier end weights on the higher lysine treatments (p <0.001, Table 3.5). Additionally, increasing dietary lysine increased ADFI (p = 0.002) but only for pigs on the Med. High treatment when compared to those on the Low lysine treatment (p = 0.001).

Table 3.5. Performance of grower-finisher pigs (boars and gilts) from 36 kg to slaughter (~110 kg), fed diets of differing SID lysine concentrations [1 2 3]

Measure	Sex	Lysine Treatment					*P*-value		
		Low	Med. Low	Med. High	High	SE	Lysine	Sex	Lysine*Sex
Start weight (kg)	**Mixed**	36.43	36.42	36.50	36.48	0.26	0.995	**0.013**	0.938
	Boar	36.75	36.64	36.95	36.80	0.37			
	Gilt	36.11	36.20	36.04	36.17	0.36			
End weight (kg)	**Mixed**	101.69^{a}	110.07^{b}	115.04^{c}	115.67^{c}	0.67	**<0.001**	**<0.001**	0.135
	Boar	102.95	109.94	116.42	117.72	0.99			
	Gilt	100.44	110.19	113.65	113.62	0.92			
ADG (kg)	**Mixed**	0.828^{a}	0.983^{b}	1.130^{c}	1.163^{c}	0.01	**<0.001**	**<0.001**	**0.010**
	Boar	0.846^{a}	0.994^{b}	1.167^{d}	1.224^{d}	0.02			
	Gilt	0.810^{a}	0.972^{b}	1.093^{c}	1.102^{c}	0.02			
ADFI (kg/day)	**Mixed**	2.389^{a}	2.449^{ab}	2.513^{b}	2.462^{ab}	0.02	**0.002**	0.183	0.966
	Boar	2.370	2.429	2.494	2.456	0.03			
	Gilt	2.408	2.468	2.531	2.467	0.03			
FCR	**Mixed**	2.91^{a}	2.50^{b}	2.23^{c}	2.13^{d}	0.02	**<0.001**	**<0.001**	**0.025**
	Boar	2.83^{a}	2.45^{b}	2.15^{c}	2.01^{d}	0.02			
	Gilt	3.00^{e}	2.55^{f}	2.32^{g}	2.25^{g}	0.02			

[1] Different superscript letters indicating significantly different means (p < 0.05).
[2] ADG = average daily gain; ADFI = average daily feed intake; FCR = feed conversion ratio.
[3] End Weight (kg), ADG (kg), ADFI (kg/day) and FCR adjusted for P1 start weight = 36.39 kg.

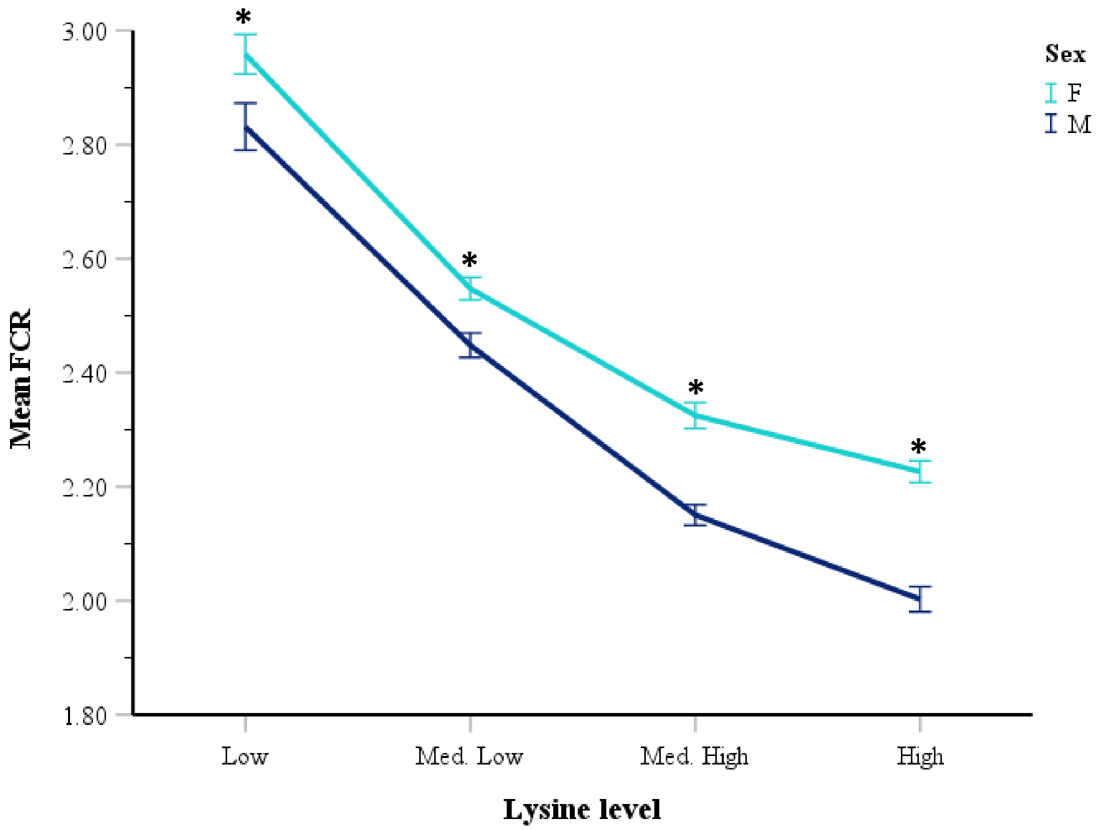

Figure 3.4. Mean FCR (feed conversion ratio) of grower-finisher pigs (boars and gilts) from 36 kg to slaughter, fed diets of differing dietary SID lysine concentrations. Error bars showing standard error. Significantly different means ($p < 0.05$) between sex indicated by *.

Slaughter and Carcass measures

The effect of lysine on backfat thickness (P2 (mm)) was different dependant on sex (lysine*sex interaction, $p = 0.037$; Table 3.6). P2 did not differ for gilts on the different lysine treatments but boars on the Med. High and High lysine treatments had significantly less backfat than those on the lower two treatments did (Med. High $p = 0.011$ and $p = 0.026$; High $p <0.001$ and $p = 0.001$ for comparison with Low and Med. Low respectively; Table 3.6). Boars had the least backfat on the High lysine treatment, with P2 on average 2 mm thinner than it was for boars on the Low lysine treatment (9.82 ± 0.32 mm versus 11.89 ± 0.36 mm respectively).

The number of days on trial taken to reach slaughter was reduced with increasing dietary lysine up to the Med. High treatment ($p = 0.216$ between Med. High and High) and lower for boars than gilts ($p <0.001$ for both; Table 3.6). Pigs on the High lysine treatment left for slaughter over 10 days sooner than those on the Low lysine treatment did and over all treatments boars left on average 2.41 ± 0.48 days sooner than gilts. Increasing dietary lysine increased the end live weight of pigs up to the Med. High level ($p <0.001$) but pigs on the Med. Low, Med. High and High lysine treatments had similar carcass cold weights ($p >0.05$), all of which were higher than pigs on the Low treatment ($p <0.001$). There was no difference between the carcass cold weights of boars and gilts ($p = 0.648$) despite boars having heavier end live weights ($p = 0.027$). Killing out percentage

(KO%) was lower for boars than gilts (p <0.001; Table 3.6) and was 1% lower for pigs on the highest lysine treatment when compared to pigs on the Med. Low lysine treatment (p = 0.022). A lysine effect was also found for lean meat percentage (LM%) (p=0.004), as increasing dietary lysine increased carcass leanness, particularly for pigs on the higher two lysine treatments (Med. High and High, p = 0.034 and p = 0.004 when compared to mean LM% of Low pigs). However, there was a tendency for only boars to show this improvement (p = 0.050, lysine*sex interaction; Table 3.6) with similar LM% values for the gilts over the dietary lysine treatments.

Table 3.6. Slaughter and carcass measures of grower-finisher pigs (boars and gilts) fed diets of differing SID lysine concentrations [1 2 3 4]

Measure	Sex	Lysine Treatment					*P*-value		
		Low	Med. Low	Med. High	High	SE	Lysine	Sex	Lysine*Sex
Start Weight (kg)	**Mixed**	36.41	36.42	36.46	36.49	0.28	0.996	**0.020**	0.942
	Boar	36.71	36.66	36.93	36.78	0.41			
	Gilt	36.11	36.17	36.00	36.21	0.38			
End Live Weight (kg)	**Mixed**	104.74^{a}	110.84^{b}	113.98^{c}	114.17^{c}	0.85	**<0.001**	**0.027**	0.145
	Boar	105.22	110.49	115.31	115.76	1.08			
	Gilt	104.25	111.19	112.65	112.59	1.10			
Carcass Cold Weight (kg)	**Mixed**	79.25^{a}	83.84^{b}	85.55^{b}	85.20^{b}	0.77	**<0.001**	0.648	0.393
	Boar	79.09	83.10	85.27	85.82	0.98			
	Gilt	79.42	84.58	85.83	84.57	1.00			
Days to Slaughter	**Mixed**	79.31^{a}	75.43^{b}	69.92^{c}	68.55^{c}	0.49	**<0.001**	**<0.001**	0.100
	Boar	78.98	74.21	68.67	66.51	0.70			
	Gilt	79.64	76.65	71.16	70.59	0.70			
KO%	**Mixed**	75.56^{ab}	75.67^{a}	75.00^{ab}	74.64^{b}	0.30	**0.029**	**<0.001**	0.198
	Boar	75.08	75.22	73.94	74.13	0.39			
	Gilt	76.04	76.12	76.05	75.16	0.40			
P2 (mm)	**Mixed**	11.72^{a}	11.27^{ab}	10.60^{bc}	10.28^{c}	0.28	**0.002**	0.459	**0.037**
	Boar	11.89^{a}	11.55^{a}	10.27^{b}	9.82^{b}	0.36			
	Gilt	11.55^{a}	10.98^{a}	10.93^{ab}	10.74^{a}	0.37			
LM%	**Mixed**	61.09^{a}	61.53^{ab}	62.12^{bc}	62.38^{c}	0.26	**0.004**	0.719	0.050
	Boar	60.92	61.22	62.33	62.79	0.34			
	Gilt	61.27	61.83	61.90	61.97	0.34			

[1] Different superscript letters indicating significantly different means (p < 0.05).
[2] KO% = killing out percentage; P2(mm) = backfat depth at P2 position; LM% = lean meat percentage.
[3] End Live Weight (kg) adjusted for days till slaughter = 73.21; Carcass Cold Weight (kg) adjusted for days till slaughter = 73.14.
[4] KO%, P2 (mm) and LM% adjusted for End Live Weight (kg) = 111.17 kg.

Feed costs and Margin Over Feed

The heavier carcass weights seen for pigs on the higher lysine treatments (Med. High and High) corresponded with higher carcass values (p <0.001; Table 3.7) but feed costs per pig (£) were significantly higher on the High lysine treatment compared to the Low lysine treatment (£64.34 ± 0.51 versus £61.91 ± 0.54, $p = 0.007$), increasing with increasing dietary lysine ($p = 0.014$). Feed costs were also higher for gilts ($p < 0.001$) who took longer to reach slaughter weight than boars. A lysine*sex interaction was observed for cost/kg gain (£) and margin over feed (£) ($p = 0.018$ and $p = 0.010$ respectively; Table 3.7) due to the differing responses of boars and gilts and the boars higher ADGs and improved feed efficiencies. Despite the higher feed costs associated with increasing dietary lysine, the cost/kg gain was reduced and the margin over feed increased for both sexes up until the Med. High level. Past this point the gilts cost/kg gain was increased ($p = 0.019$) and there was tendency for their margin over feed to be reduced ($p = 0.050$), whereas for boars these values neither worsened nor improved ($p = 1.000$). Furthermore, a 19% higher margin over feed can be achieved for boars as opposed to gilts on the highest lysine treatment ($p < 0.001$), with boars on average achieving an additional £18 profit (margin over feed £) on this treatment as opposed to boars on the Low lysine treatment. Additionally, the cost/kg gain for boars on the lowest and highest lysine treatments was significantly lower than for the gilts ($p = 0.027$ and $p < 0.001$).

Table 3.7. Economic evaluation of feeding grower-finisher pigs (boars and gilts) diets of differing SID dietary lysine concentrations [1] [2] [3]

Measure	Sex	Lysine Treatment					*P*-value		
		Low	Med. Low	Med. High	High	SE	Lysine	Sex	Lysine*Sex
Carcass Value (£)	**Mixed**	166.01^{a}	177.71^{b}	183.82^{c}	183.63^{c}	1.31	**<0.001**	0.714	0.279
	Boar	165.88	176.66	183.71	185.84	1.90			
	Gilt	166.14	178.75	183.92	181.43	1.85			
Total Feed Costs (£)	**Mixed**	61.91^{a}	62.95^{ab}	63.24^{ab}	64.34^{b}	0.54	**0.014**	**<0.001**	0.889
	Boar	60.71	61.70	61.88	62.61	0.78			
	Gilt	63.11	64.20	64.60	66.07	0.77			
Cost/ kg gain (£) [d]	**Mixed**	1.53^{a}	1.35^{b}	1.27^{c}	1.30^{c}	0.01	**<0.001**	**<0.001**	**0.018**
	Boar	1.50^{a}	1.34^{b}	1.26^{c}	1.24^{c}	0.02			
	Gilt	1.55^{d}	1.36^{b}	1.29^{c}	1.36^{b}	0.02			
Margin over Feed (£)	**Mixed**	25.87^{a}	37.12^{b}	42.94^{c}	41.59^{c}	0.92	**<0.001**	**0.009**	**0.010**
	Boar	26.77^{a}	36.85^{b}	43.37^{c}	45.17^{c}	1.34			
	Gilt	24.97^{a}	37.40^{b}	42.50^{cd}	38.02^{bd}	1.30			

[1] Different superscript letters indicating significantly different means ($p < 0.05$).

[2] End Live Weight (kg) adjusted for days till slaughter = 73.21.

[3] Carcass Value (£) estimated using the weekly AHDB standard pig price. 01/04/2023- 211.80 p/kg, 08/04/2023- 213.03 p/kg, 15/04/2023- 213.63 p/kg, 22/04/2023- 214.49 p/kg.

[4] Cost/kg gain refers to feed costs, other production costs not included.

Environmental Impact

Increasing dietary lysine increased (and more than doubled) the CO_2e values (in kg/pig) in both Phases One and Two ($p < 0.001$; Table 3.8) for pigs on the higher lysine treatments and over the growing-finishing period as a whole ($p < 0.001$), as a result of the higher protein/soya content of the Med. High and High lysine diets. However, in Phase Three a lysine*sex interaction was observed (p = 0.008; Table 3.8) as the average CO_2e associated with the diets was the same for boars on all four treatments regardless of dietary lysine concentration (all p >0.05). The same did not occur for the gilts, who still saw a 30% increase in CO_2e from the Low to the High lysine treatment, albeit with no difference between the two intermediate diets (Med. Low and Med. High, p = 1.000). Additionally, the boars CO_2e values in this phase were lower than the gilts on the Med. Low, Med. High and High treatments (p = 0.046, p = 0.002 and p <0.001 respectively), likely a result of them reaching slaughter weight faster and so consuming less feed in this phase. Over the course of the growing-finishing period gilts on average incurred around 4 kg more CO_2e per pig than boars (124.75 ± 0.68 kg/pig vs 120.36 ± 0.72 kg/pig, p <0.001).

Table 3.8. CO_2e (kg/pig) associated with feeding grower-finisher pigs (boars and gilts) diets of differing SID dietary lysine concentrations [1 2]

Measure	Sex	Lysine Treatment					***P*-value**		
		Low	**Med. Low**	**Med. High**	**High**	**SE**	**Lysine**	**Sex**	**Lysine*Sex**
CO_2e (kg/pig)									
Phase One	**Mixed**	16.33[a]	24.59[b]	34.92[c]	41.25[d]	0.42	**<0.001**	0.619	0.269
	Boar	16.43	24.46	34.59	42.02	0.60			
	Gilt	16.22	24.72	35.25	40.47	0.59			
Phase Two	**Mixed**	32.46[a]	43.36[b]	57.18[c]	70.92[d]	0.60	**<0.001**	0.279	0.393
	Boar	32.27	43.26	57.65	72.03	0.88			
	Gilt	32.64	43.46	56.71	69.80	0.84			
Phase Three	**Mixed**	38.27[a]	43.15[bc]	41.11[ab]	45.96[c]	0.88	**<0.001**	**<0.001**	**0.008**
	Boar	37.48	41.37	38.36	41.07	1.30			
	Gilt	39.06[a]	44.93[b]	43.85[b]	50.85[c]	1.21			
Total	**Mixed**	87.20[a]	111.57[b]	133.25[c]	158.18[d]	1.00	**<0.001**	**<0.001**	0.415
	Boar	86.28	109.49	130.73	154.92	1.48			
	Gilt	88.12	113.66	135.77	161.44	1.38			

[1] Different superscript letters indicating significantly different means (p < 0.05).

