Piglet birth weight as determining factor of optimal nutrient concentration in grower and finisher diets

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BSc (Agric) Animal Science

Submitted in partial fulfilment of the requirements for the degree

MSc (Agric) Animal Science: Animal Nutrition

In the Department of Animal and Agricultural Sciences

University of Pretoria

2021

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DECLARATION

I, Cara Nel, hereby declare that this dissertation submitted for the obtainment of the degree MSc (Agric) Animal Science: Animal Nutrition at the University of Pretoria is my own work and has not been previously submitted by myself for a degree at any other tertiary institution.

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Date: 23/03/2022

Acknowledgements

I would like to thank SwiNE Nutrition Management for granting me this opportunity to study further, as well as the valuable formulations and technical assistance during the trial.

I would like to thank GHB Farms, especially Dries du Plessis, for supplying the pigs for my trial, and for assisting with the transport of the pigs to the abattoir at the end of the trial.

To Reinhardt, thank you for your support and assistance during every step of my trial. Thank you for helping me with tagging and weighing of pigs and spending late nights at the pig house ensuring that the pigs are taken care of. I could never have done this without you.

A sincere thank you to Dr Christine Jansen van Rensburg, for your guidance and support, not to mention your patience.

I am grateful to Oom Roelf for aiding me with the statistical analysis of the results.

Thank you to other industry associates including CS Vet, SimpleGrow and Eskort, for your contribution to ensure the success of this trial.

Most importantly, thank you to my Heavenly Farther for always being there for me, and hearing all my prayers. I dedicate this degree to You.

Abstract

The selection for improved sow productivity has led to an increase in litter size as well as an increase in the number of low-birth-weight piglets born. Low-birth-weight pigs are associated with slower growth rates, lighter slaughter weights and carcasses as well as decreased pork quality compared to heavy-birth-weight pigs. Therefore, low-birth-weight pigs pose management challenges and may have negative economic implications for pork producers. Furthermore, the nutrient requirements suggested for grow-finishing pigs might therefore not be applicable to low-birth-weight pigs. The objective of this study was to determine the optimal nutrient concentration of grow-finishing diets based on birth weight and the effects on growth performance and carcass quality of low-birth-weight pigs compared to heavy-birth-weight pigs subject to the same diets.

The experiment was performed on 144 pigs and consisted of three feed treatments: control (CON), high standard ileal digestible (SID) lysine (HL), and low SID lysine (LL). The energy level between treatments remained constant within each feeding phase (starter, grower, and finisher). The CON, HL and LL diets within the starter phase had an energy level of 9.87 MJ NE/kg, while the CON, HL and LL diets within the grower phase had an energy level of 9.74 MJ NE/kg and, finally, the energy level of the CON, HL and LL diets within the finisher phase were 9.67 MJ NE/kg. Thus, the diets were iso-caloric for each feeding phase; therefore, SID lysine was the only variable between the three-phase treatment diets. The ratio of the other essential amino acids relative to lysine was kept constant and according to the Feeding Manual for Topigs Norsvin Finishers (2012). A total of 48 pens were used, with three pigs per pen, providing four replicates per treatment. Each pen represented an experimental unit and was allocated to treatments following a complete randomised block design with three feed treatments (control, high SID lysine, and low SID lysine), each combined with either low-birth-weight or heavy-birth-weight pigs, as well as male and female animals. The pigs were 10 weeks (70 days) of age at the start of the trial and reared for a period of 11 weeks until slaughter. The pigs were weighed weekly and the average feed intake per pen was measured weekly as well. Average daily feed intake (ADFI), average daily gain (ADG), and feed conversion ratio (FCR) were calculated per pen. The trial continued until 21 weeks (147 days) of age after which all the pigs were slaughtered to determine carcass characteristics, including hot carcass weight, cold carcass weight, backfat thickness and lean meat percentage.

During the experimental period, birth weight had significant ($P < 0.05$) effects on weight during the starter, grower and finisher phases of the trial, as heavy-birth-weight pigs were heavier at each phase of production compared to low-birth-weight pigs. Feed treatment had no significant ($P > 0.05$) effect

on start and end weights of the starter, grower, and finisher phases within birth weight groups. However, the heaviest slaughter weights for the heavy-birth-weight and low-birth-weight groups were observed for the low SID lysine and control treatments, respectively. The low SID lysine feed treatment had significant ($P < 0.05$) effects on ADG between the heavy and low-birth-weight groups for the starter, grower and finisher phases, as heavy-birth-weight pigs had higher ADG compared to low-birth-weight pigs. Throughout the experiment, heavy-birth-weight pigs had significantly ($P < 0.05$) higher ADG compared to low-birth-weight pigs. The highest ADG of the experiment were observed during the finisher phase and the SID lysine level required to optimise ADG from 120 to 147 days-of-age was found to be 6.84 g/kg for heavy-birth-weight pigs and 7.60 g/kg for low-birth-weight pigs. Throughout the experiment, heavy-birth-weight pigs had higher ($P < 0.05$) ADFI compared to low-birth-weight pigs for the low SID lysine treatment. Additionally, heavy-birth-weight pigs had on average greater feed intakes compared to low-birth-weight pigs. No significant ($P > 0.05$) differences for FCR were observed for feed treatment and birth weight during the experimental period. However, feed treatment had significant ($P < 0.05$) effects on FCR throughout the finisher phase, as the control treatment resulted in better FCR compared to the high SID lysine treatment. The SID lysine level required to optimise FCR during the finisher period (120 to 147 days of age) was found to be 6.84 g/kg. The lowest backfat thickness for the heavy-birth-weight carcasses was observed for the high SID lysine treatment ($P < 0.05$), however, lower carcass weights were observed for this treatment. The low-birth-weight group had the lowest backfat measurements for the low SID lysine level, but the lightest carcasses were observed for this treatment in comparison to the control SID lysine and high SID lysine treatments.

This study showed that the control SID lysine level and the low SID lysine level improved growth performance for low-birth-weight pigs and heavy-birth-weight pigs, respectively. These treatments allowed for the greatest return on investment, as bigger carcasses with acceptable backfat levels were produced. Furthermore, both heavy-birth-weight and low-birth-pigs did not benefit from receiving diets with high SID lysine levels, as improvements in growth performance and carcass weight was not observed.

Contents

List of Abbreviations

AA	Amino Acids
ADFI	Average Daily Feed Intake
ADG	Average Daily Gain
AID	Apparent Ileal Digestibility
BN	Basal Nitrogen
CCM	Cold Carcass Mass
CON	Control
CP	Crude Protein
DE	Digestible Energy
DM	Dry Matter
EN	Endogenous Nitrogen
FCR	Feed Conversion Ratio
FI	Feed Intake
GE	Gross Energy
HBW	Heavy-birth-weight
HI	Heat Increment
HL	High SID Lysine
IGF	Insulin-like Growth Factor
IOFC	Income Over Feed Cost
LBW	Low-birth-weight
Ld	Retained Lipid
LD	Lipid Deposition
LL	Low SID Lysine
Lys	Lysine
ME	Metabolisable Energy
NE	Net Energy
NEm	Nett Energy for Maintenance
NEp	Nett Energy for Production
Pd	Retained Protein
PD	Protein Deposition
PDmax	Maximum rate of Protein Deposition
RNA	Ribonucleic Acid
SEM	Standard Error of the Mean
SN	Specific Endogenous Nitrogen

SID	Standard Ileal Digestibility
TN	Topigs Norsvin
WCM	Warm Carcass Mass

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Chapter 1

General Introduction

The number of piglets weaned per sow is a trait of economic importance in pig production (Lund *et al*., 2002). Selection for increased litter size increases the number of pigs weaned and results in significant improvements in economic efficiency of pig production systems (Johnson *et al*., 1985). Contrarily, the selection for increased litter size has given rise to increase within litter variation in piglet birth weight (Wolf *et al*., 2008). Larger litters are susceptible to prolonged farrowing duration, piglet starvation and crushing which are all factors contributing to increased pre-weaning mortality (Wolf *et al*., 2008; Ocepek *et al*., 2017). Therefore, uniformity of birth weight is as important for piglet survival as mean birth weight (Wittenburg *et al*., 2011).

In addition to birth weight variation, the improvement of sow productivity and the increase in litter size has led to an increase in the number of low-birth-weight piglets (Beaulieu *et al.*, 2010). Low-birth-weight in pigs is defined as infants experiencing a birth weight lower than the 10th percentile of the average litter birth weight, piglets weighing less than the average birth weight minus up to two times the standard deviation, and piglets weighing less than 1 kg (De Vos, 2014). In pig production birth weight is an economically important trait (Beaulieu *et al*., 2010) and is correlated to factors such as survival and postnatal growth rates (Rehfeldt & Kuhn, 2006). Piglets born with low-birth-weights have a lower probability of survival due to their inadequate body reserves (Kitkha *et al.*, 2017; Schmitt *et al*., 2019), and are therefore associated with greater pre-weaning mortality. Furthermore, slower growth rates during the grow-finishing phases of production, and decreased pork quality is apparent in low-birth-weight pigs (Rehfeldt *et al*., 2008; Beaulieu *et al.*, 2010). Pigs born with low-birth-weights require a greater number of days to reach market weight compared to heavier littermates (Gondret *et al*., 2005), resulting in increased management and feed costs for low-birth-weight pigs due to the extended time and greater amount feed needed to obtain acceptable slaughter weights. Slaughter pigs originating from low-birth-weight pigs have poor quality carcasses, as the fat deposition is higher with lower lean meat yield compared to heavier littermates (Rehfeldt *et al*., 2008). Low-birth-weight pigs are therefore at a disadvantage compared to heavier littermates with regards to growth performance as well as carcass quality. It can be assumed that as birth weight decreases the feasibility of a pig being full value at market equally declines, which can lead to considerable production losses.

Commercial grow-finishing feed programs manage all animals as one batch, aiming to fulfil the requirements of the average pig (López-Vergé *et al*., 2018; Aymerich, *et al*., 2020). Low-birth-weight pigs have lower feed intakes compared to their heavier littermates, causing them to consume less feed and ultimately lower levels of lysine during the grow-finishing stages of production (Aymerich, *et al*., 2020). Furthermore, the growth curve of low-birth-weight pigs are different compared to their normal and heavier-birth-weight littermates (Douglas *et al*., 2014), therefore, feeding programs tailored to the average pig might not be optimal for low-birth-weight pig performance and they might need to be fed differently. Lysine is an important factor that influences maximum growth rates as well as improved feed efficiency (Li *et al*., 2012). It has been suggested that an increase in the dietary standard ileal digestible (SID) lysine level during the grow-finishing phases of production improved performance of low-birth-weight pigs (Aymerich, *et al*., 2020; Montoro *et al*., 2021). However, contradictory results have been obtained, which indicated that an increased SID lysine level of the diet did not improve growth performance of low-birth-weight pigs (Douglas *et al*., 2014; Huting *et al*.,2018).

Aim and objective of the study

The aim of the study was to determine the optimal nutrient concentration of grow-finishing diets based on birth weight and the effects of diets containing different SID lysine levels on the growth performance and carcass quality of low-birth-weight pigs compared to heavy-birth-weight pigs subject to the same diets, from 10 weeks-of-age until slaughter.

The objectives of the study were to measure the performance of pigs with varying birth weights, receiving diets with different levels of SID lysine. Performance was quantified by weekly weighing of body weight, as well as measuring feed intake and feed conversion ratio on a weekly basis. At the time of slaughter, carcass weight and quality were recorded. Furthermore, the cost of the different feed treatments was investigated to determine the economic viability.