[2] CO_2e = kg of carbon dioxide equivalent (includes associated emissions with land use change).

Feeding-related behaviours

In Phase One and three increasing dietary lysine reduced the amount of time pigs spent in the feeders per day (p = 0.031 and p <0.001; Table 3.9). Pigs on the Low lysine treatment spent significantly more time in the feeder than those on the High lysine treatment did, approximately 5 minutes longer in Phase One and almost 10 minutes longer in Phase Three (p = 0.030 for Phase One and p <0.001 for Phase Three). However, pigs on all treatments spent a similar amount of time in the feeder per day during Phase Two (p = 0.287). Additionally, in all three phases boars spent longer than gilts in the feeders (Phase One, p = 0.010; Phase Two, p = 0.001; Phase Three, p <0.001).

Average consumption rate (in kg/hour) increased with increasing lysine concentration ($p <0.001$ in Phase Two and Three; Table 3.10) but did not differ between treatments in Phase One ($p = 0.123$). In Phase Two and Three pigs on the Med. High and High lysine treatments consumed feed significantly faster than pigs on the Low lysine treatment (all $p <0.001$) and pigs on the Med. Low lysine treatment (Phase Two, $p = 0.020$ and $p = 0.014$; Phase Three, $p = 0.033$ and $p <0.001$), but at similar rates to each other ($p >0.05$). Gilts also ate significantly faster than boars (by around 7%) in Phases Two and Three ($p = 0.006$ and $p = 0.003$).

Increasing dietary lysine also reduced the average number of feeder visits (per day), which was observed over the whole experiment ($p <0.001$ for all three phases; Table 3.11) but most noticeably in Phases Two and Three where pigs took as many as four fewer trips to the feeder per day when on the High lysine treatment as opposed to the Low lysine treatment. There was also a difference between sexes in each phase as gilts on average visited the feeder more often than boars ($p = 0.004$, $p = 0.037$ and $p = 0.009$ for Phases One, Two and Three respectively).

Table 3.9. Effect of dietary SID lysine concentration on the time grower-finisher pigs spent at the feeder (minutes/day) throughout three phases of a dietary regime fed from 36 kg until slaughter (~110 kg) [1]

Measure	Sex	Lysine Treatment					***P*-value**		
		Low	**Med. Low**	**Med. High**	**High**	**SE**	**Lysine**	**Sex**	**Lysine*Sex**
Av. time at Feeder (mins/day)									
Phase One	**Mixed**	71.23^{a}	69.33^{ab}	67.41^{ab}	65.77^{b}	1.37	**0.031**	**0.010**	0.096
	Boar	71.77	72.95	67.01	69.11	1.95			
	Gilt	70.68	65.72	67.82	62.44	1.93			
Phase Two	**Mixed**	77.96	76.19	74.73	73.88	1.60	0.287	**0.001**	0.971
	Boar	80.70	78.98	76.73	76.92	2.30			
	Gilt	75.22	73.39	72.74	70.83	2.24			
Phase Three	**Mixed**	79.29^{a}	75.61^{ab}	72.04^{bc}	69.34^{c}	1.69	**<0.001**	**<0.001**	0.275
	Boar	84.97	78.62	73.01	72.25	2.48			
	Gilt	73.62	72.61	71.07	66.42	2.33			

[1] Different superscript letters indicating significantly different means ($p < 0.05$).

Table 3.10. Effect of dietary SID lysine concentration on the consumption rate (kg/hour) of grower-finisher pigs throughout three phases of a dietary regime fed from 36 kg until slaughter (~110 kg) [1]

Measure	Sex	Lysine Treatment					*P*-value		
		Low	Med. Low	Med. High	High	SE	Lysine	Sex	Lysine*Sex
Av. consumption Rate (kg/hour)									
Phase One	**Mixed**	1.39	1.40	1.49	1.42	0.03	0.123	0.059	0.248
	Boar	1.38	1.33	1.50	1.36	0.05			
	Gilt	1.39	1.48	1.48	1.48	0.05			
Phase Two	**Mixed**	1.83[a]	1.96[a]	2.16[b]	2.17[b]	0.05	**<0.001**	**0.006**	0.603
	Boar	1.75	1.86	2.15	2.09	0.07			
	Gilt	1.91	2.06	2.17	2.24	0.07			
Phase Three	**Mixed**	2.44[a]	2.71[b]	2.96[c]	3.08[c]	0.06	**<0.001**	**0.003**	0.291
	Boar	2.27	2.59	2.96	2.99	0.09			
	Gilt	2.61	2.83	2.96	3.18	0.09			

[1] Different superscript letters indicating significantly different means ($p < 0.05$)

Table 3.11. Effect of dietary SID lysine concentration on the average number of feeder visits (per day) of grower-finisher pigs throughout three phases of a dietary regime fed from 36 kg until slaughter (~110 kg) [1]

Measure	Sex	Lysine Treatment					*P*-value		
		Low	Med. Low	Med. High	High	SE	Lysine	Sex	Lysine*Sex
Av. number of visits to the feeder /day									
Phase One	**Mixed**	9.58[a]	9.55[a]	7.93[b]	7.64[b]	0.28	**<0.001**	**0.004**	0.964
	Boar	9.15	9.03	7.61	7.28	0.41			
	Gilt	10.02	10.06	8.24	8.01	0.40			
Phase Two	**Mixed**	10.04[a]	9.80[a]	6.94[b]	6.10[b]	0.32	**<0.001**	**0.037**	0.521
	Boar	10.00	9.19	6.79	5.56	0.47			
	Gilt	10.09	10.42	7.09	6.65	0.46			
Phase Three	**Mixed**	10.63[a]	9.49[a]	7.09[b]	6.57[b]	0.37	**<0.001**	**0.009**	0.209
	Boar	10.72	8.63	6.77	5.75	0.54			
	Gilt	10.54	10.34	7.41	7.40	0.50			

[1] Different superscript letters indicating significantly different means ($p < 0.05$).

3.2. Estimating lysine requirements

Phase One (day 0-21)

Linear plateau models (BLL) were unable to be fitted for Phase One ADG data but quadratic and quadratic plateau models were, with no difference in model fit between them (established by the very similar AIC (Akaike information criterion), BIC (Bayesian information criterion) and R^2 values; Table A1 in Appendix). Quadratic models estimated lysine requirements at 1.69 SID lysine for boars, 1.15 SID lysine for gilts and 1.28 SID lysine for mixed sex, whereas the quadratic plateau estimates were 1.70, 1.20 and 1.28 SID lysine for boars, gilts and mixed sex respectively (Table

3.12). These estimates for the boars were outside of the test range (0.71-128 SID lysine) and at the highest level used for mixed sex (1.28 SID lysine).

For FCR all three models could be fitted to some extent, with only the linear plateau model for gilts not fitted due to the lack of a clear breakpoint in the data. When considering the pigs as a mixed gender group the linear plateau model estimated a concentration of 1.10 SID lysine (95% CI: [1.05, 1.16]) for optimal FCR. A slightly higher estimate of 1.13 SID lysine (95% CI: [1.07, 1.19]) was predicted for boars alone (Table 3.12). The quadratic and quadratic plateau (BLQ) models gave the same estimates of 1.34 SID lysine and 1.49 SID lysine to optimize the FCR of mixed sex pigs and boars respectively. However, as with ADG, these lie outside the actual range of lysine concentrations used and the linear plateau model was better fitting (lower AIC and BIC values; Table A1 in Appendix). The lysine requirements estimated for gilts via the quadratic and quadratic plateau models (1.26 and 1.27 SID lysine) were just below the maximum lysine concentration used.

Table 3.12. Estimated SID lysine requirements (%) of grower-finisher pigs (boars and gilts) for optimal ADG (kg) and FCR throughout three phases of a dietary regime [1 2 3]

	Phase One				Phase Two				Phase Three - endpoint				Phase Three - slaughter			
	Q	Q 90%	BLL	BLQ	Q	Q 90%	BLL	BLQ	Q	Q 90%	BLL	BLQ	Q	Q 90%	BLL	BLQ
ADG																
Mixed sex	1.28	1.15	-	1.28	1.12*	1.01	0.94	1.12*	1.83*	1.65*	0.94	1.83*	1.12*	1.01*	0.90	1.12*
Boars	1.69*	1.53*	-	1.70*	1.20*	1.08	0.97	1.20*	1.94*	1.75*	0.95	1.94*	1.45*	1.31*	0.94	1.45*
Gilts	1.15	1.04	-	1.20	1.07	0.96	0.92	1.07	1.65*	1.48*	0.92	1.65*	0.97	0.87	0.76	-
FCR																
Mixed sex	1.34*	1.21	1.10	1.34*	1.06	0.95	0.85	-	1.00*	0.90	0.83	1.00*	0.98	0.88	0.74	-
Boars	1.49*	1.34*	1.13	1.49*	1.09	0.98	0.86	-	1.18*	1.06*	0.90	1.18*	1.06*	0.95	0.77	1.06*
Gilts	1.26	1.14	-	1.27	1.03	0.93	0.84	-	0.93	0.84	-	0.94	0.92	0.83	-	0.79

[1] Q = quadratic model; Q 90% = 90% of the quadratic model estimate; BLL = linear plateau model; BLQ = quadratic plateau model.
[2] * superscript indicates estimate was beyond the test range of lysine used (Phase one, 0.71-1.28 SID Lys; Phase two, 0.62-1.09 SID Lys and Phase three, 0.52-1.00 SID Lys).
[3] SID = standardized ileal digestible (%).

Phase Two (day 22-49)

In Phase Two linear plateau models estimated SID lysine concentrations for maximum ADG and FCR for both sexes separately and together (as a mixed sex group; Table 3.12). To maximise ADG, boars required an estimated SID lysine concentration of 0.97 (95% CI: [0.91, 1.02]), higher than the 0.92 SID lysine (95% CI: [0.86, 0.98]) estimated for the gilts. However, if using the 95% confidence intervals to determine whether requirements between boars and gilts differ significantly, as Aymerich et al. (2021) did, then these two estimates do not. The estimated lysine concentration for optimal ADG of the pigs as a mixed sex group was 0.94 SID lysine (95% CI: [0.90, 0.99]), an intermediate between the two, with the mean ADG for boars and gilts estimated to only increase by 3% when lysine is increased further to the boar's optimal lysine concentration of 0.97 SID lysine. While quadratic and quadratic plateau models were also fitted for ADG, the linear plateau model was found to be marginally best fitting (Table A2 in Appendix).

Linear plateau models were also fitted for the response in FCR to increasing dietary lysine, with estimated concentrations to minimise FCR being lower than those which were estimated to maximise ADG. For boars this was 0.86 SID lysine (95% CI: [0.81, 0.90]), for gilts it was 0.84 SID lysine (95% CI: [0.80, 0.89]) and mixed sex 0.85 SID lysine (95% CI: [0.82, 0.88]), Table 3.12. Estimates here are even closer than those seen for ADG, with the 95% confidence intervals largely overlapping between boars and gilts. In Phase Two the quadratic plateau model was unable to be fitted but the quadratic model gave much higher lysine estimates (Table 3.12), illustrated visually in Figure 3.5 which has the linear plateau SID lysine estimate plotted (labelled BLL) together with the maximum estimate from the quadratic regression and 90% of this estimate (Q and Q 90%). The linear plateau estimate appears to be an underestimation, occurring before the response to FCR has begun to plateau. Comparison of the models (using AIC, BIC and R^2; Table A2 in Appendix) showed the quadratic model was the best fitting of the two when applied to the FCR Phase Two data (For mixed gender; AIC = -13.21, BIC = 1.77 for linear plateau and AIC = -21.96, BIC = -6.97 for quadratic). Consequently, it is these estimates which will be used. Optimal FCR (lowest FCR) was predicted at a concentration of 1.06 SID lysine for both sexes, 1.09 SID lysine for boars and 1.03 SID lysine for gilts (Table 3.12). For 90% of the minimum FCR the quadratic model gave estimates of 0.95, 0.98 and 0.93 SID lysine for mixed sex, boars and gilts respectively. Since the maximum lysine concentration used in Phase Two was 1.09 SID lysine, the boars estimated requirement of 1.09 SID lysine should not be considered accurate.

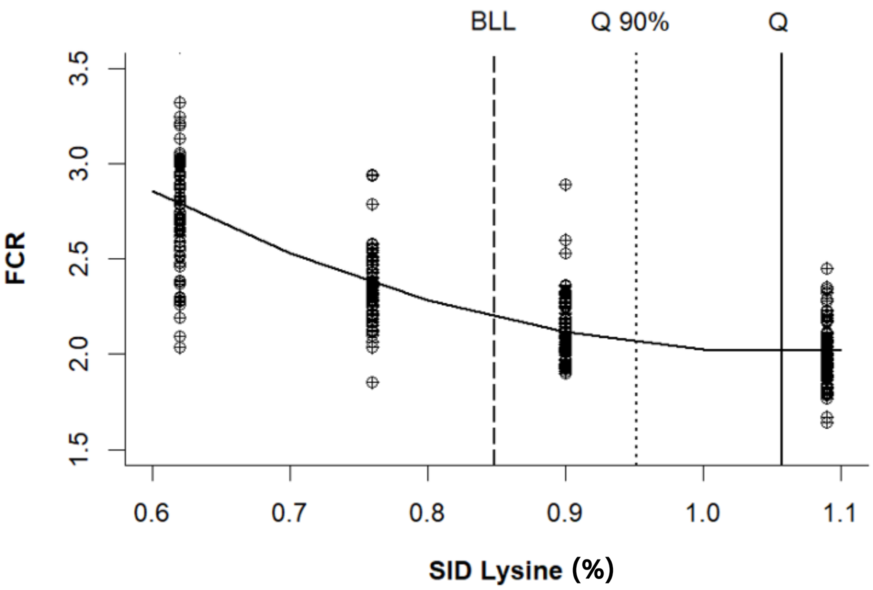

Figure 3.5. The effect of increasing dietary lysine on the FCR of finisher pigs (boars and gilts) from week four to the end of week seven (53-83 kg) with a fitted quadratic model ($y = 4.0251x^2 - 8.5098x + 6.5126$, $R^2 = 0.62$, p-value = $2.22e^{-13}$). The lysine concentration estimated by the quadratic model to minimise FCR (1.06 SID lysine) is indicated by the thick line labelled Q with 90% of this estimate also plotted (0.95 SID lysine). The dashed line labelled BLL indicates the lysine requirement estimated from a linear plateau model (0.85 SID lysine).

Phase Three to endpoint (day 50-64)

All three models were fitted for modelling the growth response of pigs in the first two weeks of Phase Three (i.e. to endpoint; Table 3.12). For ADG, model fit determined by AIC and BIC was not different between the linear plateau model and the two quadratic based models (For mixed gender; AIC = -69.76, BIC = -54.84 for BLL and AIC = -67.91, BIC = -52.99 for quadratic and BLQ models; Table A3 in Appendix). The quadratic and quadratic plateau models predicted lysine concentrations for maximum ADG that were significantly outside of the actual range of SID lysine concentrations used. These estimates also had large confidence intervals (extending into negative values). Therefore, only the predictions from the linear plateau model (BLL) will be considered for this phase. The breakpoints and thus lysine concentrations estimated to maximise ADG during this period were 0.94 SID lysine (95% CI: [0.87, 1.00]) for mixed sex, 0.95 SID lysine (95% CI: [0.88, 1.01]) for boars and 0.92 SID lysine (95% CI: [0.82, 1.02]) for gilts (Table 3.12).

For optimal FCR the predicted lysine concentrations from the quadratic and quadratic plateau models are less extreme (Table 3.12) but are still outside of the range used for boars and lie at the maximum concentration used for mixed sex (1.00 SID lysine). The BLL model provides estimates within the test range and for mixed sex provides a comparatively better fit than the other two models (AIC = 851.19, BIC = 866.11 vs AIC = 853.20, BIC = 868.12 for quadratic and BLQ models; Table A3 in Appendix). It was not possible to fit a linear plateau model for the gilts response but for the boars the breakpoint was estimated at 0.90 SID lysine (95% CI: [0.80, 1.01]) and for the response of boars and gilts as a mixed sex group at 0.83 SID lysine (95% CI: [0.75, 0.92]).

Phase Three to slaughter (day 50 - slaughter)

Looking at the performance of pigs from the start of Phase Three to slaughter, the estimated lysine levels from the quadratic and quadratic plateau models remain out of range for the ADG of mixed sex and boars, but less so than for Phase Three to endpoint. Despite this AIC and BIC values didn't show a significant difference in model fit when compared to the linear plateau model (Table A4 in Appendix). As the only estimates all within the used range of concentrations, the linear plateau models predicted optimal ADG at the following lysine concentrations; 0.90 SID lysine (95% CI: [0.83, 0.96]) for mixed sex pigs, 0.94 SID lysine (95% CI: [0.85, 1.02]) for boars and 0.76 SID lysine (95% CI: [0.68, 0.84]) for gilts (Table 3.12). Here the estimated lysine requirements for boars and gilts may be considered significantly different due to the 95% confidence intervals not overlapping.

The lysine requirements for minimum FCR using the linear plateau models were estimated at 0.74 SID lysine (95% CI: [0.68, 0.79]) for mixed sex and 0.77 SID lysine (95% CI: [0.67, 0.87]) for boars (Table 3.12). A breakpoint was not able to be estimated for the response of gilts, but requirements could be estimated for both sexes using the quadratic and quadratic plateau models, which were slightly better fitting when compared to the boars linear plateau model (AIC = 262.02, BIC = 274.07 for quadratic and BLQ models vs AIC = 265.60, BIC = 277.64 for BLL; Table A4 in Appendix). Quadratic models estimated lysine requirements at 1.06 SID lysine for boars, 0.92 SID lysine for gilts and 0.98 SID lysine for mixed sex, whereas the quadratic plateau estimates were 1.06 and 0.79 SID lysine for boars and gilts respectively (Table 3.12). Both these estimates for the boars were outside of the test range (0.52-1.00 SID lysine).

3.3. Behavioural observations

Phase One (day 0-21)

In Phase One no significant interactive effects were found between sex and lysine for all the behaviours of interest. Behavioural observations showed no effect of lysine on the % of total time spent mounting ($p = 0.360$, Table 3.13) and exploring ($p = 0.108$). But lysine did have an effect on the % of total time pigs spent drinking ($p = 0.028$), fighting/being aggressive ($p = 0.013$) and performing oral manipulation ($p = 0.039$). There was also a trend ($p < 0.1$) for increasing lysine to increase the time pigs spent inactive ($p = 0.060$).

Pigs on the Med. high treatment (1.09 SID Lys) spent double the amount of time drinking than those on the Low lysine treatment did (0.71 SID Lys, $p = 0.032$). But pigs on both these treatments spent a similar amount of time drinking when compared to those on the Med. Low and High treatments (0.90 and 1.28 SID Lys, all $p > 0.05$; Table 3.13). Increasing dietary lysine reduced the % of time pigs were observed fighting/being aggressive ($p = 0.013$), a reduction of almost 60% for pigs on the High lysine treatment when compared to those on the Low lysine treatment ($p = 0.015$). However, those on the two intermediate diets on average spent a similar percentage of their total time fighting when compared to each other and both the Low and High treatments ($p > 0.05$). Although a lysine effect was found for oral manipulation ($p = 0.039$) and the mean percentages can be seen to decrease with increasing lysine (up to the Med. High level), the post hoc test found no significant differences between these treatment means ($p > 0.05$ for all comparisons). With a more lenient post hoc test (LSD, least significant difference) a difference was seen between the Low treatment and the two higher treatments ($p = 0.018$, $p = 0.017$) indicating where the differences occurred.

For fighting/aggression a difference between boars and gilts also occurred ($p < 0.001$, Table 3.13) with boars being more aggressive than gilts. The only other sex difference in observed behaviours was seen for exploration, with gilts on average being observed exploring more often than boars (11.13 ± 0.52 % vs 9.24 ± 0.52 % of total time (120 minutes), $p = 0.011$). Boars and gilts spent a similar proportion of their time performing the remaining behaviours.

Table 3.13. Analysis of the behaviour of grower-finisher pigs (boars and gilts) from weeks two and three of finishing fed diets of differing SID lysine concentrations [1] [2]

Behaviour	Sex	SID Lysine concentration (%)					*P*-value		
		0.71	0.90	1.09	1.28	SE	Lysine	Sex	Lysine*Sex
Drinking	**Mixed**	0.86[a]	0.99[ab]	1.72[b]	1.14[ab]	0.22	**0.028**	0.823	0.347
	Boar	0.72	0.84	2.05	1.20	0.31			
	Gilt	1.01	1.14	1.39	1.08	0.31			
Mounting	**Mixed**	0.07	0.19	0.15	0.03	0.07	0.360	0.906	0.532
	Boar	0.13	0.18	0.08	0.07	0.10			
	Gilt	0.00	0.20	0.22	0.00	0.10			
Fighting/Aggression	**Mixed**	1.63[a]	1.45[ab]	1.07[ab]	0.66[b]	0.23	**0.013**	**<0.001**	0.609
	Boar	2.25	1.65	1.37	1.05	0.32			
	Gilt	1.02	1.24	0.78	0.27	0.32			
Oral Manipulation	**Mixed**	7.21[a]	6.62[a]	5.57[a]	5.56[a]	0.49	**0.039**	0.419	0.662
	Boar	7.40	6.33	6.11	5.91	0.69			
	Gilt	7.02	6.91	5.03	5.20	0.69			
Exploration	**Mixed**	11.48	10.20	10.14	8.91	0.74	0.108	**0.011**	0.728
	Boar	10.38	8.65	9.47	8.46	1.04			
	Gilt	12.58	11.74	10.82	9.36	1.04			
Inactive	**Mixed**	66.22	68.32	69.92	70.66	1.25	0.060	0.846	0.327
	Boar	66.46	70.05	69.98	69.11	1.77			
	Gilt	65.97	66.59	69.86	72.21	1.77			
Other	**Mixed**	12.53	12.24	11.43	13.03	0.68	0.405	0.524	0.386
	Boar	12.66	12.30	10.94	14.20	0.97			
	Gilt	12.41	12.17	11.91	11.87	0.97			

[1]Different superscript letters indicating significantly different means ($p < 0.05$).
[2]Data is from weekly scan sampling carried out throughout finishing and values shown are the mean percentages of time spent performing each behaviour (%).

Phase Two (day 22-49)

In Phase Two a lysine*sex interaction was observed for the % of total time pigs spent performing oral manipulation ($p = 0.017$, Table 3.14). Despite there appearing to be a reduction in the % of time boars spent on oral manipulation as dietary lysine increased, no significant differences between these means were observed (all $p > 0.05$). This was not the case for gilts, who were observed performing oral manipulation for significantly less time on the Med. High treatment (0.90 SID Lys) than on the other three treatments ($p < 0.001$, $p = 0.032$ and $p = 0.036$ for Low, Med. Low and High respectively). Increasing dietary lysine up to the Med. High level increased the % of time pigs spent inactive ($p < 0.001$) and reduced the time they spent exploring ($p < 0.001$). Increasing lysine further, to the High level (1.09 SID Lys), had no effect on inactivity and exploration (both $p = 1.000$).

Several of the observed behaviours throughout the four weeks of Phase Two were also affected by sex. When compared to boars, gilts were observed exploring for a greater % of the total time ($p < 0.001$, Table 3.14) and were less frequently observed inactive ($p = 0.002$). Additionally, boars were observed mounting ($p < 0.001$) and fighting/ being aggressive ($p < 0.001$) significantly more than the gilts, with the boars on average fighting/being aggressive over twice as often as the gilts (boars 1.51± 0.13%, gilts 0.68 ± 0.13%).

Table 3.14. Analysis of the behaviour of finisher pigs (boars and gilts) from week four of finishing to week seven (~53-83 kg) fed diets of differing SID lysine concentrations [1,2]

Behaviour	Sex	SID Lysine concentration (%)					*P*-value		
		0.62	**0.76**	**0.90**	**1.09**	**SE**	**Lysine**	**Sex**	**Lysine*Sex**
Drinking	**Mixed**	1.88	1.70	2.01	2.25	0.20	0.273	0.266	0.575
	Boar	1.66	1.46	2.14	2.13	0.29			
	Gilt	2.09	1.94	1.89	2.37	0.29			
Mounting	**Mixed**	0.23	0.14	0.10	0.14	0.05	0.322	**<0.001**	0.517
	Boar	0.43	0.24	0.20	0.28	0.07			
	Gilt	0.04	0.05	0.00	0.00	0.07			
Fighting/Aggression	**Mixed**	1.44	1.09	0.84	1.02	0.18	0.105	**<0.001**	0.263
	Boar	2.06	1.28	1.14	1.58	0.25			
	Gilt	0.83	0.91	0.53	0.47	0.25			
Oral Manipulation	**Mixed**	7.32[a]	6.83[ab]	5.24[c]	5.92[bc]	0.36	**<0.001**	**<0.001**	**0.017**
	Boar	6.12[a]	6.56[ac]	5.37[ab]	4.77[a]	0.51			
	Gilt	8.53[c]	7.11[ac]	5.11[b]	7.08[c]	0.51			
Exploration	**Mixed**	16.20[a]	13.69[b]	10.07[c]	9.44[c]	0.62	**<0.001**	**<0.001**	0.813
	Boar	14.61	12.02	8.94	7.48	0.87			
	Gilt	17.78	15.36	11.19	11.40	0.87			
Inactive	**Mixed**	62.24[a]	66.30[b]	71.52[c]	71.73[c]	0.95	**<0.001**	**0.002**	0.163
	Boar	63.76	68.83	71.21	73.78	1.34			
	Gilt	60.73	63.77	71.83	69.69	1.34			
Other	**Mixed**	10.68	10.24	10.22	9.49	0.42	0.246	0.115	0.068
	Boar	11.36	9.61	11.00	9.98	0.59			
	Gilt	10.00	10.86	9.45	8.99	0.59			

[1] Different superscript letters indicating significantly different means ($p < 0.05$).
[2] Data is from weekly scan sampling carried out throughout finishing and values shown are the mean percentages of time spent performing each behaviour (%).

Phase Three to endpoint (day 50-64)

In Phase Three (the final two weeks before the first batch of pigs went to slaughter), the interactive effect of lysine and sex on oral manipulation was no longer seen ($p = 0.112$, Table 3.15). However, a lysine*sex interaction did occur for the % of total time pigs spent inactive ($p = 0.041$). Boars were observed inactive for a similar proportion of time regardless of lysine treatment ($p > 0.05$). This is in contrast to gilts, who showed an increase in inactivity on the higher two lysine treatments (an extra

12.99% and 12.32% of the total time on the Med. High and High lysine treatments respectively) when compared to the Low lysine treatment (0.52 SID Lys, p <0.001). Gilts on this Low lysine treatment spent the least amount of time inactive, significantly less than boars on the same treatment (p <0.001).

Increasing dietary lysine once again reduced the proportion of time pigs were observed exploring (p <0.001). Pigs on the higher two lysine treatments (0.81 and 1.00 SID Lys) spent roughly half the amount of time exploring that pigs on the Low lysine treatment did (e.g. 7.11 ± 0.82% on the High treatment versus 14.70 ± 0.82% on the Low, p<0.001). But differences were not significant between the means for the Med. High and High treatments (p = 1.000) as well as between the Low and Med. Low treatments (p = 0.094). Lysine also had an effect on fighting/aggression (p = 0.017) with the proportion of time spent fighting/ engaging in aggressive behaviours significantly lower for pigs on the High lysine treatment when compared to those on the Low treatment (p = 0.015). Similar to in Phase One, those on the two intermediate diets showed no difference in the percentage of their total time fighting when compared to each other and the Low and High treatments (all p >0.05).

Despite the lack of a lysine*sex interaction, oral manipulation still differed between lysine treatments (p = 0.020) and was lowest on the Med. High treatment with no effect of sex (p = 0.647). But this mean was only significantly lower when compared to pigs on the Med. Low treatment (p = 0.017), who had the highest % of total time spent on oral manipulation. In Phases One and Two, the lowest % of total time pigs spent oral manipulating also occurred for pigs on the Med. High treatment (1.09 SID Lys in P1 and 0.90 SID Lys in P2; Table 3.13 and Table 3.14) but no difference occurred between these means and those for the pigs on the High lysine diet in all three phases (Phase One & Two, p = 1.000; Phase Three, p = 0.716).

As was seen in the previous two phases, on average gilts were observed exploring more often than boars (11.58 ± 0.58% vs 8.74 ± 0.58% respectively, p <0.001, Table 3.15) and boars spent more time mounting than gilts (p <0.001). There was also a trend for boars to fight more and be more aggressive than gilts (p = 0.078).

Table 3.15. Analysis of the behaviour of finisher pigs (boars and gilts), from week eight and nine of finishing (~83-100 kg), fed diets of differing SID lysine concentrations [1] [2]

Behaviour	Sex	SID Lysine concentration (%)					*P*-value		
		0.52	0.67	0.81	1.00	SE	Lysine	Sex	Lysine*Sex
Drinking	Mixed	1.07	1.58	1.28	1.55	0.25	0.437	0.465	0.182
	Boar	0.65	1.30	1.59	1.57	0.36			
	Gilt	1.48	1.86	0.97	1.54	0.36			
Mounting	Mixed	0.14	0.12	0.28	0.09	0.07	0.261	**<0.001**	0.109
	Boar	0.29	0.16	0.55	0.18	0.10			
	Gilt	0.00	0.08	0.00	0.00	0.10			
Fighting/Aggression	Mixed	1.16^{a}	0.68^{ab}	0.55^{ab}	0.39^{b}	0.18	**0.017**	0.078	0.998
	Boar	1.30	0.83	0.74	0.54	0.25			
	Gilt	1.02	0.53	0.36	0.23	0.25			
Oral Manipulation	Mixed	5.33^{ab}	5.77^{a}	3.80^{b}	4.83^{ab}	0.47	**0.020**	0.647	0.112
	Boar	4.86	6.83	3.80	4.67	0.66			
	Gilt	5.79	4.72	3.80	4.99	0.66			
Exploration	Mixed	14.70^{a}	11.90^{a}	6.94^{b}	7.11^{b}	0.82	**<0.001**	**<0.001**	0.195
	Boar	11.75	11.04	6.14	6.04	1.16			
	Gilt	17.64	12.77	7.73	8.18	1.16			
Inactive	Mixed	68.87^{a}	70.99^{a}	77.05^{b}	77.38^{b}	1.32	**<0.001**	**0.016**	**0.041**
	Boar	73.67^{b}	71.55^{ab}	77.04^{b}	78.36^{b}	1.86			
	Gilt	64.08^{a}	70.43^{ab}	77.07^{b}	76.40^{b}	1.86			
Other	Mixed	8.73	8.96	10.10	8.65	0.57	0.253	0.103	0.336
	Boar	7.48	8.31	10.13	8.65	0.81			
	Gilt	9.99	9.62	10.07	8.65	0.81			

[1] Different superscript letters indicating significantly different means ($p < 0.05$).
[2] Data is from weekly scan sampling carried out throughout finishing and values shown are the mean percentages of time spent performing each behaviour (%).

Overall

When looking at the behavioural observations over the whole experiment (excluding week one data and that following the removal of the first pigs for slaughter) no significant interactive effects were found between sex and lysine for all the behaviours of interest. Increasing dietary lysine up to the levels fed on the Med. High treatment (1.09, 0.90 and 0.81 SID Lys) increased the % of total time pigs were observed inactive ($p < 0.001$, Table 3.16) and reduced the % of time pigs were observed exploring ($p < 0.001$) by 12 and 37% respectively. Increasing dietary lysine further, for the High lysine treatment (1.28, 1.09 and 1.00 SID Lys), had no effect on the % of total time spent inactive and exploring ($p = 1.000$, between Med. High and High lysine treatments for inactivity and exploration).