Hypothesis of the study

The null hypothesis (H_0) of this study was that the high standard ileal digestibility (SID) lysine regime will not provide the necessary support for improved growth performance and carcass quality to the low-birth-weight pigs, whereas the alternative hypothesis (H_A) was that the high SID lysine regime will provide the necessary support for improved growth performance and carcass quality to the low-birth-weight pigs.

Chapter 2

Literature Review

2.1 The pig industry

The South African pork industry comprises of approximately 4 000 commercial producers, 19 stud farmers and 400 small farmers with an estimated 115 000 sows (DAFF, 2019). Since the early 2000's an increase in income levels lead to improved living standards. This included an increase of protein in diets which resulted in a rapid growth of meat consumption (BFAP, 2017; DAFF, 2017). Pork consumption has increased by 42% over the past decade (BFAP, 2020). Due to this increase in pork consumption, pork contribution to the gross value of agricultural production increased steadily (DALRRD, 2020). This has led to an increase in pork production and number of pigs slaughtered from 2008/09 to 2017/18 (DAFF, 2019). According to the South African Pork Producers Organisation, the number of pigs slaughtered has increased by 6% from 2020 to 2021 (SAPPO, 2021). For the period of 2006/07 to 2012/13 South Africa has been an importer of pork as more pork was consumed than produced. In 2013/14 South Africa became self-sustaining as 236 300 tons of pork was produced with a consumption of only 236 000 tons. From 2014/15 and 2017/18 the pork consumption overtook the pork production mainly due to an increase in urbanised consumers (DAFF, 2019). Regardless of South Africa being a net importer of pork, pork is exported mainly to the SADC countries. Pork accounts for 7% of the total meat consumption in South Africa from 2015 to 2017 and is regarded as one of the smallest industries contributing around 2.45% to the overall South African agricultural sector (DAFF, 2019). The South African pork industry therefore has immense potential to expand and further increase production and consumption.

From the year 2020 to 2021 a 13% growth in pig feed sales occurred (AFMA, 2021). Approximately 299 720 tons of pig feed was sold in 2021/22 which includes grains, bran, fishmeal, and premixes (AFMA, 2021). Feed costs in pig production systems make up more than 50% of the total pig production costs (Noblet & Henry, 1993; Noblet *et al*., 1994; Velayudhan, *et al*., 2015). It is therefore of the utmost importance that diets are formulated to meet the requirements and support the growth of pigs, whilst still being affordable.

In recent years, the agricultural sector in South Africa has faced some challenges; the climatic fluctuations and large-scale economic changes created a turbulent agricultural environment (BFAP, 2018). Meat, one of the main factors contributing to food inflation for 2018 and 2019 is estimated to increase by 5.5% and when comparing the single serving costs from 2015 to 2018 polony and pork chops has increased with 17% and 16%, respectively (BFAP, 2018). Food costs have therefore increased while the food security in South Africa has declined. Consequently, it is vital that economically efficient ways of feeding, and farming pigs are found and implemented to ensure improvement in pig production.

2.2 Pig production

A typical pig production system can be divided into the breeding unit, weaner unit, and grow-finishing unit. Sows are located and managed on one site during lactation and gestation, nursery pigs are housed in a different site, and grow-finishing pigs are located and managed on a single or several different sites. This allows for management to focus on the different units within the pig production cycle. The breeding unit is of importance as it provides the farmer with weaners that can be sold or transferred to the weaner unit and later to the grow-finishing unit. Factors such as number of weaners reared per sow per year, number of piglets born per litter and mortality all influence the productivity of the breeding barn (Visser, 2014). Even though the most important factor influencing profitability of the breeding barn is the number of weaners reared per sow per year (Visser, 2014); the number of full value pigs marketed per sow per year considers all phases of production which includes reproduction, nursery and finishing performance (Fix, 2010).

Piglets are usually weaned between 20–30 days of age and will weigh between 6–9 kg (Visser, 2014). According to a study performed by Smith *et al*. (2007), piglets that are born with low-birth-weights are lighter at weaning and 42 days pot-weaning compared to the piglets born heavier. Collins *et al*. (2017) determined that light pigs at weaning grow slower compared to heavier pigs at weaning (442 g/day vs 523 g/day). This corresponds to the results obtained by Škorjanc *et al*. (2007), heavy-birth-weight and low-birth-weight piglets were weighed every 7 days until weaning at 28 days-of-age. The low-birth-weight piglets remained significantly lighter at each study age compared to the heavy-birth-weight piglets. Even though low-birth-weight pigs remain light at subsequent growth stages compared to heavy-birth-weight pigs, Huting *et al*. (2019) determined that weaning at a later age (35 days) can benefit the performance of low-birth-weight pigs, which might be a strategy with long-term benefits.

The main challenge in feeding the grower pig, is to meet the nutrient requirements as closely as possible at different growth stages, with minimum wastage, whilst obtaining the highest possible returns (Visser, 2014). Phase feeding is the most widely used feeding technique to closely meet the nutrient requirements of these animals at different production stages (Andretta *et al*., 2016; Menegat *et al*., 2020). Phase feeding allows for diets to be tailored to each production stage, thus avoiding unnecessary oversupply of nutrients (Han *et al*., 1998). The number of feeding phases is influenced by the age at slaughter and the management on farm. In the past, pork producers optimised diets for average daily gain and feed conversion ratio as producers were compensated on a live-weight basis. The composition of gain was not considered as maximum growth was the only objective, which resulted in animals being excessively fat. As consumer preference changed to pork containing less fat and more meat, diets were optimised for lean growth rather than overall growth rate. As a result of this, feed programs had to be adapted to support lean growth which poses several challenges as factors like animal genotype, environment, management, and the sex of the animal all influence the designing of feed programs. Birth weight is a significant determinant of market weight (Cabrera *et al*., 2012), and can therefore be added to the beforementioned factors. In modern piggeries the number of piglets born below 1.0 kg are increasing due to an increase in litter size (Schmitt *et al*., 2019). Low-birth-weight pigs experience lower growth rates from birth to weaning, which results in reduced market weight (Cabrera *et al*., 2012). As a result, these pigs are reduced in value and consequently impact the profitability of commercial piggeries negatively. It is therefore important that birth weight is considered when designing and implementing feeding strategies during the grow-finishing phases of production.

2.3 Factors influencing birth weight

A large amount of birth weight variation is evident within litters. To address the problem of birth weight variation, it is necessary to understand the factors that influence piglet birth weight. Several factors influencing birth weight will be addressed in this section.

2.3.1 Sex

Čechová (2006) performed a study analysing factors influencing birth weight and found that males were significantly heavier than females at birth (1.292 kg vs. 1.222 kg). Similar results were obtained by Buchová *et al*. (2000), however the difference in birth weight was not significant. Baxter *et al*. (2012) and Huting *et al*. (2018) confirmed that females were significantly lighter at birth compared to males. Contradictory results were found in a study by Bocian *et al*. (2012) to determine the sex proportion in a litter and the effects on growth during weaning and fattening, where females were heavier at birth than males (1.35 kg vs. 1.23 kg).

2.3.2 Genetic factors

Genetic factors are significant in controlling birth weight. Only 25% of birth weight variance is influenced by environment, while 38-80% is genetically influenced (Johnston *et al*., 2002). Birth weight is shaped by parental, placental and foetal genes as well as an interaction with the environment (Johnston *et al*., 2002). As the sire and the dam contribute equally to the genes of the embryo, the sire should thus influence birth weight; but according to Knol & Bergsma (2004), birth weight in pigs is mainly a maternal trait. The sow is an important factor influencing birth weight as foetuses *in utero* are subject to the same environment which influence birth weight. The increase in the number of piglets born per sow per year is mainly due to the development of hyper-prolific breeds. This has led to a greater within-litter birth weight variation exceeding, 1 kg between the lightest and heaviest piglets within a litter (Cabrera *et al*., 2012; Paredes *et al*., 2012). This increase in piglets born per sow per year has led to an increase in the number of pigs weaned per sow per year. Pigs weaned per sow per year is a measurement used to determine the productivity of a breeding herd; this measurement can be used to compare herds within a country or amongst different countries (Koketsu *et al*., 2017). Over the last three decades the pigs weaned per sow per year have increased from 20 to 30 pigs and with proper sow management and genetic progress it is expected to increase from 30 to 40 pigs (Koketsu *et al*., 2017).

Selection for an increase in litter size has been aimed at increasing profitability of pig production and decreasing breeding program costs; but the selection pressure for larger litters has led to a reduction in piglet birth weight as litter size is negatively correlated to birth weight (Čechová, 2006; Rehfeldt & Kuhn, 2006; Beaulieu *et al*., 2010; Fix *et al*., 2010; Pietruszka *et al*., 2017). Larger litters have a heavier total weight, but the average piglet birth weight is lower (Newcom *et al*., 2017). Quesnel *et al*. (2008) conducted an analysis of a data set to assess the evolution of litter characteristics over a decade and found that genetic improvement over ten years resulted in 1.8 extra piglets per litter, and a reduction of 180 g in piglet birth weight. Lower birth weights lead to an increase in problems such as lower survival rates and poorer pig quality (Fix *et al*., 2010; Cabrera *et al*., 2012). Piglets born from larger litters are also inclined to grow slower (Newcom *et al*., 2017).

Beaulieu *et al*. (2010) stated that the average individual birth weight of a piglet decreased with approximately 33 g as the litter size increased. The findings of Rohe and Kalm (1997) indicated that as the litter size increased from 9 to 14 piglets, the average birth weight decreased from 1.6 to 1.4 kg. Larger litters have significantly more losses and these losses are evident amongst the lighter piglets at birth (Čechová, 2006). This is consistent with a genetic selection study performed by Johnson *et al*. (1999), where the selection for increased litter size caused in an increase in the number of stillborn pigs and a decrease in individual birth weight. As to be expected, heavier piglets are farrowed from smaller litters (Čechová, 2006); but according to Lush *et al*. (1933) the relation does not always seem to be linear.

2.3.3 Prenatal growth

During embryonic growth, tissues grow sequentially (Figure 2.1). In early embryos the components of the brain, central nervous system, and spinal cord develop first, and shortly thereafter bone formation follows. The bones form a platform around which the muscle cells can form and attach, and lastly, the adipose tissue develops (Hossner, 2005). *In utero*, a piglet attempts to express its genetic potential for growth (Knol & Bergsma, 2004). Prenatal growth is largely dependent on the combination of the uterus to provide nutrients, the ability of the placenta to transfer these nutrients and the capability of the foetuses to use the available nutrients efficiently (Rehfeldt & Kuhn, 2006). Larger litters can affect the piglet birth weight by severely increasing the competition *in utero* among litter mates for resources like oxygen, nutrients, and space (Lush *et al*., 1993; Quesnel *et al*., 2008); adequate uterine space and these resources are imperative for survival of the embryo and foetus (Alvarenga *et al*., 2012; Rekiel *et al*., 2015).

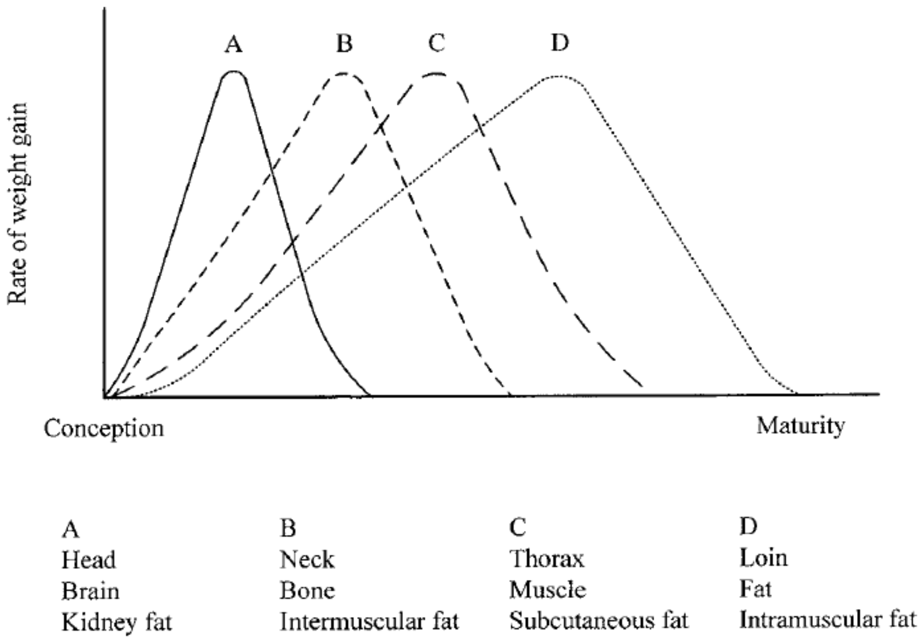

Figure 2. 1 Growth rates of body regions and tissue during development. (Hossner 2005, as adapted from Hammond 1995)

Ford *et al*. (2002) explained the capacity of the uterus the total amount of embryos that the sow can successfully carry until farrowing. As the sow has limited uterine space and as the number of embryos that attach to the placental wall increases, the space between each foetus decreases and affects the size of the piglet at birth. Placental insufficiency is a major cause of intra-uterine growth restriction linking poor uterine environment with retarded piglet growth (Baxter *et al*., 2008). Knol & Bergsma (2004) claims that litter sizes with only four or five piglets have the possibility to reach their full growth potential and maximum birth weight. Positioning of the foetus within the uterus affects the nutritional supply; this in turn will affect the growth of the foetus and consequently the birth weight (Rehfeldt & Kuhn, 2006). Compromised foetal growth rates can result in reduced birth weights resulting in impaired postnatal vitality, affecting the capability of the piglet to perform important behaviours like moving to the udder and drinking adequate colostrum which can influence subsequent growth (Baxter *et al*., 2008).

The risk of intra-uterine growth retardation (IUGR) can be increased by the selection for larger litter sizes. IUGR is defined as impaired growth and development of embryos and foetuses and their organs during pregnancy, characterised by increased growth of the brain compared to other organs (Wang *et al*., 2013; Ladinig *et al*., 2014). The 'brain-sparing' effect assists in maintaining normal development of the brain by ensuring oxygen supply, and is distinguished by asymmetrical growth of essential foetal organs (Schmitt *et al*., 2019). Alvarenga *et al*. (2012) showed that low-birth-weight pigs had lower organ weights and increased brain:organ weight ratios compared to heavier pigs at birth (0.92 vs. 0.51), which provided strong evidence of IUGR in the low-birth-weight progeny. Intra-uterine growth retardation is associated with high morbidity and mortality of new-born piglets and inhibits normal growth of pigs after birth (Wang *et al*., 2005; Ladinig *et al*., 2014). Pigs subject to IUGR have decreased reproductive performance, altered carcass composition and development of muscle fibres and, abnormal gastrointestinal morphologies (Ladinig *et al*., 2014). The delay in gastrointestinal development is one of the main reasons why piglets with IUGR grow slower compared to those with normal intra-uterine growth (Wang *et al*., 2005). Wang *et al*. (2013) showed that IUGR-affected piglets express proteins related to energy supply, muscle structure, protein metabolism, function, and proliferation differently, which indicated reduced growth and development of muscle as well as impaired metabolism. In addition to affecting birth weight, restricted uterine space limits the postnatal growth of piglets. Growth performance data in the study done by Alvarenga *et al*. (2012) showed that low-birth-weight pigs had lower body weights throughout the production phases. Intra-uterine growth retarded pigs cannot compensate their growth in later life (Paredes *et al*., 2012), thus posing economic problems for commercial meat production like lower percentage of meat and increased percentage of body fat in the carcass, and reduced feed conversion efficiency(Matheson *et al*., 2018).

2.3.4 Myogenesis

Muscle fibre formation (myogenesis) occurs only during embryonic development and is controlled by the *MyoD* gene family consisting of four genes: *myogenin*, *MyoD1*, *myf-5*, and *myf-6* (Te Pas *et al*., 1999). During muscle formation, two structurally different groups of muscle fibres develop. The primary fibres are established first in the muscle from myoblasts. Smaller secondary fibres are then formed by attaching and fusing to the surface of the primary fibres (Wigmore & Stickland, 1983; Handel & Stickland, 1987; Lefaucheur *et al*., 1995). The development of primary-and secondary muscle fibres takes place during gestation at day 35 and 65, respectively (Lefaucheur *et al*., 1995; Te Pas *et al*., 2005). At day 90 of gestation muscle fibre hyperplasia is complete (Dwyer *et al*., 1994).

Hossner (2005) defines hyperplasia as cell replication; cells replicate via the process of mitosis to increase overall mass by increasing in number. The muscle fibre number is fixed when piglets are born and cannot change during postnatal growth (Wigmore & Stickland, 1983). Prenatal factors can affect muscle fibre development during pregnancy, and the following have the greatest impacts: uterine environment, number of foetuses, nutrient availability, placental efficiency, and uterine vascular distribution (Palencia *et al*., 2018). During secondary muscle fibre formation, the susceptibility to stress caused by lack of nutrients and space *in utero* greatly reduces the number and growth of the muscle fibres (Palencia *et al*., 2018). The within-litter weight distribution is established at day 30 or 35 of gestation, therefore the first month of gestation plays an important role in birth weight variation (Quesnel *et al*., 2008). Emphasis is placed on muscle growth and development in pigs due to its commercial importance. Muscle fibre number is an important determinant of growth and lean weight, which are two traits of high economic value (Te Pas *et al*., 1999). Muscle mass and growth is determined by muscle fibre number (Dwyer *et al*., 1994) and the muscle fibre number is the most important factor restricting the size of the muscle (Handel & Stickland, 1987). The quality of muscle growth is also of importance to produce meat for consumption; and the ratio of muscle to intramuscular fat is an important measure of meat quality (Hossner, 2005).

The initial events of muscle development determine the number of muscle fibres (hyperplasia) that are formed during pregnancy, and this is positively correlated to birth weight (Te Pas *et al*., 1999; Rehfeldt & Kuhn, 2006). Rehfeldt & Kuhn (2014) found a positive relationship between birth weight and muscle fibre number, indicating that most low-birth-weight pigs had low numbers of muscle fibres differentiating during myogenesis, and that muscle fibre number is important in determining birth weight (Figure 2.2). A greater birth weight leads to greater growth rates and carcass weights; in addition to this, more muscle fibres lead to greater lean meat yield (Te Pas *et al*., 1999).

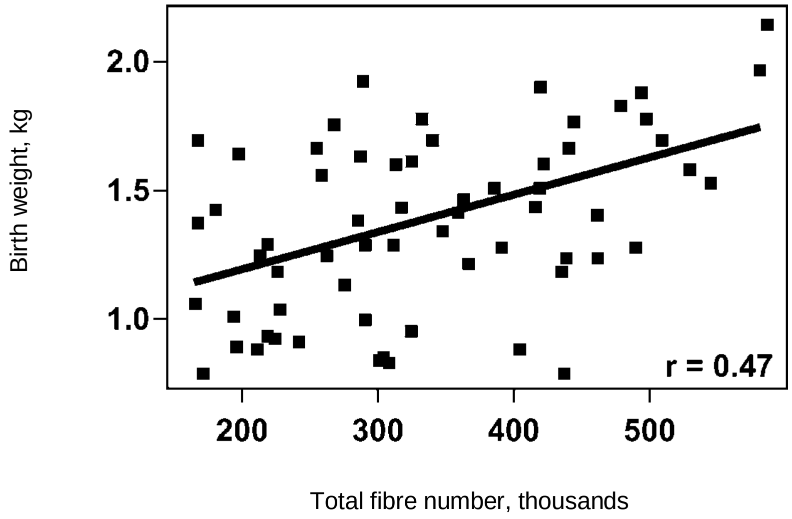

Figure 2. 2 Relationships of birth weight with semitendinosus muscle fibre number by phenotypic correlation (r) estimated from data of 62 piglets born to 23 German Landrace sows ($P < 0.0001$) (Rehfeldt & Kuhn, 2014)

The difference in fibre number between littermates is due to the different number of secondary muscle fibres around each primary fibre. Small piglets at birth have smaller primary fibres which decrease the surface area the secondary fibres can attach to; this results in overall less muscle fibres (Wigmore & Stickland, 1983). Rehfeldt & Kuhn (2014) observed that low-birth-weight piglets had significantly lower muscle fibre numbers during foetal development which resulted in a lower number of secondary muscle fibres (Figure 2.3).

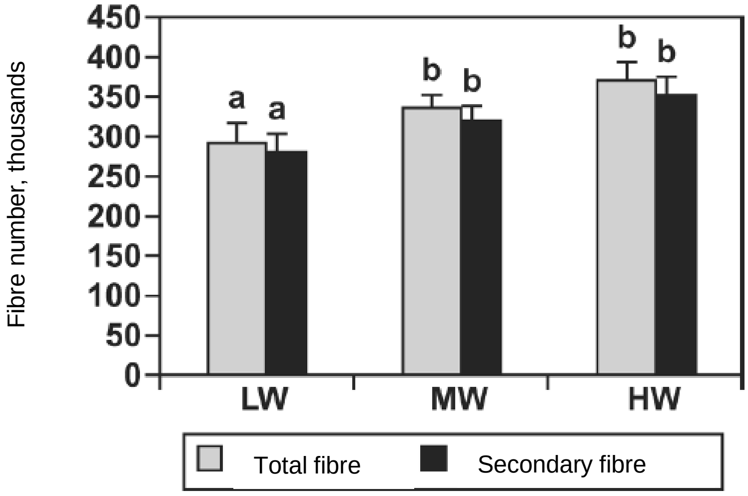

Figure 2. 3 Total and secondary muscle fibre numbers of semitendinosus muscle in different birth weight groups (LW = low, MW = middle, HW = heavy) of new-born piglets (n = 47). Within total or secondary fibre number, least squares mean without a common superscript differ between the birth weight groups ($P < 0.05$) (Rehfeldt & Kuhn, 2014)

Larger piglets within a litter contain more muscle fibres than the smaller piglets (Handel & Stickland, 1987) and this allows for postnatal catch-up growth (Rehfeldt & Kuhn, 2006). Small piglets with a lower number of muscle fibres have a lower potential for postnatal lean growth and thus deposit increased amounts of fat (Alvarenga *et al*., 2012). From 25 kg until slaughter the number of muscle fibres are positively correlated to postnatal growth rates and feed conversion (Rehfeldt & Kuhn, 2006; Dwyer *et al*., 1994). The increase in skeletal muscle mass after birth is due to an increase in muscle fibre size (hypertrophy) which is limited by genetic and physiological factors (Rehfeldt & Kuhn, 2006).

Muscle fibre number differences between large and small piglets within a litter can be explained by malnutrition during pregnancy and uterine positioning (Wingmore & Stickland, 1983). Intra-uterine crowding causes a reduction in muscle fibre hyperplasia and growth of muscle fibres (Pardo *et al*., 2013). The amount of foetuses within the uterus influences development of the muscle fibre number; as the number of foetuses increases the fibre number decreases (Rehfeldt & Kuhn, 2006). A study done by Palencia *et al*. (2018) showed that piglets in smaller litters with less competition for nutrients and space *in utero*, allowed for a more normal development of primary muscle fibres compared to larger litters. In the study done by Wigmore & Stickland (1983), the total number of muscle fibres were compared between the smallest and largest piglets within a litter, after 64 days the largest foetus had more muscle fibres at any given stage than the smallest foetus and at birth there was a 17% difference in total muscle fibre number between the large and small piglets.