Lysine effects were also seen for oral manipulation ($p < 0.001$) and fighting/aggression ($p < 0.001$). Pigs on the higher two treatments were observed performing oral manipulation for a significantly lower % of their total time than pigs on the Low lysine treatment were (comparison with Med. High, $p < 0.001$ and High, $p = 0.035$). No difference was seen in observed oral manipulation between pigs on the Low and Med. Low lysine treatments ($p = 1.000$), between those on the Med. High and High lysine treatments ($p = 0.708$) and those on the Med. Low and High lysine treatments ($p = 0.073$). Although the latter shows there was a tendency for oral manipulation to be higher on the Med. Low treatment. Additionally, there was also a tendency for gilts to spend more time performing oral manipulation than boars ($p = 0.080$) and a trend for a lysine*sex interaction ($p = 0.057$). In regard to fighting/aggression, the proportion of time spent fighting/showing aggressive behaviours was significantly higher for pigs on the Low lysine treatment when compared to pigs on the Med. High and High treatments ($p = 0.003$ and $p = 0.001$). Increasing lysine above the Med. Low treatment, slightly decreased the mean values for % of total time spent fighting/being aggressive but no significant differences were seen between the Med. Low, Med. High and High lysine treatments (all $p > 0.05$).

Over the finishing period boars and gilts differed in various observed behaviours. Gilts were observed exploring for a greater % of the total time ($p < 0.001$, Table 3.16) and were inactive for a lower % of total time ($p = 0.002$) when compared to the boars. Furthermore, in comparison to gilts, boars were observed mounting ($p < 0.001$) and fighting/ being aggressive ($p < 0.001$) for a greater proportion of the total time. But drinking did not differ between boars and gilts ($p = 0.284$).

All observed behaviours except mounting ($p = 0.565$) differed between the phases of the dietary regime implemented over the finishing period (Table 3.17). Across the three phases the mean % of time spent exploring ($p < 0.001$) and Drinking ($p < 0.001$) was significantly higher in Phase Two but similar in Phases One and Three. Both fighting/aggression ($p = 0.005$) and oral manipulation ($p < 0.001$) did not significantly differ when comparing Phase One and two but were significantly lower in Phase Three than in the first two phases. Similarly, % of time spent inactive ($p < 0.001$) did not differ between Phases One and Two but was significantly higher in Phase Three compared to both Phase One and Phase Two.

Table 3.16. Analysis of the behaviour of grower-finisher pigs (boars and gilts) fed diets of differing SID lysine concentrations (%) from 36 kg to ~100 kg [1,2]

Behaviour	Sex	Lysine Treatment					*P*-value		
		Low	Med. Low	Med. High	High	SE	Lysine	Sex	Lysine*Sex
Drinking	**Mixed**	1.31	1.38	1.64	1.68	0.14	0.133	0.284	0.058
	Boar	1.06	1.15	1.86	1.64	0.20			
	Gilt	1.56	1.60	1.42	1.73	0.20			
Mounting	**Mixed**	0.16	0.14	0.15	0.10	0.04	0.583	**<0.001**	0.378
	Boar	0.31	0.20	0.25	0.19	0.05			
	Gilt	0.02	0.09	0.05	0.00	0.05			
Fighting/Aggression	**Mixed**	1.39^{a}	1.05^{ab}	0.80^{b}	0.75^{b}	0.12	**<0.001**	**<0.001**	0.237
	Boar	1.89	1.23	1.07	1.16	0.17			
	Gilt	0.90	0.87	0.53	0.34	0.17			
Oral Manipulation	**Mixed**	6.67^{a}	6.39^{ac}	4.84^{b}	5.43^{bc}	0.27	**<0.001**	0.080	0.057
	Boar	6.00	6.45	5.04	4.91	0.38			
	Gilt	7.34	6.34	4.64	5.96	0.38			
Exploration	**Mixed**	14.28^{a}	12.01^{b}	8.94^{c}	8.36^{c}	0.47	**<0.001**	**<0.001**	0.607
	Boar	12.48	10.57	8.01	7.00	0.65			
	Gilt	16.09	13.45	9.87	9.72	0.65			
Inactive	**Mixed**	65.43^{a}	68.52^{b}	73.04^{c}	73.41^{c}	0.76	**<0.001**	**0.002**	0.148
	Boar	67.45	70.35	72.90	74.29	1.06			
	Gilt	63.41	66.68	73.19	72.53	1.06			
Other	**Mixed**	10.75	10.51	10.58	10.26	0.34	0.769	0.536	0.181
	Boar	10.81	10.05	10.86	10.80	0.47			
	Gilt	10.69	10.97	10.31	9.72	0.47			

[1] Different superscript letters indicating significantly different means ($p < 0.05$).
[2] Data is from weekly scan sampling carried out throughout finishing and values shown are the mean percentages of time spent performing each behaviour (%).

Table 3.17. The change in activity time budgets of grower-finisher pigs (boars and gilts) over a three-phase dietary regime from ~36-100 kg [1,2]

Behaviour	Dietary Phase				
	One	Two	Three	SE	*P*-value
Drinking	1.18^{a}	1.96^{b}	1.37^{a}	0.14	**<0.001**
Mounting	0.11	0.15	0.16	0.04	0.565
Fighting/Aggression	1.20^{a}	1.10^{a}	0.69^{b}	0.12	**0.005**
Oral Manipulation	6.24^{a}	6.33^{a}	4.93^{b}	0.27	**<0.001**
Exploration	10.18^{a}	12.35^{b}	10.16^{a}	0.46	**<0.001**
Inactive	68.78^{a}	67.95^{a}	73.57^{b}	0.75	**<0.001**
Other	12.31^{a}	10.16^{b}	9.11^{c}	0.33	**<0.001**

[1] Different superscript letters indicating significantly different means ($p < 0.05$).
[2] Values shown are percentages of the total time (120 minutes).

3.4. Lesion scores

Phase One (day 0-21)

In Phase One three lysine*sex interactions were found; for the total number of lesions ($p = 0.005$; Table 3.18), the number of lesions located in the middle of the pig ($p < 0.001$) and the number of mild severity lesions ($p = 0.003$). A decrease in the number of mild lesions and the total number of lesions was seen for boars on the highest lysine treatment (1.28 SID Lys), when compared to the Low and Med. Low treatments (Mild, $p = 0.003$ and $p = 0.011$; Total, $p = 0.005$ and $p = 0.006$). But gilts on the Low and High lysine treatments had a similar number of lesions in total ($p = 0.429$) and of mild severity ($p = 0.526$). There was no effect of dietary lysine on the number of lesions on the middle region of boars ($p > 0.05$) but gilts on the two intermediate diets (Med. Low and Med. High, 0.90 and 1.09 SID Lys) had significantly more middle lesions than gilts on the Low ($p < 0.001$ and $p = 0.007$) and High ($p < 0.001$ and $p = 0.012$) lysine treatments did. Dietary lysine also affected the number of lesions on the front ($p < 0.001$) and rear of the pig ($p < 0.001$; Table 3.18), but counts were not different between sexes ($p = 0.218$ for the front and $p = 0.136$ for the rear). Those on the High lysine treatment had significantly fewer lesions on the front of their body than those on the Low, Med. Low and Med. High treatments did ($p = 0.010$, $p < 0.001$ and $p = 0.003$). But the differing dietary lysine levels used in the lower three treatments had no effect on the number of front lesions (all $p > 0.05$). Rear lesions were significantly higher for pigs on the Med. High treatment ($p = 0.038$, $p = 0.047$ and $p < 0.001$ for comparisons with 0.71, 1.09 and 1.28 SID Lys respectively) but differences between the other three treatments were not seen ($p > 0.05$). No interaction was found between lysine and sex for moderate/severe lesions ($p = 0.335$) but when considered separately both lysine and sex affected the number of moderate/severe lesions ($p = 0.022$ and $p < 0.001$; Table 3.18). The average number of lesions scored moderate/severe was highest for pigs on the Med. Low treatment and lowest for pigs on the High lysine treatment (0.19 ± 0.02 vs 0.12 ± 0.02). While these two means were significantly different ($p = 0.024$) they each did not differ significantly from the number of moderate/severe lesions pigs had on the Low and Med. High treatments (comparisons all $p > 0.05$). Gilts on average had fewer moderate/severe lesions than boars ($p < 0.001$).

Table 3.18. Effect of dietary SID lysine concentration on the number of lesions in total, in three different locations and of differing severity on the body of boars and gilts throughout the first three weeks of growing-finishing (35-53 kg) [1 2 3]

No. of lesions	Sex	SID Lysine concentration (%)					*P*-value		
		0.71	0.90	1.09	1.28	SE	Lysine	Sex	Lysine*Sex
Total (whole body)	**Mixed**	3.18^{a}	3.61^{b}	3.29^{ab}	2.74^{c}	0.10	**<0.001**	0.532	**0.005**
	Boar	3.42^{a}	3.41^{a}	3.27^{ac}	2.82^{c}	0.14			
	Gilt	2.95^{bc}	3.83^{d}	3.32^{ab}	2.66^{c}	0.14			
Front	**Mixed**	2.29^{a}	2.45^{a}	2.32^{a}	1.96^{b}	0.08	**<0.001**	0.218	0.513
	Boar	2.42	2.41	2.37	2.01	0.12			
	Gilt	2.17	2.49	2.28	1.91	0.12			
Middle	**Mixed**	0.45^{ac}	0.60^{b}	0.51^{ab}	0.38^{c}	0.04	**<0.001**	0.075	**<0.001**
	Boar	0.52^{b}	0.51^{b}	0.44^{b}	0.37^{b}	0.05			
	Gilt	0.39^{a}	0.72^{c}	0.60^{c}	0.40^{ab}	0.06			
Rear	**Mixed**	0.33^{a}	0.46^{b}	0.34^{a}	0.27^{a}	0.04	**<0.001**	0.136	0.117
	Boar	0.36	0.42	0.37	0.32	0.05			
	Gilt	0.31	0.50	0.31	0.23	0.05			
Mild severity	**Mixed**	3.01^{a}	3.38^{b}	3.07^{ab}	2.57^{c}	0.10	**<0.001**	0.686	**0.003**
	Boar	3.22^{ab}	3.15^{ab}	2.97^{ac}	2.61^{c}	0.13			
	Gilt	2.81^{ac}	3.63^{b}	3.18^{ab}	2.53^{c}	0.14			
Moderate/Severe severity	**Mixed**	0.13^{ab}	0.19^{b}	0.16^{ab}	0.12^{a}	0.02	**0.022**	**<0.001**	0.335
	Boar	0.15	0.20	0.21	0.14	0.03			
	Gilt	0.12	0.17	0.12	0.09	0.03			

[1] Different superscipt letters indicating significantly different means ($p < 0.05$).
[2] The three different locations; the front, middle and back third of the pigs body are defined in Figure 2.1.
[3] Data is from d1 and weekly lesion scoring in phase one.

Phase Two (day 22-49)

In Phase Two there were no longer interactive effects of lysine*sex on the total number of lesions ($p = 0.260$), lesions in the middle of the pig ($p = 0.784$) and mild lesions ($p = 0.279$; Table 3.19). But lysine still affected three measures ($p = 0.005$, total lesions; $p < 0.001$, middle lesions and $p = 0.028$, mild lesions) as well as on the number of moderate/severe lesions ($p = 0.006$) but not on the number of lesions on the front ($p = 0.145$) or the rear ($p = 0.465$). Although there were no significant differences in the number of mild lesions across all treatments ($p > 0.05$), there was a trend for pigs on the Med. High treatment (0.90 SID Lys) to have more mild lesions than those on the Low and High treatments (0.62 and 1.09 SID Lys, $p = 0.071$ and $p = 0.095$). The number of middle lesions was also higher on the Med. High lysine treatment when compared to the lower two lysine treatments ($p = 0.026$ and $p = 0.001$) but was similar to that of pigs on the High lysine treatment ($p = 0.155$). For the total lesions pigs on the Med. High treatment again had significantly more lesions, but when compared to those on the Med. Low and High treatments ($p = 0.010$ and $p = 0.026$) with similar numbers of lesions to pigs on the Low lysine treatment ($p = 0.059$).

There was also an effect of lysine on the number of moderate/severe lesions (p = 0.006), shown by the lower occurrence of these for pigs on the Med. Low treatment when compared to the Low and Med. High treatments (p = 0.041 and p = 0.007). In terms of sex differences, boars had more mild lesions (p = 0.041), more lesions located on their front (p <0.001) and a higher number of total lesions than gilts did (p = 0.021; Table 3.19).

Table 3.19. Effect of dietary SID lysine concentration on the number of lesions in total, in three different locations and of differing severity on the body of boars and gilts from week four of finishing to the end of week seven (53-83 kg) [1 2 3]

No. of lesions	Sex	SID Lysine concentration (%)					*P*-value		
		0.62	**0.76**	**0.90**	**1.09**	**SE**	**Lysine**	**Sex**	**Lysine*Sex**
Total (whole body)	**Mixed**	2.69^{ab}	2.62^{a}	3.04^{b}	2.65^{a}	0.10	**0.005**	**0.021**	0.260
	Boar	2.66	2.68	3.26	2.85	0.15			
	Gilt	2.72	2.55	2.84	2.46	0.13			
Front	**Mixed**	1.48	1.42	1.63	1.45	0.07	0.145	**<0.001**	0.335
	Boar	1.52	1.55	1.84	1.67	0.11			
	Gilt	1.44	1.30	1.45	1.27	0.10			
Middle	**Mixed**	0.60^{a}	0.53^{a}	0.79^{b}	0.64^{ab}	0.05	**<0.001**	0.562	0.784
	Boar	0.59	0.51	0.75	0.66	0.07			
	Gilt	0.61	0.55	0.84	0.62	0.07			
Rear	**Mixed**	0.56	0.60	0.57	0.50	0.05	0.465	0.339	0.230
	Boar	0.51	0.55	0.63	0.47	0.07			
	Gilt	0.62	0.65	0.52	0.54	0.06			
Mild severity	**Mixed**	2.43^{a}	2.45^{a}	2.75^{a}	2.44^{a}	0.09	**0.028**	**0.041**	0.279
	Boar	2.39	2.52	2.92	2.63	0.14			
	Gilt	2.47	2.39	2.60	2.26	0.13			
Moderate/Severe severity	**Mixed**	0.24^{a}	0.14^{b}	0.27^{a}	0.18^{ab}	0.03	**0.006**	0.332	0.729
	Boar	0.26	0.14	0.32	0.19	0.05			
	Gilt	0.23	0.15	0.23	0.17	0.04			

[1] Different superscipt letters indicating significantly different means (p < 0.05).

[2] The three different locations; the front, middle and back third of the pigs body are defined in Figure 2.1.

[3] Data is from weekly lesion scoring in phase two.

Phase Three to endpoint (day 50-64)

In Phase Three there were no lysine*sex interactions or effects of sex. Nevertheless, differences between lysine treatments were seen for the total number of lesions (p <0.001), the number of mild lesions (p <0.001) and the number of lesions at each location (Front, p <0.001; Middle, p = 0.027; Rear, p = 0.026; Table 3.20). When compared to pigs on the other three treatments (Low, Med. Low and Med. High/0.52, 0.67 and 0.81 SID Lys), pigs on the highest lysine treatment (1.00 SID Lys) had significantly fewer lesions in total (p <0.001, p <0.001 and p = 0.002 respectively) on the front of the body (p = 0.007, p <0.001 and p = 0.028) and of mild severity (p <0.001, p <0.001 and p = 0.007). The average numbers of total lesions, mild lesions and lesions on the front were not significantly different between the Low, Med. Low and Med. High lysine treatments (p >0.05). Pigs on the High lysine treatment also had the fewest middle and rear lesions (see Table 3.20) but only significantly fewer when compared to pigs on the Med. Low treatment who had the highest number of middle and rear lesions (p = 0.023 and p = 0.019). For middle and rear lesions, both these means (Med. Low and High) were not significantly different from the means of the remaining two lysine diets (Low and Med. High, p >0.05).