2.3.5 Sow parity

Sow parity can be seen as a cause contributing to low birth weight in piglets (Zotti *et al*., 2017). Anatomical differences between primiparous and multiparous sows influence the prenatal development of piglets (Zotti *et al*., 2017). Primiparous sows are still growing, and they have a higher requirement for energy and protein compared to older sows. Taking this into account the partitioning of nutrients between the gilt for growth and the development for embryos can affect muscle fibre hyperplasia (Da Silva *et al*., 2013). Multiparous sows are seen as more mature animals due to their older age and previous experience as mothers. Offspring of older sows are higher producing animals as they are hardy with superior growth (Craig, 2019). Krahn (2015) found that the highest piglet birth weight was evident in 2nd parity sows and decreased as sow parity increased, the lowest birth weights were observed in parities 1, 7 and greater. According to the study done by Čechová (2006), birth weights peaked at the 5th parity (1.337 kg) and thereafter gradually decreased. Contradictory to the above results, Da Silva *et al*. (2013) determined that the highest piglet birth weight was perceived in 3rd parity sows followed by 4th and 2nd parities. Despite inconsistent results, it is evident that parity has an influence on birth weight. As the parity of a sow increases, the birth weight of piglets tends to increase as well (Da Silva *et al*., 2013; Zotti *et al*., 2017). Lavery *et al*. (2018) confirmed that the average piglet birth weight was lowest in gilts, with piglets weighing 0.1 kg less compared to piglets born to 3rd and 4th parity sows.

2.3.6 Sow nutrition

Among production animals, swine are a prime example of foetal growth retardation, causing high variability in piglet birth weights (Moreira *et al*., 2020). Due to an increase in the prolificacy of sows, it is necessary that nutritional adjustments are made during gestation, as inappropriate sow nutrition can be associated with growth retardation leading to an increase in litter variability (Moreira *et al*., 2020). Increasing the number of piglets born alive can be achieved by improving litter uniformity, thus increasing the survival of piglets pre- and post-weaning as well as growth performance after weaning (Yuan *et al*., 2015). Gestation feed requirements are divided into early (day 1 to 28), middle (day 29 to 84) and late (day 85 to 115) gestation (De Vos, 2014). Sow feed intake is increased mid gestation to meet the energy requirements for maternal weight gain and maintenance (De Vos, 2014). During late gestation, the focal point is on foetal growth and mammary development; feed intake is also increased during this time (De Vos, 2014). Primary muscle fibres are regarded as genetically fixed and are not susceptible to environmental influences, whereas secondary muscle fibre formation can be affected by factors *in utero* like nutrition (Bee, 2004). The maternal diet provides amino acids, glucose, and other essential nutrients that influence the growth of the embryo and foetus directly (Rehfeldt & Kuhn, 2006). Restricting sows during gestation is a strategy implemented as an attempt to decrease production costs, but this strategy is related to a higher rate of intra-uterine growth retardation and as a result low-birth-weight piglets (Vázquez-Gómez *et al*., 2020). At about 30 days of gestation, the competition *in utero* amongst litter mates for space and nutrients become critical (Ford *et al*., 2002); the restriction of nutrients will cause a wide distribution in litter weights, growth rates and muscle fibre numbers (Dwyer *et al*., 1994). Dwyer *et al*. (1994) performed a study to determine if the secondary muscle fibre number will improve by increasing the sow feed intake at different times during gestation. The results of the study indicated that increasing the sow feed intake during early pregnancy will increase production of the secondary muscle fibres by 3%, resulting in increased postnatal growth, especially during the finishing phase. Vázquez-Gómez *et al*. (2020) concluded that maternal nutrient restriction did not have adverse effects on birth weight but rather in the growing and finishing phases of production. When sows were fed 70% of their daily requirements from day 38 until day 90 of gestation the offspring had poor growth patterns and feed conversion ratios. If feed is inadequate during the last part of gestation; low-birth-weight, reduced mammary cell number and lower possible milk production will be evident, establishing an environment for pre-weaning mortality (Edwards, 2002).

A possible nutritional strategy to improve the viability of piglets at birth, is to supplement functional amino acids, like arginine, and increase the amino acid levels of the diet (Moreira *et al*., 2020). Arginine is a precursor of biologically active molecules that support embryonic and foetal development and growth (Moreira *et al*., 2020). Quesnel *et al*. (2014) determined that supplementing L-arginine during the last third of gestation, the within-litter variation of birth weight was slightly decreased. Another potential way to reduce the birth weight variation within-litters is to feed dextrose during the weaning-to-oestrus interval (Van den Brand *et al*., 2009). An indicator of uniformity in embryonic development, and eventually within-litter birth weight variation, is oocyte maturity (Van den Brand *et al*., 2009). Feeding dextrose increases the plasma insulin and IGF-1 levels, which improves the oocyte and follicle development and quality due to an increase in luteinizing hormone (LH) (Yuan *et al*., 2015). Additional studies on alternative methods for increasing birth weight was performed by Rehfeldt *et al*. (2001) and Lösel *et al*. (2009). Rehfeldt *et al*. (2001) discovered the effect of porcine somatotropin (pST) treatment during early gestation on embryonic and foetal survival and the internal environment for foetal growth. Treatment of pST in early pregnancy increased the birth weight of light piglets within a litter more than that of piglets born with medium to heavy weights. Another method to increase birth weight via nutrition is to supplement L-carnitine during gestation, as L-carnitine supplementation triggers increased prenatal muscle fibre formation (Lösel *et al*., 2009). To conclude, maternal nutrition during gestation can have equivalent effects on foetal growth due to physical maternal constraints like uterine and placental capacity. It is however evident that feed restriction of sows during gestation has lifelong destructive effects on postnatal muscle growth.

2.4 Birth weight and economically important traits

Birth weight is a trait of economic importance which is regularly neglected (Alves *et al*., 2018). Many factors determine the value of a pig at slaughter, including survival, growth, and pork quality; all of which are influenced by birth weight. It is therefore of interest to understand what implications birth weight holds for economically important growth and carcass traits, as this is crucial to the success and profitability of pig producers.

2.4.1 Survival

Efficient pork production depends on producing the highest number of slaughter pigs within farm system boundaries, which is correlated to the amount of piglets born and the survival of these piglets. Therefore, it is apparent that dead pigs decrease the efficiency and profitability of pig production systems. Knol & Bergsma (2004) described survival as vitality, the piglet's potential to adapt to the environment provided. Edwards (2002) interpreted vitality as the ability of the piglet to quickly stand and become active, find the udder, compete with littermates for teat access and ingest adequate colostrum. Factors including litter size, birth weight, birth order, farrowing length, environmental temperature, dystocia, health, nutritional status, and maternal and piglet behaviour all influence pre-weaning survival (Panzardi *et al*., 2013). Piglet mortality remains a major problem as it accounts for the largest number of mortalities in commercial pig production and can range from 10-20% of live born pigs (Fix *et al*., 2010; Devilliers *et al*., 2011). Knowledge on factors influencing pre-weaning mortality is important in order to reduce economic losses in the swine industry.

Larger litters have a higher pre-weaning mortality compared to smaller litters (Nuntapaitoon & Tummaruk, 2018). In the study done by Nuntapaitoon & Tummaruk (2018), pre-weaning mortality increased two-fold as the litter size increased from 11-12 to 13-16 piglets. Birth order affects per-weaning survival as piglets that have a high birth order (born later during the farrowing process) are more susceptible to death (Baxter *et al*., 2008; Baxter *et al*., 2009). Results obtained in the study done by Panzardi *et al*. (2013) established that piglets born later are likely to suffer from asphyxiation which impairs adaptation to the postnatal environment resulting in a lower chance of survival. Colostrum intake is essential as it provides systemic immunological protection through the absorption of IgG and energy for thermoregulation, furthermore, colostrum stimulates growth and function of the intestines (Cabrera *et al*., 2012). Piglets are born hairless with no brown adipose tissue to facilitate metabolic heat production and are therefore susceptible to hypothermia (Baxter *et al*., 2008). Hypothermia and starvation lead to piglet lethargy, subsequent crushing, and death (Baxter *et al*., 2008). Piglets within a litter compete for access to teats within the first few hours and days after birth (Milligan *et al*., 2001). The competition between littermates can have an influence on pre-weaning piglet growth and survival, because if a piglet cannot establish ownership of a teat, they usually die or only suckle opportunistically (Milligan *et al*., 2001). Piglets that do not consume sufficient colostrum have low IgG serum concentrations and are more likely to die before weaning (Cabrera *et al*., 2012).

Direct selection for survival is ineffective as the trait has a low heritability, but individual piglet birth weight is associated with survival and can be used to indirectly improve survival (Čechová, 2006; Roehe *et al*., 2009). Most pre-weaning mortalities occur within three days after birth, and mainly affect piglets with low-birth-weights and low weight gains (Baxter *et al*., 2008; Devilliers *et al*., 2011). As illustrated in Figure 2.4, pigs with low-birth-weights have a low chance of survival (Paredes *et al*., 2012). Litters with low piglet birth weights tend to have higher mortalities compared to litters with medium and high birth weights (12.8%, 12.1% and 10.5%, respectively) (Nuntapaitoon & Tummaruk, 2018). The capacity of pigs to thermoregulate is directly related to birth weight. Low-birth-weight piglets have a high body surface in relation to their weight and are prone to hypothermia (Panzardi *et al*., 2013). Low-birth-weight pigs take longer to reach the udder, thus consuming less colostrum which provides essential nutrients and energy necessary for survival (Fix *et al*., 2010; Panzardi *et al*., 2013; Nevrkla *et al*., 2017; Zotti *et al*., 2017). In addition to piglets taking longer to reach the udder, they also fail to establish ownership of a functional teat resulting in low-birth-weight piglets to die (Milligan *et al*., 2001).

The classification of optimal birth weight in relation to survival varies considerably across studies. Feldpausch *et al*. (2019) established that piglets born with weights less than 1.11 kg are more susceptible to pre-weaning mortality. Various studies have determined that pigs with birth weights of less than 1 kg have a higher risk of mortality (Bereskin *et al*., 1973; English and Morrison, 1984; Kisner *et al*., 1995; Beaulieu *et al*., 2010; Cabrera *et al*., 2012) and still birth (Fix *et al*., 2010). According to Cabrera *et al*. (2012) piglets that weigh 0.9 kg or less at birth have a lower survival rate (68%) compared to piglets weighing 1.6 kg or more (89%). As birth weight increases, survival rates also tend to increase (Grandinson *et al*., 2002).

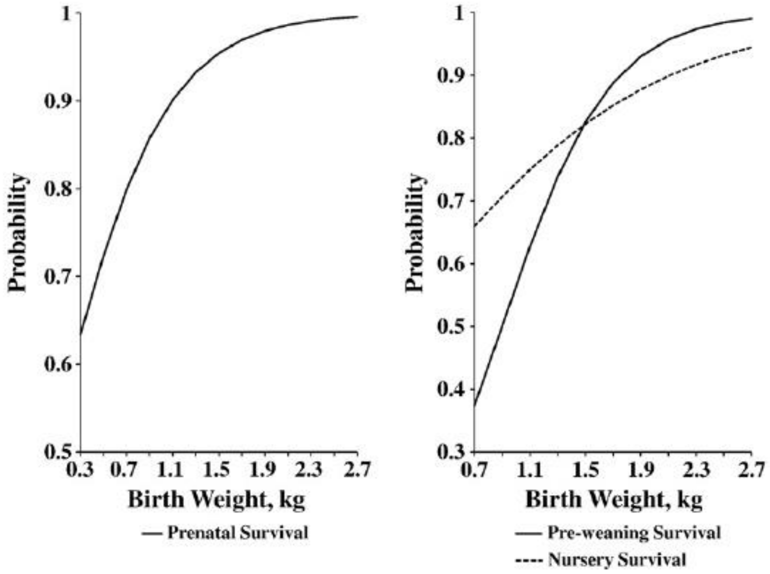

Figure 2. 4 Estimated associations for birth weight with prenatal (linear: P<0.01), pre-weaning (linear: P<0.01), and nursery (linear: P<0.01) survival (Fix *et al*., 2010)

A number of studies have been conducted on low-birth-weight and heavy-birth-weight pigs, determining the effect of birth weight on survival, growth performance and carcass characteristics. A summary of the birth weight categories used in experiments conducted is displayed in Table 2.1.

Table 2. 1 Summary of low-birth-weight and heavy-birth-weight categories

Low-birth-weight (kg)	Heavy-birth-weight (kg)	Reference
< 1	-	Quesnel *et al*. (2008)
< 1	-	Vázquez-Gómez *et al*. (2020)
< 1.2	> 1.62	Rehfeldt &Kuhn (2014)
0.75 – 1.25	1.75 – 2.05	Gondret *et al*. (2005)
0.60 – 1.45	1.54 – 2.10	Lanferdini *et al*. (2018)
0.80 – 1.3	> 1.7	Madsen & Bee (2015)

2.4.2 Growth

Growth occurs through the formation of bone, adipose and lean tissue in the body through continuous anabolic and catabolic processes related to tissue turnover (Whittemore & Kyriazakis, 2006). At cell level growth occurs in two ways, through hyperplasia, and hypertrophy. Hyperplasia is the increase in cell number and hypertrophy is defined as the increase in cell size and volume (Hossner, 2005). To summarise, growth is thus the increase in body weight and size, or an accretion of protein fat and bone over time that reflects the changes in size, development and structure of various organs and tissues (Moloney & McGee, 2017). Growth can be measured objectively as it is a quantitative factor. The simplest and most common method to measure growth is to measure body weight (Hossner, 2005). When animals are reared under 'ideal' environmental and dietary conditions, the pattern of growth or growth curve is a sigmoidal or 'S-shaped', displayed as the weight gain of an animal plotted against age (Figure 2.5). The sigmoidal growth curve is characterised by an initial exponential growth phase, where the slope is maximal, and growth is rapid. This is followed by an inflection point, where the shape of the curve changes from rapid growth to a slower growth rate, at about the age of puberty. Lastly, a growth plateau is reached, where the growth is very slow and ultimately ceases (Hossner, 2005).

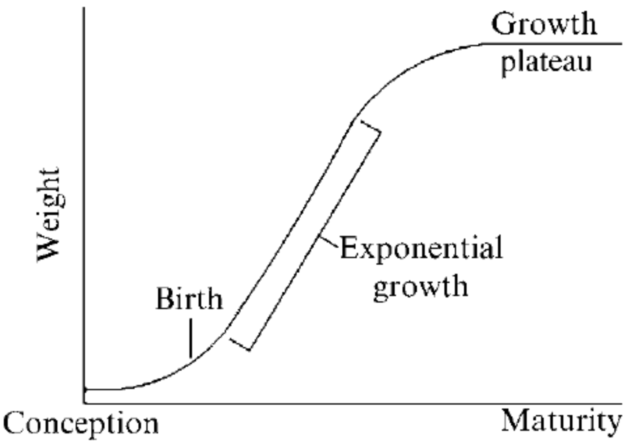

Figure 2. 5 Sigmoidal growth curve (Hossner, 2005)

The increase in muscle mass as well as the quality of muscle growth, defined as the ratio of fat to muscle, is important for producers and ultimately, consumers. The optimal production strategy is to produce pigs with a high lean meat content with acceptable growth rates and feed consumption. Efficient lean meat production in pigs is dependent on the optimisation between protein and fat deposition (De Greef, 1992). Whittemore and Fawcett (1976) described the response of pigs to increasing energy intakes in terms of protein deposition and fat deposition, which is referred to as the Linear-Plateau concept. The observation of the study was that within certain limits, protein deposition is always accompanied by fat deposition and at high levels of energy intake, fat deposition significantly increases. It was suggested that as the energy intake increases, protein deposition increases linearly, but this is limited as pigs are believed to have an intrinsic maximum of protein deposition capacity (PDmax). The PDmax is an important constraint on pig growth (Moughan *et al.*, 2006), as it influences the partitioning of available energy and nutrients (Martínez-Ramírez & De Lange, 2007). In addition, it is assumed that there is a minimal amount of fat or lipid deposition (LD) per unit of protein deposition (PD), therefore there is a minimal ratio between LD and PD. Energy is divided between PD and LD (below the intrinsic maximum for protein deposition); according to this minimal ratio (r), and above the protein deposition capacity, all the remaining energy will be used for fat deposition. The Linear-Plateau concept is illustrated in Figure 2.6, and it clearly indicates that there is an upper limit for protein deposition. Protein deposition is a function of genotype (Martínez-Ramírez & De Lange, 2007), weight and age, which are important factors to estimate the nutrient requirements of the animal to support the genetic upper limit of protein deposition (Moughan *et al.*, 2006; Whittemore & Kyriazakis, 2006). Whittemore (1986) stated that fat deposition will only start to increase once the genetic potential for lean protein growth has been achieved, and that animals with a greater genetic potential for lean tissue growth can achieve higher feed intakes and improved feed efficiency without an increase in fat deposition.

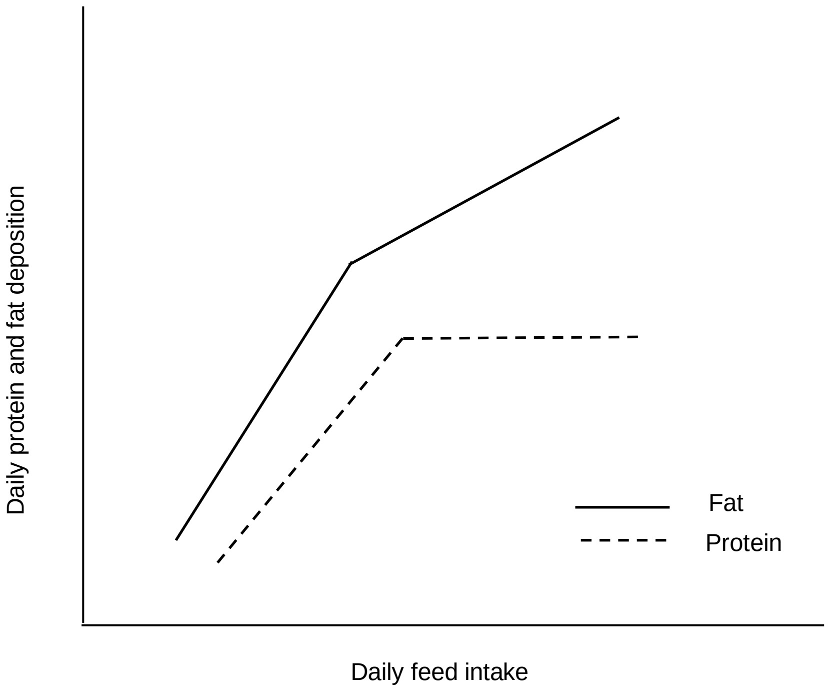

Figure 2. 6 Genetic potential for lean and fat tissue deposition (Whittemore, 1986)

De Greef (1992) validated the Linear-Plateau model initially proposed by Whittemore & Fawcett (1976) to predict protein and fat deposition. Two assumptions were made by Whittemore & Fawcett (1976), (i) it was assumed that the composition of protein and fat deposition was independent of energy intake, up to the plateau level of protein deposition, and (ii) that the minimal ratio of fat to protein deposition was constant over the fattening weight range. De Greef (1992) concluded that as the energy intake increases whilst remaining below PDmax, the ratio between protein and fat deposition also increases, which does not support the concept of a constant partitioning between protein and fat deposition as proposed by Whittemore & Fawcett (1976). De Greef (1992) stated that the ratio of fat to protein deposition is not constant and increases with energy and live weight intake.

Growth is determined by genetic and non-genetic factors. The most important factors that control growth, health and production of an animal is the genetic makeup, the environment the animal is exposed to and nutritional intake (Hossner, 2005). These factors have provided foundation for the control and manipulation of animal growth. Genotype and environment will be discussed in short, whereas nutrition will be discussed more extensively later in this review.

Genotype

The genetic background of an animal provides the basic potential for rapid growth, body composition and adult size (Hossner, 2005). Sustainable farming requires efficient production of protein which has caused interest in enhancing feed efficiency and growth rates of monogastric animals (Moloney & McGee, 2017). Selection for higher growth rates in swine has led to rapid improvements in production characteristics like higher lean growth potential and reduced backfat thickness (Webb *et al*., 2006). Growth rates (average daily gains) have increased by almost 50%, feed intake has increased by 35% and the efficiency of feed utilisation has improved by 13% over the ten generations (Hossner, 2005). Barea *et al*. (2010) determined the differences of total tract amino acid digestibility and nutrient utilisation between two pig genotypes (indigenous pigs and lean-type pigs). The results showed that lean-type pigs presented a higher growth performance and improved feed efficiency, due to an increased capacity to efficiently utilise nitrogen and other energy yielding nutrients. Campbell & Taverner (1998) determined that differences in growth performance between different boar strains were due to genetic differences and their respective capacity for protein growth. Friesen *et al*. (1994) performed a study to determine the effects of the interrelationship between genotype, sex and dietary lysine on growth performance and carcass composition. The comparisons were made between pigs characterised with either a high or medium potential for lean tissue gain. At 104 kg, the high-lean pigs had increased average daily gains and improved feed conversion ratios compared to medium-lean pigs.

Environment

The environment a pig is exposed to affects the behaviour and performance of the animal. Stressors like high temperatures, regrouping, and restricted floor space reduce the feed intake and weight gain of pigs (Hyun *et al*., 1998). Temperature ranges between 10ºC and 23.9ºC is optimal for finishing pigs, and temperatures above 23.9ºC will decrease feed intake and subsequently growth (White *et al*., 2008). In addition to reduced feed intake and growth, heat stress can cause losses in other areas of production such as inconsistent market weights, altered carcass traits, infertility, and mortality (Rauw *et al*., 2017). White *et al*. (2008) housed pigs at different temperatures to determine the effect on performance as well as carcass quality. Data from the study indicated that both temperatures, above the thermoneutral zone, and high stocking densities, affected growth performance and carcass quality; a decrease in growth and feed intake was observed as well as poor feed conversions. This is in line with the findings of Rauw *et al*. (2017) that heat stressed pigs had reduced feed intakes and body weight gains which resulted in leaner pigs and smaller carcasses at slaughter. Gonyou & Stricklin (1998) examined the effects of stocking density on productivity of grow-finishing pigs and concluded that stocking densities less than 0.76 m^2/pig reduced average daily gain and average daily feed intake. Management strategies like improvement of housing designs, reducing stocking densities, and improving feeding strategies and feed composition can be implemented to alleviate heat stress (Rauw *et al*., 2017).

Schinckel *et al*. (1999) performed three genotype by environmental interaction trials to determine the direct effects and interactions between the genetic potential for lean growth and environment. In each trial, two or three genetic populations were reared under two different environments. The genetic by environmental interactions observed in the trials determined that the evaluation of the genetic populations in one environment cannot be used to predict the performance of pigs in a different environment, and it would be beneficial to identify the genotype most suited to an environment to realise increased economic benefits. The genetic makeup directly influences tolerance to heat stress because of differences in metabolic rate resulting from the level of lean tissue growth (White *et al*., 2008). Selection for increased production results in increased environmental sensitivity (White *et al*., 2008).