Table 3.20. Effect of dietary SID lysine concentration on the number of lesions in total, in three different locations and of differing severity on the body of boars and gilts from week eight of finishing to the end of week nine (83-100 kg) [1 2 3]

No. of lesions	Sex	SID Lysine concentration (%)					*P*-value		
		0.52	0.67	0.81	1.00	SE	Lysine	Sex	Lysine*Sex
Total (whole body)	Mixed	2.30^{a}	2.53^{a}	2.13^{a}	1.57^{b}	0.13	**<0.001**	0.621	0.338
	Boar	2.34	2.54	1.93	1.60	0.19			
	Gilt	2.27	2.51	2.35	1.53	0.18			
Front	Mixed	1.33^{a}	1.55^{a}	1.27^{a}	0.92^{b}	0.10	**<0.001**	0.371	0.265
	Boar	1.35	1.58	1.10	0.91	0.15			
	Gilt	1.31	1.52	1.47	0.94	0.14			
Middle	Mixed	0.42^{ab}	0.46^{a}	0.32^{ab}	0.25^{b}	0.06	**0.027**	0.800	0.987
	Boar	0.43	0.46	0.33	0.27	0.08			
	Gilt	0.42	0.47	0.32	0.24	0.07			
Rear	Mixed	0.41^{ab}	0.43^{a}	0.40^{ab}	0.23^{b}	0.07	**0.026**	0.788	0.806
	Boar	0.42	0.42	0.38	0.26	0.09			
	Gilt	0.40	0.44	0.43	0.20	0.08			
Mild severity	Mixed	2.17^{a}	2.40^{a}	2.00^{a}	1.51^{b}	0.13	**<0.001**	0.856	0.347
	Boar	2.26	2.40	1.83	1.56	0.18			
	Gilt	2.08	2.40	2.19	1.47	0.17			
Moderate/Severe severity	Mixed	3.60×10^{-6}	9.48×10^{-5}	2.99×10^{-3}	2.21×10^{-6}	0.54	0.133	0.228	0.484
	Boar	5.02×10^{-6}	8.50×10^{-5}	3.83×10^{-3}	2.50×10^{-6}	0.39			
	Gilt	2.59×10^{-6}	1.06×10^{-4}	2.33×10^{-3}	1.95×10^{-6}	0.75			

[1] Different superscipt letters indicating significantly different means (p < 0.05).
[2] The three different locations; the front, middle and back third of the pigs body are defined in Figure 2.1.
[3] Data is from weekly lesion scoring in phase three.

Overall

As was the case in Phase One, when looking at the lesion scores over the whole experiment, three lysine*sex interactions were found. These interactions were for the total number of lesions (p = 0.040), the number of lesions located in the middle of the pig (p = 0.010) and the number of mild severity lesions (p = 0.029; Table 3.21). These interactions demonstrate that the effect of dietary lysine on the number, location and severity of lesions was not the same between boars and gilts throughout the finishing period. Boars on all treatments had a similar number of lesions on their middle ($p > 0.05$) but boars on the High lysine treatment had fewer mild lesions compared to those on the Low and Med. Low treatments ($p = 0.017$) and fewer lesions in total compared to boars on all other treatments ($p = 0.008$, $p = 0.011$ and $p = 0.006$ for Low, Med. Low and Med. High respectively). Gilts on the High lysine treatment also had significantly fewer lesions in total and of mild severity when compared to those on all other treatments (Low, $p = 0.005$ and $p = 0.023$ respectively and for Med. Low and Med. High $p < 0.001$ for both total and mild lesions). However, gilts on the Low lysine treatment also had fewer lesions, in total and of mild severity when compared to those on the Med. Low treatment ($p = 0.006$ and $p = 0.003$). Differences in these lesions (total and mild) between the two intermediate diets were not significant ($p = 0.884$ and $p = 0.876$) but gilts on these treatments had more lesions located on their middle than those on the Low and High lysine treatments did (Med. Low, $p = 0.005$ and $p = 0.003$; Med. High, $p = 0.001$ for both).

In addition to this, lysine also affected the number of front, rear and moderate/severe lesions ($p < 0.001$ for front and rear lesions, $p = 0.037$ for moderate/severe lesions; Table 3.21). Pigs on the high lysine treatment had significantly fewer lesions on their front and rear (Front; $p = 0.004$, $p < 0.001$ and $p < 0.001$, Rear; $p = 0.010$, $p < 0.001$ and $p = 0.044$, comparisons with Low, Med. Low and Med. High treatments). With no differences seen in the number of front or rear lesions between the Low, Med. Low and Med. High treatments ($p > 0.05$). Pigs also had fewer moderate/severe lesions when on the High lysine treatment as opposed to the Med. High lysine treatment ($p = 0.023$). But pigs on both these treatments had a similar number of moderate/severe lesions to those on the Low and Med. Low treatments did ($p > 0.05$). Over the experiment, boars on average had significantly more moderate/severe lesions ($p = 0.005$) and more lesions located on their front ($p = 0.003$; Table 3.21).

Including phase in the analyses, also allowed for differences in the lesion scores to be looked at over the three phases, with these results presented in Table 3.22. The number of lesions in total, in each location and of differing severity decreased over the three phases ($p < 0.001$ for all). The average number of lesions recorded for all these measures, except the number of front lesions, were significantly different between all three phases (highest in Phase One, lowest in Phase Three; see Table 3.22 and Figure 3.6). But the number of front lesions had only a tendency ($p < 0.1$) to decrease from Phase Two to three ($p = 0.058$).

Table 3.21. Total number, severity and location of lesions on grower-finisher pigs (boars and gilts) from approximately 36 kg to 100 kg, fed diets of differing SID lysine concentrations (%) [1 2]

No. of lesions	Sex	Lysine Treatment					*P*-value		
		Low	Med. Low	Med. High	High	SE	Lysine	Sex	Lysine*Sex
Total (whole body)	**Mixed**	2.98[a]	3.17[a]	3.10[a]	2.61[b]	0.06	**<0.001**	0.107	**0.040**
	Boar	3.10[b]	3.09[b]	3.11[b]	2.72[a]	0.09			
	Gilt	2.86[a]	3.26[b]	3.08[ab]	2.49[c]	0.09			
Front	**Mixed**	1.86[a]	1.95[a]	1.91[a]	1.64[b]	0.05	**<0.001**	**0.003**	0.658
	Boar	1.94	1.98	1.96	1.74	0.07			
	Gilt	1.77	1.92	1.86	1.55	0.07			
Middle	**Mixed**	0.58[ab]	0.64[a]	0.67[a]	0.53[b]	0.03	**0.001**	0.098	**0.010**
	Boar	0.62[a]	0.57[a]	0.61[a]	0.53[a]	0.04			
	Gilt	0.54[a]	0.72[b]	0.74[b]	0.53[a]	0.04			
Rear	**Mixed**	0.50[a]	0.54[a]	0.48[a]	0.39[b]	0.03	**<0.001**	0.763	0.166
	Boar	0.49	0.50	0.51	0.41	0.04			
	Gilt	0.50	0.59	0.45	0.37	0.04			
Mild severity	**Mixed**	2.75[a]	2.95[a]	2.85[a]	2.43[b]	0.06	**<0.001**	0.393	**0.029**
	Boar	2.86[ab]	2.86[ab]	2.82[abc]	2.52[c]	0.09			
	Gilt	2.64[a]	3.05[b]	2.88[ab]	2.33[c]	0.09			
Moderate/Severe severity	**Mixed**	0.21[ab]	0.21[ab]	0.23[a]	0.17[b]	0.02	**0.037**	**0.005**	0.461
	Boar	0.22	0.22	0.28	0.19	0.03			
	Gilt	0.20	0.20	0.19	0.15	0.02			

[1] Different superscript letters indicating significantly different means ($p < 0.05$).
[2] Data is from weekly lesion scoring carried out over 10 weeks and values shown are mean numbers of lesions per pig.

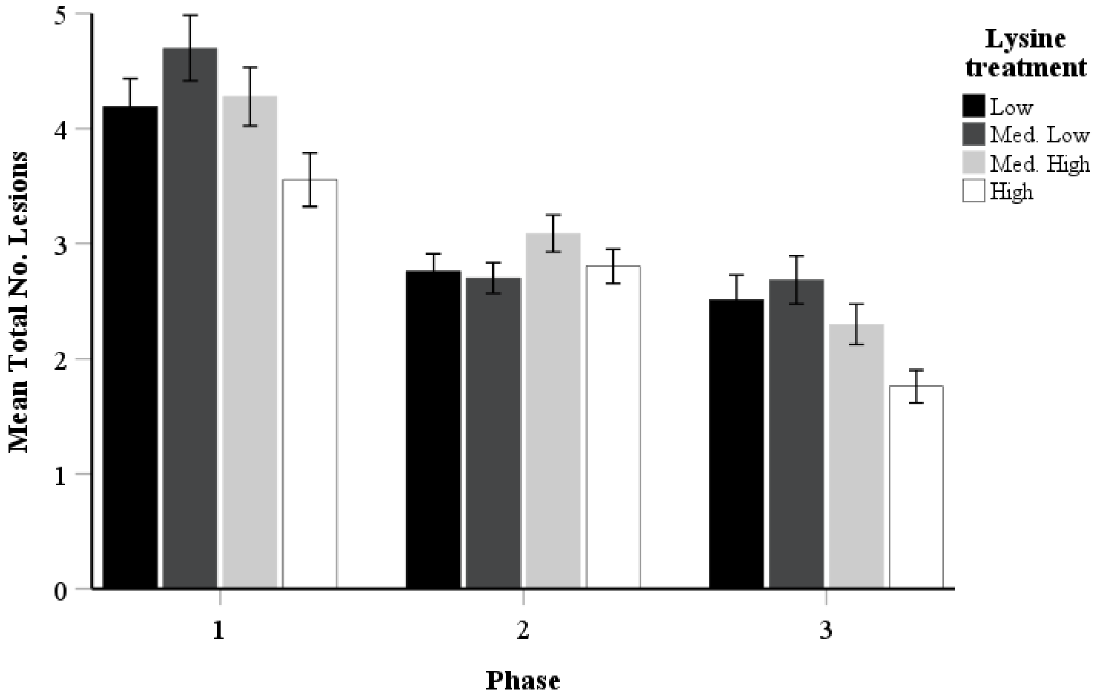

Figure 3.6. The average number of lesions on grower-finisher pigs during each phase of a three-phase dietary regime., when fed diets of differing dietary lysine concentrations.

Table 3.22. The average number of lesions in total, at different locations and of differing severity over the three different phases of a three-phase dietary regime over the growing-finishing period (from 36-100 kg) [1 2]

No. of lesions	**Dietary phase**				
	One	**Two**	**Three**	**SE**	***P*-value**
Total	4.10[a]	2.78[b]	2.26[c]	0.06	**<0.001**
Front	2.80[a]	1.55[b]	1.42[b]	0.05	**<0.001**
Middle	0.79[a]	0.64[b]	0.44[c]	0.03	**<0.001**
Rear	0.48[a]	0.56[b]	0.39[c]	0.03	**<0.001**
Mild	3.77[a]	2.55[b]	2.13[c]	0.06	**<0.001**
Moderate/Severe	0.31[a]	0.22[b]	0.12[c]	0.02	**<0.001**

[1] Different superscript letters indicating significantly different means ($p < 0.05$).
[2] Data is from weekly lesion scoring carried out over 10 weeks and values shown are mean numbers of lesions per pig.

Chapter 4. Discussion

4.1. Growth performance and differences between sex

Increasing dietary lysine in finisher pig diets, increased the pigs ADG, end weight and improved their feed efficiency (FCR), in line with previous research (King et al., 2000; O'Connell et al., 2006; Rikard-Bell et al., 2012; Aymerich et al., 2021). These improvements relate to lysine's primary function as an amino acid in protein synthesis and its short supply in the cereals making up swine diets (i.e. it's the first limiting amino acid). By increasing the lysine available to the pigs for protein synthesis the corresponding increase in synthesis rate can increase deposition of lean tissue (muscle), explaining the raised rate of gains and thus end weights. Feed efficiency is consequently improved as a result of the improved growth rates. It may also be linked to lean tissue deposition requiring comparatively less energy (and so less feed) for the same weight gain by fat deposition, which has been shown to increase when pigs have insufficient amino acids/protein for muscle growth (Pomar et al., 2014). This could have contributed to the higher backfat of pigs on the Low and Med. Low lysine treatments. Feed efficiency also worsened over the phases of the finishing period as is to be expected with age due to the natural increase in fat deposition and the higher maintenance costs at heavier weights (Millet et al., 2018a). This means a greater amount of feed must be consumed before energy and amino acids can be directed towards growth.

When lysine concentrations reach levels above the pigs' requirements, feed efficiency and performance has also been seen to decrease (Van Lunen and Cole, 1996; Moore et al., 2012) because of the need for excess lysine to be deaminated and removed (expending energy which could otherwise be used for growth). In this study, reductions in feed efficiency at the highest lysine level weren't observed for both sexes. However, in Phase One and Phase Three to endpoint, pigs had similar feed efficiencies on the Med. High and High lysine treatments, and additionally in Phase Three to slaughter and over the whole experiment for gilts. In Phase One this plateau in feed efficiency at the highest lysine level coincided with a plateau in ADG for both sexes, which could have been a result of the pigs on this treatment having a lower ADFI. Supporting Aymerich et al. (2020) who observed a slight but nonsignificant decrease in ADFI ($p = 0.052$, $p = 0.089$ for boars and gilts respectively) with increasing dietary lysine. Alternatively, as this diet contained the highest concentration of lysine used throughout the experiment (1.28 SID lysine) it could still be assumed that the lysine requirements were exceeded, and growth was impacted due to the energy expenditure on deamination, hence the lack of further improvements to ADG and FCR.

ADFI was increased on the higher lysine treatments in Phases Two and Three. Both Hyun et al. (1997) and Soto et al. (2019) also saw feed intake increases in response to increasing lysine, but others found no effect (Witte et al., 2000; Jin et al., 2010; Aymerich et al., 2020). In this study the observed increase in ADFI for pigs on the higher lysine treatments could instead be a result of their considerably heavier weights from the end of Phase One onwards, due to ADFI being a function of body weight and so gut capacity (Fornós et al., 2022). Having said that, despite the heavier weights of pigs on the High lysine treatment they did not have higher ADFIs compared to those on the Med. High treatment. It has been recognised that when fed *ad libitum* pigs are able to adjust their feed intake in response to differing diet aspects/compositions (Li and Patience, 2017) and can eat to reach their required levels of energy and other nutrients (Nyachoti et al., 2004; Schiavon et al., 2018). This theory generally concerns pigs raising their feed intake on a diet insufficient in these aspects but could also be used to explain why pigs on the higher two treatments maintained their voluntary feed intake at similar levels. Diets were isoenergetic, so pigs could have been eating to their lysine requirements and on the higher two treatments not consuming feed in excess of what they required. This is supported to an extent by studies which found pigs are able to self-select their diets. For example, Kirchgessner et al. (1999) found that piglets more often selected a diet high in lysine when given a choice between this and one containing low levels of lysine. Nevertheless, further increases in feed intake could instead have been limited by environmental factors (social or physical), rather than the meeting of requirements, as they can influence feeder access and other feeding related behaviours (Nyachoti et al., 2004).

As expected, the boars exhibited a better growth performance than gilts throughout the experiment and responded differently to increasing dietary lysine. In agreement with previous research, they had higher ADGs and were more feed efficient (Moore et al., 2012; Rikard-Bell et al., 2012; Aymerich et al., 2020; Aymerich et al., 2021) in all phases except Phase Three to endpoint where boars and gilts showed similar feed efficiencies. They also had similar feed intakes (ADFI) throughout the whole finishing period, consistent with the findings of O'Connell et al. (2006), Moore et al. (2012), Rikard-Bell et al. (2012) and Aymerich et al. (2020). The faster growth of boars is not unexpected as they have a higher protein deposition potential (Aymerich et al., 2020) and so are able to deposit more lean tissue than gilts, contributing to their larger daily weight gains and end weight after each phase. However, Aymerich et al. (2021) suggested that the NRC (2012) only estimated the boars ADG to be 2.8% higher than the gilts during growth from 75 to 100 kg. Looking at the performance of pigs in Phase Three to endpoint (~83-100 kg) the ADG of boars on the Med. Low lysine treatment (which was at the lower end of NRC (2012) requirements) was 11% higher than the mean ADG of the gilts. This is a much more substantial difference than the 2.8% and an even greater difference of 19% was observed when comparing the ADG of boars and gilts on the High lysine treatment. This would already suggest that boars and gilts growth performance differ more significantly than recommendations account for, with Aymerich et al. (2020) and O'Connell et al. (2006) also finding higher sex differences in ADG (9.2% and 17.6% higher for boars respectively for growth from 75-100 kg and 70-105 kg).