There is a strong positive correlation between birth weight and mature weight, animals having greater mature weights have greater weights at birth (Whittemore & Kyriazakis, 2006). Birth weight is an important indicator of subsequent body weights, especially weaning weights (Smith *et al*., 2007; Fix *et al*., 2010) and is therefore an indication of the growth potential of a pig (Václavková *et al*., 2012). When low-birth-weight pigs survive past weaning, they are usually of lower quality compared to their heavy-birth-weight counterparts (Fix *et al*., 2010). Low-birth-weight pigs are inferior at weaning, finisher placement and slaughter (Fix et al, 2010; Lanferdini *et al*., 2018). The rate of gain to market weight is an important factor in efficient pig production, as fast weight gain results in pigs reaching slaughter weights at an earlier stage, thereby lowering maintenance costs (Whatley, 1942). Pigs born light grow slower and are lighter at slaughter or require an additional number of days to reach the desired slaughter weight, resulting in inflated feed costs (Nevrkla *et al*., 2017). The growth of pigs born in different weight classes is illustrated in Figure 2.7, showing the slower growth rate in low-birth-weight pigs (Václavková *et al*., 2012).

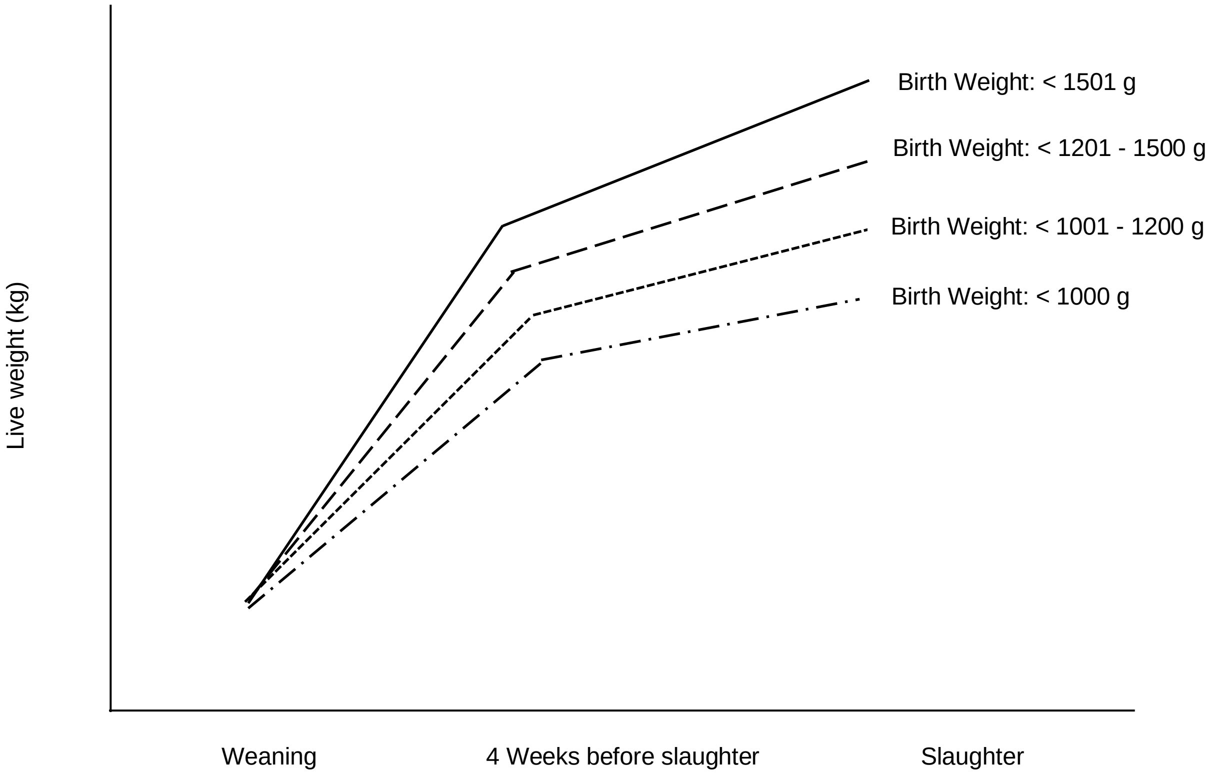

Figure 2. 7 Growth intensity of piglets with different birth weight (Václavková *et al*., 2012)

Within an all-in, all-out system only a limited amount of time is available to reach the required slaughter weight and pig producers might be penalised by processors due to light carcasses which can result in profit losses. An experiment conducted by Rehfeldt & Kuhn (2014) demonstrated that low-birth-weight piglets had remarkable differences in body composition. These piglets had higher percentages of skin, bones, and other internal organs; but the muscle tissue was smaller than that of the heavy-birth-weight pigs. They contained less fat and protein but had a higher water content which is indicative of their immaturity. Nevrkla *et al*. (2017) found that at weaning (28 days) the difference in weight between the lowest and heaviest pigs were about 2 kg. Smith *et al*. (2007) determined in their study that low-birth-weight pigs were lighter at 42 days post weaning. This corresponds to the effect of litter size on birth weight and the impact of birth weight on future performance; pigs born heavier at birth are inclined to grow faster and require less days to reach slaughter (Newcom *et al*., 2017).

2.4.3 Carcass characteristics

Carcass classification is an important part of efficient animal production, determination of meat price and meeting consumer demands (Webb, 2015). Distinct characteristics that are important to the meat industry, retailers and consumers, are used to define carcasses in a carcass classification system (Webb, 2015). Thus, a classification system can be used as a guideline by the producer as a means to provide a product that meets consumer demands. In South Africa, pig carcasses are classified into six groups (PORCUS) based on their measured backfat thickness and calculated lean meat content (Table 2.2). The PORCUS classification system relies on *Longissimus thoracis (LT)* muscle depth and subcutaneous backfat depth to determine the lean meat depth of the carcass (Needham *et al*., 2020). Pigs with high lean meat content and low backfat thickness are favoured and classified as P and O, whereas the carcasses classified as 'RCUS' are less desirable as they are considered older with more subcutaneous fat (Hugo & Roodt, 2015; Needham *et al*., 2020). The back fat thickness is measured 45 mm from the midline, using a Hennessy Grading Probe ® which is an optical device known to be more accurate compared to other methods (Chikwanda *et al*., 2015).

Table 2. 2 Classification system of pork carcasses in South Africa according to the PORCUS system (Adapted from Needham *et al*., 2020)

Classification	Subcutaneous fat thickness (mm)	Estimated lean meat percentage in carcass*
P	≤ 12	≥ 70
O	13 – 17	68 – 69
R	18 – 22	66 – 67
C	23 – 27	64 – 65
U	28 – 32	62 – 63
S	> 32	≤ 61

* Lean meat percentage = 72.5114 – (0.4618 x fat thickness (mm)) + (0.0547 x muscle thickness) as estimated with the Hennessey grading probe ®

Eating quality or palatability encompassing taste, flavour, tenderness and juiciness, is a key factor that impacts consumer choice of animal protein (Moeller *et al*., 2010). Meat quality is influenced by water-holding capacity, colour, fat content composition and pH, which in turn is influenced by factors such as genotype, feeding strategy, pre-slaughter handling and slaughter methods (Rosenvold & Andersen, 2003; Koćwin-Podsiadła *et al*., 2006; Kim *et al*., 2016). The classification of pork quality is executed through visual observation by a professional assessing the appearance, colour, and post-mortem pH (Kim *et al*., 2016). The initial and ultimate preferred pH ranges are 6.3-6.7 and 5.7-6.1, respectively (Kim *et al*., 2016). A study performed by Boler *et al*. (2008) determined that the pH measured at 24 hours post-mortem is the best predictor of pork quality characteristics. Profitability of pork production systems depend on the production of pigs that efficiently convert feed, have a high lean meat yield and that are fast growing. Selection for these traits have resulted in animals that have a higher susceptibility to stress, resulting in the occurrence of meat quality defects such as Pale Soft Exudative (PSE) and Dark Firm Dry (DFD) meat (Adzitey & Nurul, 2011). PSE meat is induced through a high initial temperature and low pH post-mortem, and long-term stress pork demonstrates characteristics of DFD which maintains a high ultimate pH (Kim *et al*., 2016).

Low-birth-weight pigs are associated with a decreased pork quality (Beaulieu *et al*., 2010), as negative relationships between birth weight and carcass fatness, drip loss, meat tenderness and lighter carcasses have been determined (Fix *et al*., 2010). As previously discussed, uterine capacity influences the muscle fibre development between day 30 and day 90 of gestation and if space is limited during this time impaired muscle fibre formation occurs (Nevrkla *et al*., 2017). Pigs susceptible to limited uterine space tend to have less but larger muscle fibres at birth which are more susceptible to post-mortem pH decline and high drip loss; these factors are known to alter meat tenderness (Gondret *et al*., 2006). A study performed by Rehfeldt & Kuhn (2014) revealed that low-birth-weight pigs had the highest percentage of large fibres which was associated with poor meat quality. The loin tenderness was negatively correlated to fibre size (r = -0.34), consequently the low-birth-weight pigs had a lower loin tenderness score compared to heavier pigs at birth. As muscle development is restricted low-birth-weight pigs have a limited potential for muscular lean accretion, thus maximum muscle fibre hypertrophy is achieved earlier and energy obtained from the diet cannot be used for muscle growth but will be redirected to fat deposition (Nevrkla *et al*., 2017; Vázquez-Gómez *et al*., 2020). In the study performed by Pardo *et al*. (2013), the carcasses of low-birth-weight pigs compared to heavy-birth-weight pigs were fatter at slaughter due to the ratio of fat and muscle deposition being affected. They also determined that impaired feed efficiency demonstrated by low-birth-weight pigs in the grow-finishing period affects pork cuts, due to a greater amount of intramuscular fat present in the belly. Bérard *et al*. (2010) found that heavier pigs at birth had heavier hams and deposited less back fat compared to low-birth-weight pigs.

2.5 Nutrient requirements for growth

The amounts of nutrients animals require are often referred to as “feeding standards”. The term “nutrient requirements” is also used and is the average amount of nutrients required for a particular function by an animal (McDonald *et al*., 2011). According to Reese *et al*. (2000) specific factors (nutritional, environmental and managerial) (Figure 2.8) affect the nutrient requirements of animals and provide the framework for developing nutrient recommendations.

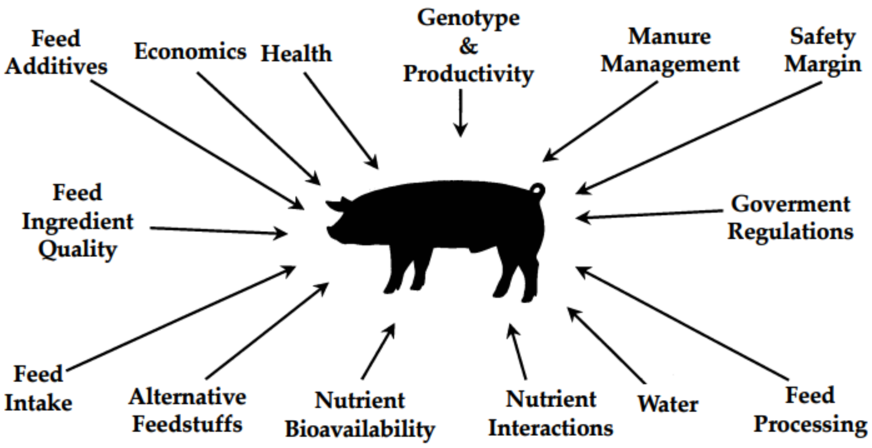

Figure 2. 8 Nutritional, environmental and managerial factors that are considered when developing nutrient recommendations (Reese *et al*., 2000)

Animals require nutrients for maintenance and growth. When an animal's body composition remains constant, and it doesn't give rise to a product or perform any work on its environment, an animal is in a state of maintenance (McDonald *et al*., 2011). Less productive animals use more of their energy intake for maintenance, and if an animal is deprived of food it draws on its energy reserves to meet its nutrient requirement for maintenance. Animal growth and nutrition are linked, the nutrient requirements of an animal is determined by its growth. Contrarily, altering nutrition can influence and modify the growth pattern of an animal (Hossner, 2005; McDonald *et al*., 2011). Ingredients used in diets provide nutrients for normal animal production. Pigs do not require specific ingredients in their diets, but rather require energy, amino acids, minerals, and vitamins (Reese *et al*., 2000). Optimal pig production relies on the accurate supply of energy and nutrients, as nutrient deficiencies can reduce animal performance. Knowledge on nutrient content and availability in feed ingredients is therefore important to meet animal requirements.