These sex differences may be more apparent both at higher lysine concentrations and towards the latter end of finishing. Throughout the finishing period and the different dietary phases, boars and gilts on the lower two lysine treatments showed no difference in ADG. Aymerich et al. (2021) also reported little difference in the performance of boars and gilts when fed diets with low concentrations of SID dietary lysine: NE. It is probable that these diets were limiting the growth of boars and contained insufficient lysine for their full growth potentials to be expressed. In terms of differences over time, the improved performance of boars has previously been predicted to start being observed around 40-70 kg (Aymerich et al., 2020). The diverging nature of their performance in this study clearly illustrates this. When comparing the ADGs of boars and gilts on the Med. High treatment, the mean ADG for the boars is around 3% higher than the gilts in Phase One (~35-53 kg), 5% higher in Phase Two (~53-83 kg) and 12% higher in Phase Three to endpoint (~83-100 kg). In parallel to the changing performance differences, Dunshea et al. (2013) modelled the differing lysine requirements of boars and gilts throughout finishing, showing them to similarly diverge and become increasingly different towards the end.

In dose-response studies such as this, the estimation of nutrient requirements for optimal growth are based on the concept that performance will plateau once the requirement has been reached, with diminishing returns in productivity improvement before it is met (Hauschild et al., 2010). In Phase One there were no lysine*sex interactions for ADG and FCR, and the plateau in performance seen for pigs on the highest lysine level for both these measures, suggests lysine requirements during this stage were met and the sex specific lysine requirements for both sexes were likely not too different. In Phase Two however, both ADG and FCR did not plateau and continued to improve for pigs on the High lysine treatment, albeit to a slightly smaller degree at the highest levels. The trend for only boars to show an improved ADG at the highest level implies that the gilts lysine requirements could have been met, whilst the boars may have been just outside of the range of concentrations used. In Phase Three (to slaughter) the differing responses of boars and gilts became more pronounced, boars continuing to respond to the highest lysine concentration whereas the performance of gilts (ADG and FCR) was observed to plateau after the Med. High level. This could have been a result of gilts not being able to make use of all the dietary lysine available to them in the High diet, with some requiring deamination and excretion. While boars on the higher two treatments had leaner carcasses with reduced backfat (P2), differences were not observed between these two treatments or between the P2 values of gilts on all four treatments, despite improvements to their performance still being observed. Meaning it was not always clear whether ADG increases were predominantly driven by fat or lean tissue deposition. A clearer understanding of these changes could have been achieved by measuring the pigs body composition or levels of the blood metabolites urea (blood urea nitrogen, BUN) and creatinine. Urea arises from the catabolism of excess amino acids and so lower blood urea nitrogen levels indicate better nitrogen efficiency and mean less nitrogen will be excreted to the environment (Kohn et al., 2005), whereas creatinine is a product of muscle turnover and correlates with total muscle mass (Montoro et al., 2022). Measuring these could have helped to enhance our understanding of the performance differences and should be considered in future studies.

4.2. Estimating lysine requirements

While it is clear that the growth performance in response to increasing lysine does differ between sex, modelling these responses in order to estimate lysine requirements proved problematic and accurate estimates for each phase couldn't always be obtained. To accurately estimate nutrient requirements there should be differing diets formulated both below and above the requirements so the performance and any implications at such concentrations can be assessed (Main et al., 2008). Unfortunately, with the range of lysine levels used in the different treatments and diets of this experiment, the plateau past which increasing lysine has no effect on performance was not reached for boars towards the end of the finishing period. This meant that the quadratic and quadratic-plateau models often predicted values outside of the range of concentrations used. These extreme predictions are a drawback of quadratic models as highlighted by Sileshi (2022) and extrapolated estimates should be considered unreliable. On the other hand, linear plateau models notably tend to underestimate the nutrient/lysine requirements (Robbins et al., 2006; Aymerich et al., 2021; Song et al., 2022). They are also more representative of an individual's response to increasing concentrations of a nutrient rather than a group of individuals, which actually show a more curvilinear response (Millet et al., 2018b). Quadratic plateau models have therefore been suggested as the most appropriate as they are able to capture both the curvilinear response and the plateau in performance (Hauschild et al., 2010). However, as mentioned above this wasn't always the case in this experiment, as estimated requirements were often overestimated and had large 95% confidence intervals. These modelling results would suggest that four lysine levels weren't sufficient to accurately estimate the lysine requirements of boars and gilts over the finishing period and boars would likely have responded to higher levels of lysine than those used. As reflected in the out of range model estimates. Adding another two lysine levels above the High treatment (particularly at the end of finishing) would have improved the ability to model growth performance and estimate requirements. Additionally, where estimates were close to the maximum concentrations used, these additional lysine levels could have confirmed whether the maximum response had indeed been reached (i.e. if ADG and FCR showed no further improvements at these higher concentrations).

In spite of these issues, some conclusions can still be drawn from the performance and modelling results about the differing lysine requirements between sex. Particularly, that the lysine requirements for boars are higher than diets are currently being formulated to. At the start of the experiment where performance between sexes did not differ as significantly, the estimated lysine concentration to maximise feed efficiency for both sexes as a mixed sex group from ~36-53 kg was 1.10 SID lysine. Still around 12% higher than the NRC (2012) estimate for pigs from 25-50 kg (0.98 SID lysine; Table 1.1). In Phase Two (~53-83 kg) the linear plateau estimates for maximum ADG were 0.97 SID lysine for the boars and 0.92 SID lysine for the gilts. Both of which again were higher than the sex specific requirements proposed by the NRC (2012) from 50-75 kg of 0.88 and 0.87 SID lysine for boars and gilts. However, for optimal feed efficiency the linear plateau estimates were comparable to these (0.86 and 0.84 SID lysine for boars and gilts) but given that FCR significantly improved as dietary lysine increased up to the highest lysine treatment (1.09 SID lysine) these estimates were likely an underestimate and the better fitting quadratic model actually produced much higher estimated requirements of 1.09 and 1.03 SID lysine respectively. Both of which are substantially above the NRC recommendations. At the end of finishing where performance differences between sex would suggest requirements differ the most, is indeed where some of the modelled estimates are most noticeably different. From 83-110 kg the linear plateau model estimated boars lysine requirements at 0.94 and 0.77 SID lysine to maximise ADG and feed efficiency respectively. The ADG estimate is above that given by the NRC (2012), of 0.82 SID lysine, for entire males from 75-100 kg (notably a lower weight range, so the NRC estimate would be expected to be slightly higher). Whereas for FCR the boar's requirement appears below the recommended level. Although, the better fitting quadratic plateau model actually estimated boars minimal FCR at 1.06 SID lysine, which was slightly out of range but nevertheless indicates the true requirements were higher than the 0.77 SID lysine estimate. For gilts estimated requirements during this phase, were 0.76 SID lysine for optimal ADG (linear plateau) or 0.76/0.79 SID lysine for optimal FCR (linear plateau/quadratic plateau). Considerably lower than the boars estimated requirements, yet similar to the NRC (2012) recommendation of 0.77 SID lysine (from 75-100 kg). However, when modelling the performance from Phase Three to endpoint (~83-100 kg) the estimates for gilts were higher (e.g. 0.92 SID lysine, linear plateau), indicating they could have increased since 2012 (NRC), as boars have.

Estimated requirements are somewhat comparable to those calculated in other studies. Converting the estimated requirements to SID lysine in g/kg allowed theses comparisons to be made, with estimates from other studies found in Table 1.2 (Chapter 1). When looking at the linear plateau model estimates from Phase One (~36-53 kg), the estimated lysine concentrations for mixed sex and boars optimal FCR (11.04 and 11.30 g/kg respectively) were slightly lower than that estimated by O'Connell et al. (2005) in their third experiment for boars and gilts group housed from 40-62 kg (12.7 g/kg). They were also below the 12 g/kg estimate from Giles et al. (1987) for boars to maximise ADG from 20-50 kg. But if the higher quadratic estimates are instead compared to these two studies, then estimated lysine requirements in Phase One were either similar or higher (e.g. 12.82 g/kg and 13.42 g/kg for mixed sex optimal ADG and FCR respectively) but exceeding actual concentrations used. In Phase Two (~53-83 kg) where the quadratic model was best fitting for FCR, the boars estimated lysine requirement of 10.88 g/kg was very similar to the 10.9 g/kg estimated by O'Connell et al. (2006) to maximise both sexes FCR (from 60-90 kg). However, O'Connell et al. (2006) did not find a difference in requirements between sex, in contrast to this study where the gilts lysine requirement (for optimal FCR in Phase Two) was estimated at a lower concentration of 10.32 g/kg. For ADG, the lysine requirement estimates for boars, gilts and mixed sex obtained by linear plateau models (9.65, 9.21 and 9.45 g/kg) were all below the estimate for both sexes by O'Connell et al. (2006) for maximal ADG (10.8 g/kg). O'Connell et al. (2006) also performed two studies taking pigs to heavier weights (80-100 kg) either housed in groups or in pairs. For the latter a difference in requirements between boars and gilts was seen to maximise ADG and FCR (Boars, 11.8 and 11.9 g/kg respectively; Gilts, 9.9 and 10.0 g/kg respectively). These values were again higher than those estimated in this study for Phase Three to endpoint (83-100 kg, linear plateau estimates, Boars, 9.45 and 9.04 g/kg for ADG and FCR respectively; Gilts, 9.20 g/kg for ADG). This was likely due to O'Connell et al. (2006) using higher lysine concentrations (up to 13.5 g/kg, as opposed to 10 g/kg for Phase Three in this study) and the lysine requirements in this study being underestimated as discussed above.

Aymerich et al. (2021), using the results from a meta-analysis of relevant studies, estimated that from 70-100 kg ADG and G:F (gain to feed ratio) were maximised at concentrations of 1.06 and 1.11 SID lysine for boars and, 0.92 and 0.95 SID lysine for gilts. These estimates were from quadratic models which they found to be better fitting than linear plateau and quadratic plateau models. In Phase Three to endpoint (~83-100 kg) only the gilts FCR estimates from the quadratic models were within range, at 0.93 and 0.94 SID lysine, but as seen are very similar to the 0.95 SID lysine estimate given by Aymerich et al. (2021). Likewise, the linear plateau models in this study estimated similar values to Aymerich et al. (2021) of 0.95 and 0.92 SID lysine for the optimal ADG of boars and gilts from 83-100 kg. Although for boars it is reasonable to assume this was an underestimate given the issues aforementioned. Nevertheless, what is clear from both this study and the meta-analysis by Aymerich et al. (2021) is that lysine requirements between boars and gilts (during the finishing period) do differ, supporting the findings from a number of other studies (Batterham et al., 1985; Giles et al., 1987; Exp. 2, O'Connell et al., 2006; Moore et al., 2012; Rikard-Bell et al., 2012 and Aymerich et al., 2020). To further highlight these differences, Aymerich et al. (2021) proposed the lysine requirements of boars to be 115% that of gilts, but looking at the different requirements estimated in Phase Three to slaughter (~83-110 kg) the boars requirements in this study could have been as much as 124% that of the gilts. With the large differences in ADG during this time explaining these requirement differences. Even where requirements couldn't be compared between sexes, the fact that the gilts estimates were almost always within the range of lysine concentrations used and the boars weren't, suggest they differ. Therefore, these results, while not able to give accurate requirements for boars and gilts, give adequate confirmation that requirements for dietary lysine do differ between boars and gilts during the growing-finishing stage of production and regardless of this are higher for high performing pigs than current recommendations advise. These different requirements could be a result of genetic improvements to maximum protein deposition (Aymerich et al., 2020), advancements in nutrition improving the growth performance of pigs (Pomar et al., 2021) or the heavier weights of pigs altering nutritional requirements (Wu et al., 2017).

4.3. Slaughter measures and costs

Improvements to growth performance as a result of increasing dietary lysine or sex, subsequently improved some of the production and carcass quality measures recorded at slaughter. The heavier end weights of boars and pigs on the higher lysine treatments did not increase carcass fatness with pigs on the higher two treatments having leaner carcasses (higher LM%) and reduced backfat (P2). With the opposite observed for those on the lowest lysine diet (lower LM% and higher P2). This supports the results of a study by Martínez-Ramírez et al. (2008) who were looking at the effect of amino acid restriction on boar's body composition and protein deposition to determine if compensatory growth after lifting the restriction occurs. They found that restricting amino acids in the diet by 15 and 30% below requirements decreased protein deposition (measured through nitrogen balances and body composition analyses) and increased lipid deposition, when compared to the control (formulated to 115% of requirements). Even though diets in the current study weren't intentionally formulated to restrict amino acid/lysine levels as considerably as this, if lysine requirements are higher than recommendations, as implied by the results, then the lower two treatment diets could have been comparably restricting amino acids. Some studies also found boars had leaner carcasses (compared to gilts) as a result of their improved ability to deposit lean tissue (Quiniou et al., 2010; Aymerich et al., 2020), but in this case boars had a similar lean meat percentage (LM%) to gilts at slaughter. They did however have a significantly lower carcass fatness (backfat thickness, P2) compared to gilts on the highest lysine treatment. It is also worth noting the lysine*sex interaction for LM% was on the boundary of significance ($p = 0.050$; Table 3.6, Chapter 3) and the increase in carcass leanness (LM%) with increasing dietary lysine was only seen for the boars. Aymerich et al. (2020) reported similar results and concluded that gilts aren't able to increase deposition of lean tissue to the same extent as boars when dietary lysine is increased. Similarly, gilts backfat (P2) did not differ between treatments whereas increasing lysine reduced the backfat of boars on the higher two lysine treatments. In contrast to these effects, pigs on the highest lysine treatment (boars and gilts) had the lowest killing out percentage (KO%) and boars had lower KO% than gilts. For boars this could have been due to the removal of their heavier weight reproductive organs (Aymerich et al., 2020) and for pigs on the high lysine treatment it could be linked to their higher weights and ADGs prior to slaughter increasing the weight of the gut and viscera, which is not included in the carcass yield (Gispert et al., 2010).

Increasing the concentration of dietary lysine above that currently recommended in finisher pig diets may increase the profitability of production by increasing end weight and reducing the time it takes for them to reach slaughter weight. The higher ADGs observed with increasing lysine resulted in heavier end weights and thus carcass values, despite pigs being sent to slaughter on a weight basis. Pigs on the lower two lysine treatments went to the abattoir on average 1 week to ten days later than those on the highest lysine treatments did and still at a lighter weight (almost 10 kg lighter on the Low treatment). So, in addition to the reduced carcass values these pigs attained, the extra time they had to spend in the finisher accommodation would have incurred further costs to diminish the margin over feed. These housing costs weren't accounted for in this study but regardless of this and the higher feed costs of the higher lysine diets, increasing dietary lysine still increased the margin over feed profit and reduced the cost/kg gain. This undoubtably can be attributed to the pigs improvements in performance (ADG and FCR) and heavier end weights.

Having said that, feeding finisher pigs at the highest lysine levels used in this experiment would likely be no more cost effective than feeding them the Med. High lysine diets due to the similar cost/kg gain and margin over feed values. The considerably higher feed costs and lesser response of gilts to increasing dietary lysine meant that gilts on the highest lysine treatment had a higher cost/kg gain and a tendency for a lower margin over feed. On the other hand, despite boars on the higher two lysine treatments going to slaughter at similar times and having similar cost/kg gain and margin over feed values, from Phase Two onwards the improvements in growth rate and feed efficiency for those on the highest lysine treatment could still be beneficial for production. Feed costs did not differ between these diets and the improved feed efficiency in particular could mean that the environmental impact of their production was reduced (due to its link to nitrogen retention and excretion). Conversely, the similar feed efficiencies of gilts on these higher two treatments throughout most of the experiment (except Phase Two), would further discourage feeding them at this level, as it may mean their nitrogen output was raised on the highest lysine treatment. Even though both sexes could cost effectively be fed at the Med. High treatment level, these differences, and the clear difference in lysine requirements for boars and gilts in this study would support the move towards split sex feeding.