2.5.1 Energy

All biological processes in pigs rely on energy, even though it is not a nutrient, therefore a sufficient supply of energy in relation to other nutrients is essential for optimal pig production. The cost of feed ingredients that provide energy in the diet contribute the largest portion of total feed cost, and accurate estimation of energy requirements of the pig and feed energy values can reduce the costs of pig production (Kil *et al*., 2013). The original definition of energy is associated with the potential capacity to carry out work, but from a nutritional point of view, energy is evaluated as the oxidation of organic compounds (NRC, 2012). In growing pigs, the recommendations for adequate energy supply are based on a factorial approach that depends on estimates of the energy requirements for growth and maintenance (Naatjes & Susenbeth, 2014). The classical partitioning of feed energy is illustrated in Figure 2.9.

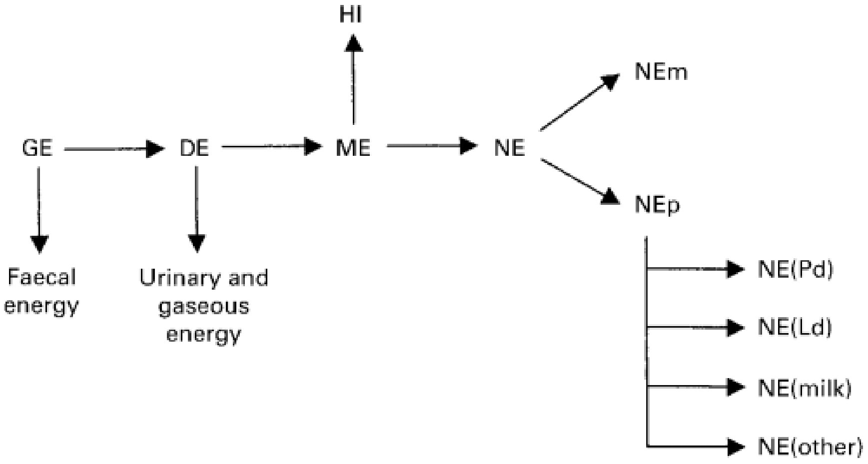

Figure 2. 9 Classical energy hierarchy. Digestible energy (DE) is gross energy intake (GE) less faecal losses; metabolizable energy (ME) is DE less urinary and gaseous losses; net energy (NE) is ME less heat increment of feeding (HI). NE can be further subdivided into net energy for maintenance (NEm) and products (NEp); NEp can be attributed to retained protein (Pd), retained lipid (Ld), milk, and other products. (Birkett & De Lange, 2001)

Gross energy (GE) is defined as the amount of heat arising from the complete oxidation of a unit weight of food (McDonald *et al*., 2011). Not all the GE in food is available for use in the animal, as some is lost in the form of solid, liquid, and gaseous excretions as well as heat. The subtraction of these losses from a food's GE content gives rise to further descriptive measures of food energy supply. The digestible energy (DE) is the energy absorbed by the animal and is calculated by subtracting the GE content of the faeces from the GE content of the feed. The faecal energy loss is the most important and variable loss of energy from animal feed; therefore, DE is a better measure of energy available to the animal to support production compared to GE (McDonald *et al*., 2011). Birkett & De Lange (2001) defined ME as the energy an animal can use which is supplied by the feed after accounting for faecal, gaseous, and urinary losses. Small amounts of gasses are produced by pigs and are thus ignored in the calculations of ME (Kil *et al*., 2013). Net energy (NE) provides a more precise prediction of body composition and growth performance of pigs and is thus the closest representative value of "true energy" for pigs. Net energy values are determined by subtracting the energy losses (heat increment) during metabolism of nutrients from ME (Kil *et al*., 2013).

2.5.2 Lysine

Proteins are polymers of amino acids, where the carboxyl group of one amino acid reacts with the amino group of another amino acid (NRC, 2012; Van Milgen & Dourmad, 2015). Amino acids are therefore the building blocks of protein, consisting of an amino group (-NH_2), a carboxyl group (-COOH), and a side chain specific to an amino acid (Van Milgen & Dourmad, 2015). In addition to the general requirement of protein, monogastric animals have a specific dietary requirement for essential amino acids (McDonald *et al*., 2011). The quality and efficiency of protein use in the pig depends on the digestibility and capability of protein to provide amino acids in the right amounts and proportions required by the pig (NRC, 2012; Van Milgen & Dourmad, 2015). Protein is an expensive nutrient in pig diets and the conversion of protein to tissue requires digestion, absorption, and postabsorptive metabolism of amino acids (NRC, 2012). Amino acids provided in excess will be deaminated and excreted in the urine, which is an energy expense for the animal, and it is therefore important to find a balance between amino acid supply and requirement (Van Milgen & Dourmad, 2015). Lysine, methionine, threonine, tryptophan, phenylalanine, histidine, isoleucine, and leucine are essential amino acids (Whittemore *et al*., 2001). These amino acids are indispensable or essential or because a pig does not have the metabolic capacity to synthesise the carbon chains of these amino acids to meet the demands for maintenance, growth, and reproduction (NRC, 2012; Van Milgen & Dourmad, 2015). In 1840, Von Liebig proposed the law of the minimum which was originally applied to plant growth. The concept states that by increasing the limiting nutrient (the nutrient most scarce in relation to the requirement of the plant), only then will the plant grow. This concept is now applicable to all organisms, including pigs, as a general model of limiting factors (Figure 2.10). Thus, an animal can only grow and utilise nutrients until the first nutrient becomes limiting. The first limiting amino acid in pig diets is typically lysine, and the other amino acids are expressed relative to the Lysine requirement (D'Mello, 2003; NRC, 2012; Van Milgen & Dourmad, 2015).

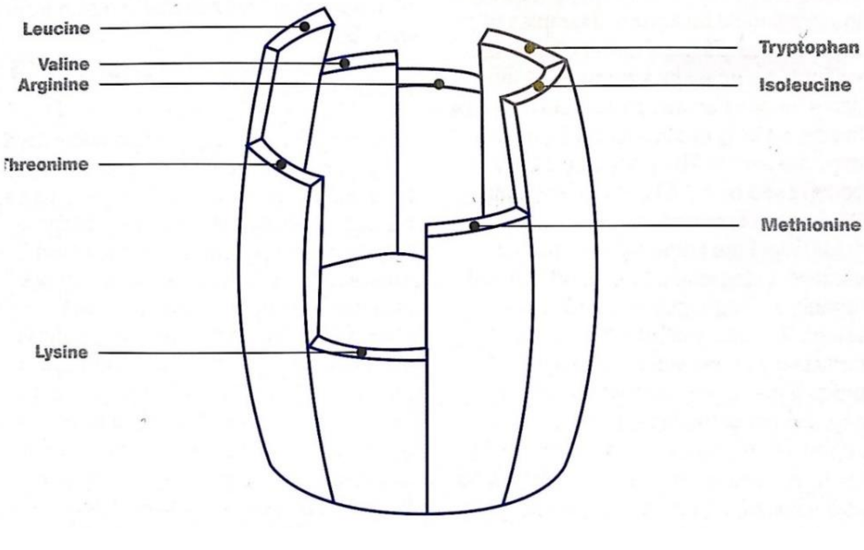

Figure 2. 10 Von Liebig's barrel analogy for amino acid balance where lysine is the first limiting amino acid (Kleyn, 2013)

To accurately formulate pig diets in terms of amino acid supply, it is essential that the amino acid availabilities of individual feed ingredients are determined (Nyachoti *et al*., 1997). To determine the true digestibility of protein, the contribution of nitrogen of endogenous origin and the contribution of nitrogen of the digesta must be considered. As digesta collected from the ileum may contain dietary undigested materials and endogenous protein and amino acids (Adeola *et al*., 2016). Endogenous nitrogen (EN) contains non-food substances entering the intestine and can be divided into two fractions, basal nitrogen (BN) and specific endogenous nitrogen (SN) (McDonald *et al*., 2011). Basal nitrogen is unrelated to the quantity and quality of protein and is only dependant on the quantity of dry matter passing though the gut, whereas SN is related to the quantity and quality of the dietary protein (Figure 2.11). The ileal digestibility of amino acids calculated without considering endogenous amino acid losses is defined as the apparent ileal digestibility (AID) (Adeola *et al*., 2016). The lack of additivity in ingredient mixes, within-ingredient variability, and overestimation of the actual amino acid availability are a few concerns about the use of AID of amino acids in feed formulation (Libao-Mercado *et al*., 2006). Some of these concerns can be overcome by using standardised ileal digestibility (SID) of amino acids instead. The SID values are obtained from AID by relating total ileal AA flow minus basal endogenous ileal AA losses to the dietary AA intake and is the preferred measure of amino acid digestibility in swine diets (Libao-Mercado *et al*., 2006; Adeola *et al*., 2016).

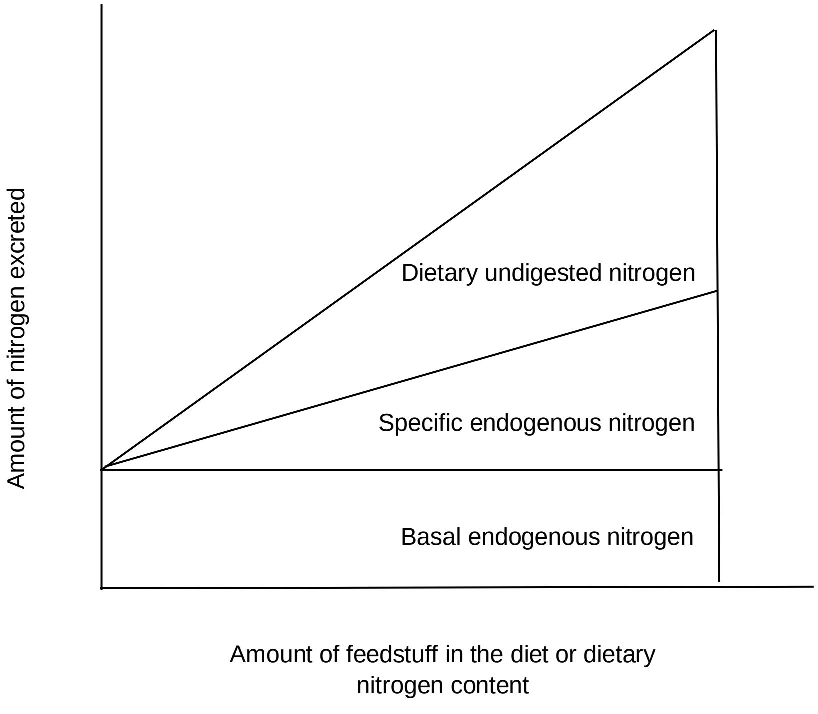

Figure 2. 11 Origin of excreted nitrogen (Adapted from McDonald *et al*., 2011)