4.4. Split sex feeding and environmental considerations

Split sex feeding would allow boars and gilts to be fed different diets, each formulated to meet their sex specific lysine requirements to improve production efficiency and reduce nutrient wastage. However, other factors associated with this must be considered. For most commercial farms, which lack precision feeding technology, feeding growing-finishing pigs by sex would require penning them on a sex basis, which can raise some concerns. When rearing boars, aggression, fighting and sexual behaviours like mounting all cause problems for welfare (Fredriksen et al., 2008) and may be exacerbated in all male pens, although studies on this vary. In a study by Björklund and Boyle (2006) mounting was decreased for boars in mixed sex pens but remained the same throughout for boars in single sex pens. Gilts however, experienced much less mounting in female only pens and would likely have improved welfare in split sex pens, as opposed to mixed as was the case for boars. Although Rydhmer et al. (2006) found higher numbers of lesions and leg problems in all male pens, they still proposed that housing boars in mixed sex pens would not reduce their mounting and aggressive behaviours and concluded that boars will perform sexual behaviours to other pigs regardless of the recipient's sex. They therefore suggest sparing the gilts from this and the boars increased levels of aggression by means of single sex pens (Rydhmer et al., 2006), which would also avoid the issue of some gilts being pregnant at slaughter (Rydhmer et al., 2013; More et al., 2017),an ethical issue which may become more of a problem with increasing slaughter weights. These studies demonstrate the differing arguments for and against splitting pens by sex, but if one sex sees reduced welfare regardless of strategy (mixed/single sex pens), then the other benefits of splitting pens by sex must be evaluated to determine if they outweigh the potential reduction in welfare. Strategies to alleviate the boars alleged poorer welfare in single sex pens could also be investigated and implemented, for example, chemical castration, altered housing and environmental enrichment, production practices (such as sibling rearing (Fredriksen et al., 2008)) and dietary strategies. Additionally, with precision feeding technologies (where pigs can receive individually tailored diets) it is possible to feed pigs housed in the same pen differently formulated diets (Pomar et al., 2021), allowing boars and gilts to still be housed together should it be deemed better for their welfare.

In terms of the benefits of split sex feeding, as already mentioned it would allow diets to be formulated closer to each sex's nutrient requirements, reducing nutrient wastage. One of the primary concerns with oversupplying nutrients, and in particular protein and amino acids, is the excretion of nitrogen and its consequent effects on the environment such as eutrophication, acidification and ammonia emissions (Lenis, 1989; Millet et al., 2018a). Although faecal samples couldn't be analysed for nitrogen, previous studies have shown nitrogen excretion and dietary protein to be correlated (Millet et al., 2018a). Lower levels of excretion and improved utilisation of nitrogen have been achieved by lowering the crude protein in the diet and providing amino acids in crystalline form (Wang et al., 2018). Conversely, the higher protein levels (in order to increase lysine concentration) of the diets fed on the Med. High and High lysine treatments could have increased the pigs' nitrogen excretion, worsening the environmental impacts of their production. However, their improved growth and feed efficiency would alternatively suggest that protein in the diet (and thus nitrogen) was actually used more efficiently (Millet et al., 2018a; Grossi et al., 2019). In addition to this, amino acid deficiencies or imbalances can impact an individual's ability to make use of other amino acids in the diet (Millet et al., 2018a), which could have caused the undersupply of lysine on the lower two treatments to increase nitrogen excretion and reduce nitrogen efficiency. Without analysing the faecal samples from this study, the true response to increasing dietary lysine cannot be determined. Nevertheless, it can be assumed that by feeding boars and gilts separate diets, tailored to their lysine requirements, the oversupply of protein/lysine is minimized and as a consequence the excretion of nitrogen and other nutrients reduced.

Feeding gilts lower lysine diets than the boars could not only reduce their feed and production costs but also the carbon footprint of their diets. Feeding gilts at the Med. High level as opposed to the High lysine level (which may be best suited for boars), would avoid the higher cost/kg gain for gilts on the High lysine treatment whilst maintaining performance and slaughter characteristics. Furthermore, by feeding them at this level the carbon dioxide equivalents associated with the feed can be reduced by approximately 25 kg/pig over the whole growing-finishing period. Feed production is one of the main contributors to overall greenhouse gas emissions from the livestock sector, accounting for around 60-80% of the total emissions in pig production (Grossi et al., 2019). The increase in carbon dioxide equivalents with increasing dietary lysine, can largely be attributed to the use of soya bean meal and its high levels of land use change. This is due to its damaging production in South America, whereby previously forested land is being cleared for soyabean farming, raising carbon dioxide emissions and impacting biodiversity (zu Ermgassen et al., 2016). Looking into alternative protein sources like legumes, insect meal or plant derived by-products (Parrini et al., 2023) to reduce soya bean inclusion or using sustainable suppliers (who haven't implemented land use change) can help reduce the environmental impact of pig production. But changes made must be carefully evaluated to ensure the growth performance of pigs and the carcass quality is not negatively impacted. Which is why feeding pigs the lower lysine diets (where growth was impacted) would not necessarily be suitable, despite the positive impact it would have on the CO_2e of the feed. As previously mentioned, it may also influence the nitrogen excretion and so worsen the environmental impact of production elsewhere. Additionally, it is generally accepted that by improving the pigs productivity and feed efficiency (i.e. with sex specific diets that meet requirements and optimise performance), overall environmental impacts can actually be reduced, when considered for a unit of product produced (Grossi et al., 2019). Meaning split sex feeding should be considered for both the performance and welfare effects, as well as the environmental improvements it can lead to.

4.5. Feeding related behaviours

Changes in dietary lysine not only affected the ADFI of pigs but it altered their feeding related behaviours. Pigs on the high lysine treatment spent less time in the feeders per day by taking fewer trips to the feeders and eating at a faster rate. The faster consumption rate could be considered linked to the heavier weights and so larger physical capacities of the pigs on the higher lysine diets (Nielsen, 1999), especially given that there was no difference in consumption rate in Phase One when weights between treatments did not differ as significantly. However, it cannot wholly be attributed to weight because gilts were found to consume feed at a faster rate than boars (boars being heavier than gilts throughout). Additionally, pigs on the low lysine treatment may have been expected to consume more feed and at a faster rate, so they could meet lysine requirements (Schiavon et al., 2018), but this was not observed. Nevertheless, the higher number of feeder visits and total time spent in the feeders could have been a result of the pigs on the low lysine treatment having an increased motivation to consume feed. There remains ambiguity around whether diet composition and undersupplying certain nutrients can impact feed intake, although more consistent results have been seen with diets low in energy (Schiavon et al., 2018; Smit et al., 2021). With only a few studies focusing on amino acids.

One of which by Hyun et al. (1997) found that pigs on higher lysine diets consumed fewer meals (per day), spending longer in the feeder during these meals. While "meals" weren't distinguished from feeder visits in this study, the reduction in feeder visits is reasonably comparable to these results. Hyun et al. (1997) and de Haer and de Vries (1993) also used similar electronic feeders to record the pigs feed intake and associated behaviours, but on average the logged number of visits per day were higher in their studies than in this (approximately 12 per day and 15-20 per day respectively, as opposed to ~10 for pigs on the Low lysine treatment and ~6-7 per day for pigs on the High lysine treatment). Differences which could have been the result of the different pig breeds used, which has been shown to also influence feeding related behaviours (de Haer and de Vries, 1993; Averós et al., 2012; Fornós et al., 2022). For example, de Haer and de Vries (1993) found that Great Yorkshire pigs visited the feeder more frequently and so had a higher number of meals than Dutch Landrace pigs (using boars and gilts of both breeds). Similarly, the meta-analysis by Fornós et al. (2022) highlighted that Duroc and Landrace pigs have been observed in numerous studies to consume feed in larger and fewer meals, whilst Large White and Pietrain breeds are more likely to take frequent visits and small meals (Labroue et al., 1997; Baumung et al., 2006; Fernández et al., 2011). This could explain why individual pigs in this study ((Large White x Landrace) x Danish Duroc) showed high variability in the number of feeder visits, ranging from 3 to 26 per day across the study, but when considered as a group had average numbers of visits which were accordingly low for their genotype. There is also the influence of age and size with pigs generally reducing their feeder visits (and correspondingly increasing meal size) as they grow (Fornós et al., 2022).

In addition to breed and age, the number of feeder visits pigs take could be linked to the level of competition between pigs. As social animals, pigs may attempt to eat in synchrony when housed in groups but when the number of feeders or feeder space is limited this social facilitation can cause competition between pigs (Young and Lawrence, 1994). Competition which may be increased if group size is increased, and in these instances, pigs have been found to take fewer visits to the feeder (Young and Lawrence, 1994; Hyun and Ellis, 2002). Alternatively, increasing competition by other means (e.g. reducing the number of feeders/feeder spaces) also led to fewer feeder visits (Nielsen et al., 1996; Georgsson and Svendsen, 2002). While both these factors were kept the same in this study, these results might suggest that the lower number of feeder visits with increasing dietary lysine were a result of increased competition. However, this is not supported by the behavioural results of this study as pigs on the higher lysine treatments were observed fighting and exploring the least but inactive the most. Instead, it could be the pigs on the lower lysine treatment that experienced the most competition. González-Solé et al. (2023) who looked at younger pigs (post-weaning) found that a diet composed with a low nutrient density increased competition between pigs, as indicated by their increased levels of aggression near the feeder compared to control pigs. Highlighting the potential for diet composition to influence competition. Additionally, a higher number of feeder visits in other studies has been linked to high levels of feeder displacement, occurring with strong feeder competition (Bus et al., 2021). These higher number of visits being interpreted as the pigs attempt to counteract the frequent displacements and maintain their feed intake. This would require further investigation, but particularly with the behavioural results these changes could imply that higher dietary lysine reduced feed associated competition.

These feeding behaviour differences between lysine treatments likely had some influence on the differences in growth performance that were seen. On the lowest lysine diet pigs ate slower, over a greater number of visits, spending longer in the feeders in total. Typically, pigs which are spending more time eating (per day) have been shown to have lower ADGs, end weights and feed efficiencies (Carcò et al., 2018), all of which were evident in this experiment. Conversely, a faster consumption rate has been strongly associated with improved growth performance (Fornós et al., 2022), again supporting the performance results from this experiment for pigs on the higher lysine diets (who had higher ADGs and better feed efficiencies). However, a faster consumption rate of feed has also been linked to a reduction in feed efficiency (Andretta et al., 2016a) which wasn't observed in this experiment. Having said that, the fastest consumption rate throughout the experiment was seen in Phase Three for gilts on the high lysine treatment and as previously mentioned their poorer feed efficiency did not have a definitive cause, given the maintained feed intake and improved ADGs. Together with the need to excrete excess lysine the faster consumption rate could have contributed to the reduced feed efficiency. This is thought to be because digesta will move through the gut at a faster rate, impeding the digestion and efficient absorption of nutrients (de Haer et al., 1993).

With the exception of consumption rate in Phase One, boars and gilts differed in these feeding related behaviours throughout the experiment. Boars spent longer in the feeders, ate at a slower consumption rate and took fewer trips to the feeder. In recent years, studies looking at the feeding related behaviours of pigs have mostly used barrows as opposed to entire males, but a meta- analysis concluded that boars, gilts and barrows did not differ significantly in their feeding-related behaviours, with apparent differences attributed to different body weights (Averós et al., 2012). This could explain why Hyun et al. (1997) found no difference in some of these behaviours between gilts and boars, as the difference in end weight was just over 3 kg. However, a comparably small difference in end weights (2 kg heavier Dutch Landrace boars) was seen in a study by de Haer and de Vries (1993) who still found boars took fewer visits to the feeder than gilts, in agreement with this study. Therefore, alternative explanations for the inconsistent results are the differing feeder types used, the methods by which behaviours are recorded in studies (Cross et al., 2020) and differing levels of competition (Fornós et al., 2022).

The increase in consumption rate with increasing weight/age has already been mentioned but cannot be used to explain the higher consumption rate in gilts. Instead, some of these sex differences may be linked to competition for access to the feeder (Cross et al., 2020; Fornós et al., 2022). Strong competition with the larger and likely more dominant boars could have meant that gilts were prevented from spending as long in the feeders as boars did. Driving them to consequently increase their consumption rate and take more frequent trips to the feeder, so they could maintain their desired ADFI. Faster consumption rates have also been found to correlate with a decrease in total time spent eating (Fornós et al., 2022) as was seen for these gilts. Looking at the times at which boars and gilts occupied the feeder would have helped to clarify whether feeder competition contributed to the differing feeding related behaviours. Given that most pigs fed *ad libitum* show two daily peaks in feeding activity (Simonsen, 1990), gilts consuming feed outside of these general peaks (or throughout the night) could be doing so due to competition (Chen et al., 2010). Determining whether the gilts feeding related behaviours differ in single sex pens would also aid in the understanding of these behaviours and the role of competition.

It is evident from this and previous studies that feeding related behaviours can differ between pigs for a variety of reasons (e.g. competition), reasons which themselves may arise in response to other changes, like diet composition. The changes to the feeding related behaviours as a result of increasing dietary lysine may have had some influence on the beneficial improvements to growth performance that were observed. Therefore, clearly understanding these changes and why they might occur should be considered when diets are formulated.

4.6. Behavioural observations and lesion scores

Behavioural observations and lesion scoring can aid in the assessment of pig welfare, giving an insight into any potentially undesirable effects of dietary strategies or management practices. Literature on the behavioural effects of dietary lysine is limited, but given the importance of lysine as the first limiting amino acid, any associated behavioural impacts must be identified and managed to avoid adversely affecting their welfare. In this study differences were largely seen between pigs on the highest and lowest lysine treatments, with those on the lowest lysine treatment engaging in more fighting and aggression, spending more time exploring and less time inactive. Increasing dietary lysine also appeared to reduce oral manipulation, but not consistently throughout the experiment.

As omnivores, exploration is part of a pig's natural repertoire of behaviours, one which they are motivated to carry out even in indoor environments. Typically, their wild counterparts would explore environments, seeking out differing food resources to ensure their dietary needs are met (Brunberg et al., 2016). Although pigs will be unable to obtain food this way in most indoor commercial environments, promoting exploratory behaviour, via enrichment, is normally associated with improved welfare. This is a result of its influence on other more harmful behaviours, like aggression, which often are lower with environmental enrichment, where pigs have sufficient stimulation to explore (Mkwanazi et al., 2019). Thus, pigs may primarily be motivated to explore their surroundings by hunger, but also by novelty and the need to relieve boredom. Diets provided with nutrients below nutrient requirements may therefore increase exploratory and foraging behaviours (Jensen et al., 1993). As was seen in this experiment, with pigs on the lower two lysine diets spending more of their time exploring than those on the higher lysine diets did. Given that the diets of the two intermediate lysine treatments were formulated to meet nutrient requirements (NRC, 2012), the elevated levels of exploration on the Med. Low diet (indicating that the pigs nutritional needs were not met) may suggest that pigs true lysine requirements are now higher than recommendations. This is in agreement with the performance data results.

Exploratory behaviours also differed over the course of the experiment and between boars and gilts. Gilts on all four treatments spent more of their time exploring than boars did, when considered over the whole growing-finishing period. The higher estimated lysine requirements of boars might mean they'd be expected to be more adversely impacted by the lower lysine diets (McAuley et al., 2022) and so show a greater behavioural response, but evidently this was not observed. Exploration, along with fighting/aggression is often highest at the start of the growing-finishing period when pigs have been mixed and moved into the new finisher accommodation (O'Malley et al., 2021). However, in this study exploration was highest in Phase Two and similar at the start and end of the experiment (Phase One and Phase Three). It also tended to decrease over the course of each phase, increasing for the first week of each new diet (i.e. the first week of Phase Two and Phase Three). Pastorelli et al. (2012) similarly found that pigs post weaning increased activity and exploration around the feeder when the diet was changed. This could be a result of the new diets containing lower levels of lysine and other nutrients (as requirements decrease with age), meaning pigs are initially receiving suboptimal levels of nutrients (McAuley et al., 2022) prompting an increase in exploration. Dietary changes are also associated with an initial dip in performance, attributed to lower feed intakes, increased energy expenditure (from behavioural changes) and diet composition factors like an increase in fibre and a reduction in protein content (Pastorelli et al., 2012). It has also been proposed that they may result in an increase in damaging behaviours (Day et al., 2002; McAuley et al., 2022).

Changes to exploration coincided with changes to inactivity, with increasing dietary lysine increasing the percentage of time pigs spent inactive. In indoor environments pigs spend the vast majority of their time inactive (Mkwanazi et al., 2019; O'Malley et al., 2021) ranging from 60 to 80% (Buijs and Muns, 2019). The average % of time pigs spent inactive in this experiment was much the same, ranging from around 60-78%, across the different treatments, sexes, and phases. Pigs on all treatments were most inactive in Phase Three, as anticipated, given the general reduction in activity that occurs with age (O'Malley et al., 2021). Higher levels of inactivity have been negatively associated with insufficient enrichment and stimulation (Beattie et al., 2000; Mkwanazi et al., 2019). But considering that each pen had the same environmental enrichment, it is more probable that the changes in inactivity were a consequence of the altered activity levels. Higher activity levels e.g. for pigs on the lower lysine diets (with increased exploration and fighting/aggression) can raise the pigs energy maintenance costs (Fornós et al., 2022), which could also have factored in to their reduced growth performance.

For pigs housed in commercial indoor environments, an increase in damaging behaviours may be predicted to occur in conjunction with an increase in exploration, due to minimal enrichment and the lack of other novelties for their exploration to be directed at (Studnitz et al., 2007; McAuley et al., 2022). In this study oral manipulation didn't reduce with increasing dietary lysine as consistently as exploration did, but results do imply that pigs on the lower two lysine treatments performed more oral manipulation. This again may be attributed to the suboptimal levels of lysine provided in the diets. Greater occurrences of aggression and oral manipulation were also found by van der Meer et al. (2017) when grower-finisher pigs were on a low crude protein diet. They provided a number of possible explanations for this including that the imbalance in amino acids drove pigs to increase their foraging behaviours which in turn were re-directed to other pigs, or that changes to aggression could have been a result of lower tryptophan levels influencing serotonin synthesis or other hormone levels. Alternatively, the higher incidence of damaging behaviours could have been indirectly a result of the pigs reduced growth performance with insufficient amino acids in the diet (Fraser et al., 1991; van der Meer et al., 2017).

With respect to sex differences, gilts were observed performing more oral manipulation than boars in Phase Two. But these differences were only apparent on both the lowest and the highest dietary lysine treatments. Suggesting both a deficiency and a surplus of lysine may increase undesirable behaviours in gilts. This was also proposed by Taylor et al. (2010) for growing-finishing pigs in their meta-analysis on tail biting. They concluded this from the results of a production trial run by the MLC (2005), which saw grower-finisher pigs perform more tail biting on a one phase diet (with lysine levels kept the same) than those on a blend/phased feeding regime where two diets were delivered in different proportions to more closely meet requirements. Alternatively, these sex differences in exploration and oral manipulation may simply be the result of female omnivores naturally higher levels of activity and damaging behaviours (Brunberg et al., 2016). Numerous studies have reported an effect of diet on damaging behaviours (Taylor et al., 2010; van der Meer et al., 2017; Boyle et al., 2022), although few have directly focused on dietary lysine. However, diet ingredients, feed consistency (solid/liquid) and the method of feed delivery/ feed systems may all influence these behaviours (Boyle et al., 2022). Additionally, referring back to diet changes, Day et al. (2002) saw increased tail biting when pigs were changed to a finisher diet (from a grower diet) during the growing-finishing period. This was likely on account of the finisher diet containing lower concentrations of nutrients, which might initially be below the pigs requirements, causing them to increase their foraging and thus tail biting behaviour. The concern with these damaging behaviours (such as the oral manipulation of other pigs' ears and tails) is largely due to the stress associated with them and the resulting lesions, which negatively impact both health and welfare (Boyle et al., 2022). However, lesions aren't exclusively a result of oral manipulation and damaging behaviours, they can also be obtained from fighting and aggressive interactions between pigs.

Increasing dietary lysine reduced the observed occurrences of fighting and aggression in boars and gilts at the start and end of the growing-finishing period (Phase One and Phase Three). But only when compared to the pigs on the lowest lysine treatment, who spent longer fighting and engaging in aggressive behaviours. This is similar to the results from van der Meer et al. (2017) who, as previously mentioned, saw increased aggression on low crude protein diets and proposed it could have been due to the lower tryptophan levels influencing serotonin or other hormones as found by Martínez-Trejo et al. (2009) and Koopmans et al. (2005) respectively. In agreement with current knowledge, boars were found to fight more often and display more aggression than gilts throughout the first two phases of the experiment (Björklund and Boyle, 2006; Nielsen et al., 2018; Mkwanazi et al., 2019). Sex differences were perhaps not seen in Phase Three due to the lower occurrences of these behaviours for both boars and gilts when compared to Phases One and Two. In general, the recordings of fighting and aggression were low throughout the experiment, with the 15 minute scan sampling interval potentially insufficient to accurately capture the true frequencies of these incidents. Oliveira et al. (2018) carried out scan sampling at 10 minute intervals and suggested that for behaviours which pigs only perform intermittently and over short periods of time, such as aggression and mounting, continuous observation methods would be preferable. As even at 10 minute intervals these behaviours may not be accounted for. Unfortunately, in this study the lack of cameras meant continuous observations weren't possible and with 32 pens (with 10 pigs in each) scan sampling each pen at intervals less than every 15 minutes was also not feasible. This did mean that for mounting in particular, the estimated values in the activity time budgets were most likely below the true values. Nevertheless, boars were still observed performing mounting on more occasions than gilts in Phases Two and Three, also in line with previous studies (Björklund and Boyle, 2006). Injuries and lesions inflicted from mounting are often concentrated on the rear of pigs (Faucitano, 2001) but both sexes had similar numbers of lesions on their rear throughout the experiment, which could suggest that both boars and gilts were equally on the receiving end of this behaviour as suggested by Rydhmer et al. (2006).

The beneficial effects of increasing dietary lysine and conversely the unfavourable effects of low dietary lysine diets appear to go beyond the growth performance of pigs, with changes to both behaviour and lesions also observed. Some of these behavioural changes can reasonably explain the differing lesion scores. Pigs on the highest lysine treatment had fewer lesions in total, on the front of their body and of mild severity at the start and end of the experiment (Phase One and Phase Three). They also had fewer lesions on the middle and rear of their bodies but only when compared to those on the Med. Low lysine treatment (who had higher numbers of lesions). This reduction in lesions can be attributed to the pigs' lower levels of fighting/aggression in both these phases and perhaps somewhat to the lower amount of oral manipulation they performed overall. Both of these behaviours contributing to lesions as discussed above. The locations of these lesions further support these suggestions, given that reciprocal fighting predominantly gives rise to lesions on the front of the pig, whilst those from bullying may more often be on the rear (Turner et al., 2006). Since some of the main targets for oral manipulation are the tail, ears and belly (Brunberg et al., 2016) lesions across all three locations could have been a result of this behaviour.

The total number of lesions, in each location and of each severity decreased over the course of the experiment. Particularly at the start of the growing-finishing period, exploration and fighting is expected to be highest (O'Malley et al., 2021). In terms of fighting, this is because when moved into the finisher accommodation, pigs were mixed with new individuals and fighting/aggression is the means by which they will have established dominance hierarchies in these new social groups (McGlone, 1986). This often-vigorous fighting is a welfare concern when mixing pigs because of the resulting injuries and lesions. Lesions were accordingly highest in Phase One, but as mentioned lower on average for pigs on the highest lysine treatment. Meaning increasing dietary lysine above current levels recommended could have a positive welfare effect by reducing undesirable behaviours, lesions and the repercussions of these on growth performance. Besides this, when sending pigs to slaughter on a weight basis, the removal of some pigs from a pen will disrupt the established dominance hierarchies. Which would imply a rise in fighting to re-establish them and an increase in lesions (Björklund and Boyle, 2006). It could therefore be worthwhile investigating whether pigs on the highest lysine diets, who appeared less aggressive and had fewer lesions throughout, may be more adept to cope with these changes and the potential stress of split-marketing. Additionally, the variations in weight between pigs in the same pen could have been looked at in this study as large differences in weight are generally why split marketing is implemented. On higher lysine diets if the pigs performance was less variable and their weights more similar, pigs could benefit from being sent to slaughter at the same time by avoiding any potential negative impacts of split marketing.

Although boars engaged in more fighting, aggression and mounting than gilts, this didn't necessarily correspond with more lesions consistently throughout the experiment. In Phase One they had similar numbers of lesions to the gilts in all locations, but a higher number of these were scored moderate or severe as opposed to mild. This is likely a result of both boars and gilts partaking in the hierarchy associated fighting but the boars being heavier thus stronger and fighting more aggressively/vigorously, causing more serious lesions to be inflicted (Turner et al., 2006; Weiler et al., 2016). In Phase Two, boars had more lesions in total than gilts, more located on the front and of mild severity. Which was likely a result of the continued higher levels of fighting and aggression performed by boars during this time. In Phase Three however no sex differences in any of the lesion measures occurred, reflecting the lower levels of fighting, aggression and oral manipulation.

Chapter 5. Conclusion

This research was carried out to further clarify the response of finisher pigs to increasing dietary lysine, the extent to which this response and the growth performance between boars and gilts differs and to assess whether feeding finisher pigs diets containing lysine below or above requirements has any impact on their behaviour and consequently the number and severity of lesions. Not unexpectedly boars had higher ADGs than gilts, so grew faster, but consumed similar quantities of feed to gilts and were therefore more feed efficient. Both sexes responded to increasing dietary lysine with improvements to feed efficiency, rate of gain and end weight but not to the same extent. Performance plateaued after the Med. High treatment at the start of the growing-finishing period but not in the later stages of finishing, with the exception of feed efficiency which plateaued for gilts. Despite this, the range of dietary lysine concentrations used was for the majority of the time insufficient to capture the upper limit of the boars growth response. But this and the higher lysine requirements estimated for boars where possible still gave clear evidence for lysine requirements differing between sex. Estimates also suggested that true lysine requirements may be above the concentrations currently recommended and used in pig diets, which could have behavioural and welfare consequences. Pigs on the highest lysine treatment had fewer lesions, engaged in less fighting/aggression and on average spent more time inactive in comparison to those on the lowest lysine treatment, below recommendations, who at times showed increased exploration, damaging and aggressive behaviours as well as different feeding related behaviours. The higher frequency of feeder visits and overall time spent in the feeder (with a slower consumption rate) compared to those on the high lysine treatment could have further contributed to their poorer growth performance. If boars were to be fed at the highest lysine concentration used in this study, the further improvements to feed efficiency could improve production efficiency and potentially reduce their environmental impact, but it would increase cost/kg gain for gilts and could conversely increase their nutrient excretion. Based on these findings split sex feeding may be beneficial, but splitting pens by sex could have opposing welfare effects for boars and gilts. Therefore, further evaluation of the economic benefits and any potential welfare or environmental effects (adverse or beneficial) should be carried out before recommendation of this strategy. Nevertheless, increasing dietary lysine above current recommended concentrations can positively improve the growth performance, carcass quality, behaviour and welfare of growing-finishing pigs and as advances in precision feeding technologies continue, feeding boars higher lysine diets than gilts could further enable improvements to production.

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Appendix

Table A1. Comparing the model fit of three models: Linear plateau, Quadratic plateau and Quadratic regression, fitted to the ADG and FCR performance data from Phase One [1 2]

	Linear plateau (BLL)			Quadratic plateau (BLQ)			Quadratic		
	AIC	BIC	R^2	AIC	BIC	R^2	AIC	BIC	R^2
ADG									
Mixed Sex	*	*	*	-261.69	-246.65	0.18	-261.69	-246.65	0.18
Boars	*	*	*	-142.71	-130.53	0.24	-142.71	-130.53	0.24
Gilts	*	*	*	-119.68	-107.33	0.15	-120.31	-107.96	0.15
FCR									
Mixed Sex	151.22	166.26	0.42	159.41	174.45	0.41	159.41	174.45	0.41
Boars	-56.59	-44.41	0.62	-48.24	-36.07	0.60	-48.24	-36.07	0.60
Gilts	*	*	*	141.28	153.63	0.34	141.27	153.62	0.34

[1] AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; BLL = Broken line linear; BLQ = Broken line quadratic; ADG = average daily gain; FCR = feed conversion ratio.

[2] Values with a * indicate where models were unable to be fitted

Table A2. Comparing the model fit of three models: Linear plateau, Quadratic plateau and Quadratic regression, fitted to the ADG and FCR performance data from Phase Two [1 2]

	Linear plateau (BLL)			Quadratic plateau (BLQ)			Quadratic		
	AIC	BIC	R^2	AIC	BIC	R^2	AIC	BIC	R^2
ADG									
Mixed Sex	-225.71	-210.73	0.52	-221.50	-206.52	0.51	-221.50	-206.52	0.51
Boars	-114.17	-102.08	0.58	-111.93	-99.83	0.58	-111.93	-99.83	0.58
Gilts	-118.49	-106.16	0.47	-116.32	-103.99	0.47	-116.34	-104.01	0.47
FCR									
Mixed Sex	-13.21	1.77	0.61	*	*	*	-21.96	-6.97	0.62
Boars	-56.24	-44.15	0.69	*	*	*	-66.72	-54.62	0.71
Gilts	17.69	30.02	0.58	*	*	*	15.89	28.21	0.59

[1] AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; BLL = Broken line linear; BLQ = Broken line quadratic; ADG = average daily gain; FCR = feed conversion ratio.

[2] Values with a * indicate where models were unable to be fitted

Table A3. Comparing the model fit of three models: Linear plateau, Quadratic plateau and Quadratic regression, fitted to the ADG and FCR performance data from Phase Three to endpoint [1 2]

	Linear plateau (BLL)			Quadratic plateau (BLQ)			Quadratic		
	AIC	**BIC**	**R^2**	**AIC**	**BIC**	**R^2**	**AIC**	**BIC**	**R^2**
ADG									
Mixed Sex	-69.76	-54.84	0.49	-67.91	-52.99	0.49	-67.91	-52.99	0.49
Boars	-77.19	-65.20	0.65	-76.17	-64.18	0.65	-76.17	-64.18	0.65
Gilts	-23.90	-11.60	0.38	-22.82	-10.52	0.37	-22.82	-10.52	0.37
FCR									
Mixed Sex	851.19	866.11	0.18	853.20	868.12	0.18	853.20	868.12	0.18
Boars	277.05	289.04	0.36	276.79	288.78	0.36	276.79	288.78	0.36
Gilts	*	*	*	516.80	529.10	0.12	516.69	528.99	0.12

[1] AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; BLL = Broken line linear; BLQ = Broken line quadratic; ADG = average daily gain; FCR = feed conversion ratio.

[2] Values with a * indicate where models were unable to be fitted

Table A4. Comparing the model fit of three models: Linear plateau, Quadratic plateau and Quadratic regression, fitted to the ADG and FCR performance data from Phase Three to slaughter [1 2]

	Linear plateau (BLL)			Quadratic plateau (BLQ)			Quadratic		
	AIC	**BIC**	**R^2**	**AIC**	**BIC**	**R^2**	**AIC**	**BIC**	**R^2**
ADG									
Mixed Sex	-100.37	-85.44	0.40	-101.89	-86.96	0.40	-101.89	-86.96	0.40
Boars	-54.29	-42.25	0.51	-54.58	-42.54	0.51	-54.58	-42.54	0.51
Gilts	-67.81	-55.53	0.33	*	*	*	-69.16	-56.88	0.33
FCR									
Mixed Sex	581.33	596.26	0.26	*	*	*	579.00	593.94	0.27
Boars	265.60	277.64	0.31	262.02	274.07	0.33	262.02	274.07	0.33
Gilts	*	*	*	308.76	321.04	0.24	309.78	322.05	0.23

[1] AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion; BLL = Broken line linear; BLQ = Broken line quadratic; ADG = average daily gain; FCR = feed conversion ratio.

[2] Values with a * indicate where models were unable to be fitted