2.5.3 Lysine: energy ratio

Pigs tend to consume feed until their energy requirements are satisfied, therefore the amount of energy in a diet influences the voluntary feed intake of pigs (Kil *et al*., 2013). Expressing amino acid requirements as a ratio to energy ensures that adequate amino acids are consumed (Oresanya *et al*.,2007; *Kil et al*., 2013). Growth of pigs depend on the lysine and energy supplied by the diet, and inadequate or excessive lysine to energy ratios negatively impact growth performance (Zhang *et al*., 2011). An increase in the supply of lysine will result in a linear increase of lean tissue growth until the maximum potential for lean tissue growth is obtained, only if sufficient energy is provided to the pig (Whittemore & Kyriazakis, 2006). Whereas a reduction of lysine in the diet is associated with a decreased growth rate and feed efficiency utilisation resulting in increased body fatness (Noblet *et al*., 1987). A study completed by Oresanya *et al*. (2007), determined that the growth rate of pigs increased as the lysine:DE ratio increased, due to the increase in amino acid supply at a level that supported optimal growth. Similar results were observed by Smith *et al*. (1999), where increased lysine:calorie ratios improved the average daily gain and feed conversion of pigs. Zhang *et al*. (2011) performed a study to investigate the effect of energy density and SID Lysine:NE ratio on the performance and carcass characteristics of growing and finishing pigs. Diets that contained excessive or inordinate levels of amino acids decreased protein utilisation and lean tissue deposition, similar results were obtained with excess or deficient energy in diets. They concluded that maximum lean tissue growth and minimum fat deposition will only be obtained if a diet is formulated with the appropriate lysine:energy ratio.

2.5.4 Nutrient requirements and birth weight

Low-birth-weight pigs exhibit reduced growth efficiency and greater fat deposition compared to heavier littermates. These traits are of economic importance and low-birth-weight pigs place efficient and successful commercial pig production at risk. Low-birth-weight pigs are on a different growth trajectory compared to their littermates (Douglas *et al*., 2014) and consequently different feeding strategies can be applied as an attempt to alleviate the poor production low-birth-weight pigs display during the grow-finishing phase.

Compensatory growth is a phenomenon in which animals that have been restricted in feed intake, and therefore growth rate, respond to *ad libitum* feeding with accelerated growth, compared to animals given feed *ad libitum* continuously (Therkildsen *et al*., 2002). It is proposed that this process is mediated by increased protein turnover (Lametsch *et al*., 2006). Studies have revealed that compensatory growth influences the deposition of lean and fat tissue deposition, thereby altering the carcass composition (Heyer & Lebret, 2007). In the pork industry compensatory growth can be explored to enhance pork production efficiency by improving carcass and meat quality, nutrient utilisation, reduce gut health problems due to excess protein intake, and to simplify feeding strategies (Martínez-Ramírez & De Lange, 2007). Martínez-Ramírez & De Lange (2007) determined that the rate and extent of compensatory growth is determined by genotype, energy and nutrient availability following the period of restricted feed intake. Furthermore, the extent of compensatory growth is restricted by the PDmax and is unlikely to occur in pigs with low lean tissue growth potential. Madsen & Bee (2015) investigated if a compensatory growth feeding strategy would be a suitable solution for alleviating the negative effects on growth and carcass composition of low-birth-weight pigs. Results of the study showed that low-birth-weight pigs had poorer feed efficiency and increased fat deposition in general, but the low-birth-weight pigs that were subject to restricted feeding prevented excessive fat accumulation on the carcass; therefore, restricting dietary energy intake could be a possible feeding strategy for low-birth-weight pigs. Metges *et al*. (2015) tested the effect of restricting feed for a 3-week period, followed by a refeeding period for 5-weeks, on fat deposition in low-birth-weight female pigs during the growth period. The results indicated that low-birth-weight pigs had higher amounts of subcutaneous fat at 11 weeks of age and more abdominal fat at 19 weeks of age, proposing that subcutaneous fat is laid down earlier compared to abdominal fat. Furthermore, low-birth-weight pigs subjected to feed restriction at 60% of the average DM intake of the control group, showed greater average daily gains, improved feed efficiency and less body fatness. It can be concluded that low-birth-weight pigs and normal-birth-weight pigs subject to restricted feeding showed similar changes in body composition, and low-birth-weight pigs did not deposit more fat during refeeding. Recent research suggests that low-birth-weight pigs can improve performance when provided with a better-quality feeding regime compared to a commercial feeding regime (Beaulieu *et al*., 2015). On this basis, Douglas *et al*. (2014) performed a study to determine whether a high specification starter regime and increased amounts of feed would have a positive effect on the performance of low-birth-weight pigs. The following conclusions were made, (i) feeding a high specification starter regime and providing more feed to low-birth-weight pigs will ensure that similar weaning weights are achieved compared to normal-birth-weight pigs, and (ii) separating low-birth-weight pigs at weaning will allow for feeding of an improved regime as heavier pigs at birth are suited to a commercial diet. Furthermore, by providing a high specification regime to low-birth-weight pigs maximum growth performance will be realised as well as increased profitability. These findings provided the basis for Douglas *et al*. (2014) to investigate if low-birth-weight pigs would benefit from consuming a higher nutrient specification diet (higher in amino acid:energy ratio) in a similar way to normal-birth-weight pigs previously subject to feed restriction, during the grower phase. The results suggested that a diet higher in amino acid:energy ratio in the grower phase did not improve the performance of low-birth-weight pigs, and the absence of this response could be because the lower nutrient specification diet provided met the nutrient requirements of the low-birth-weight pigs. Whereas normal-birth-weight pigs were able to display compensatory growth and were more efficient when fed a higher specification diet. Chen *et al*. (2016) hypothesised that low-birth-weight pigs have a higher energy requirement compared to normal-birth-weight pigs. Increasing the energy intake increases insulin-like growth factor I (IGF-I) in animals and that IGF-I signalling is compromised in low-birth-weight pigs resulting in decreased growth. Results suggested that although increased plasma IGF-I concentration and muscle mRNA expression of IGF-I was observed, the increase in growth of low-birth-weight pigs were modest and other nutrients might have limited growth. Impaired growth of low-birth-weight pigs are associated with impaired digestive development. A digestive system that is underdeveloped causes reduced digestive capacity which can lead to lower adaptation of post-weaning diets by limiting nutrient utilisation and intake in low-birth-weight pigs (Morise *et al*., 2007). Hawe *et al*. (2020) hypothesised that low-birth-weight pigs will have improved growth performance and carcass composition when diet transitions were carried out based on weight rather than transitioning diets at pre-determined intervals. Results indicated that low-birth-weight pigs have the physiological capacity to improve growth performance when a feeding regime customised to their weight and stage of development was offered, as they exhibited improved nutrient intake and liveweight at slaughter due to more time allowed for digestive development between diet changes.

Chapter 3

Materials and Methods

This research was approved by the Animal Ethics Committee of the University of Pretoria, reference number EC078-17.

3.1 Birth weight ranges

The low-birth-weight and heavy-birth-weight ranges were determined prior to the trial. At GHB Farms in Bronkhorstspruit South Africa, a total of nine hundred and sixty-four piglets born within one farrowing cycle were weighed at birth, or within 24 hours of birth, and the weights were recorded. The birth weights obtained were used to create a normal distribution curve (Figure 3.1).

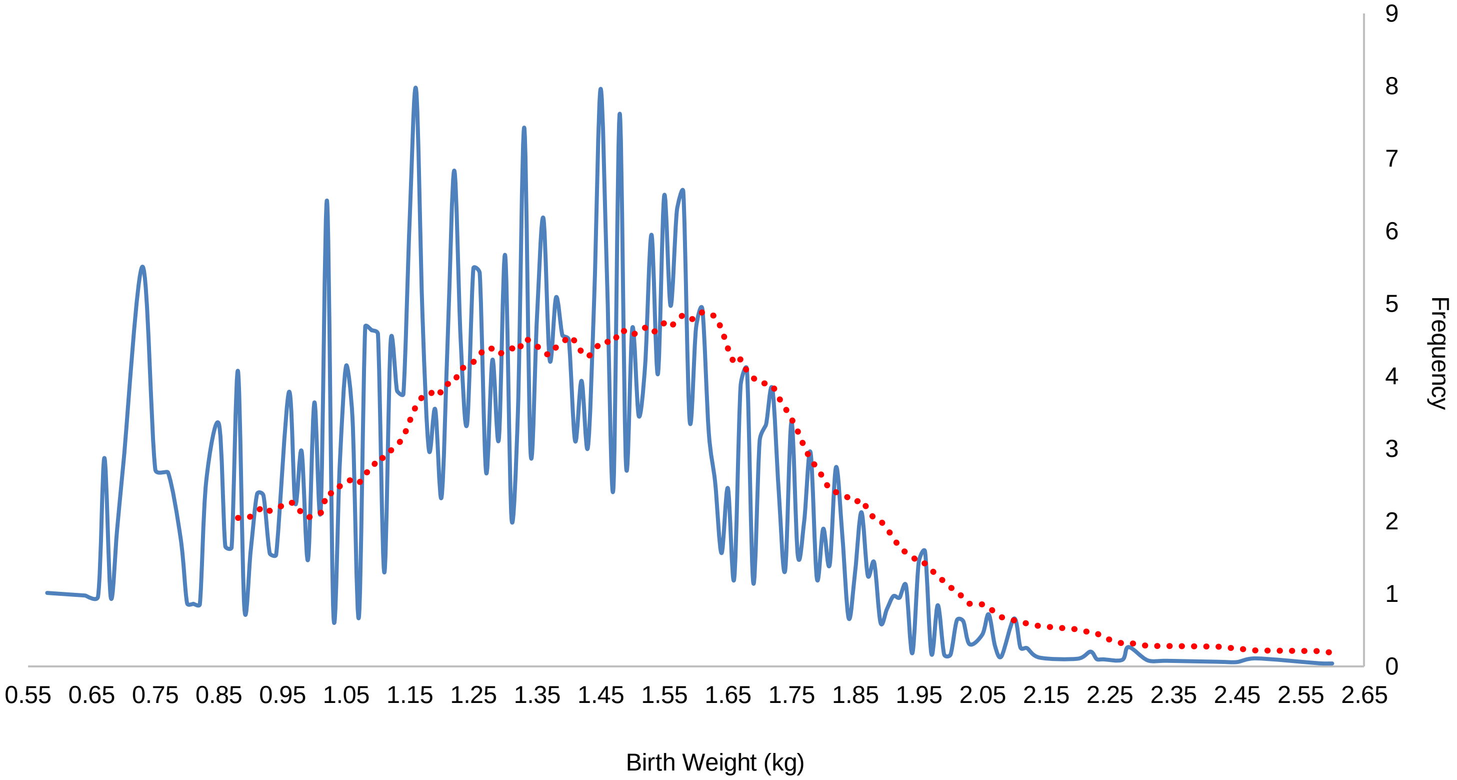

Figure 3. 1 Piglet birth weight distribution within one farrowing cycle

The normal distribution curve was used to determine the birth weight ranges that would be used for the trial. Piglets weighing between 0.9-1.2 kg were classified as low-birth-weight and piglets weighing between 1.7-2.0 kg were classified as heavy-birth-weight. The average piglet birth weight (around 1.5 kg) was not included within the respective ranges, as these piglets were classified as normal-birth-weight. Piglets that exhibited extreme weights established from the normal distribution (below 0.9 kg and above 2.0 kg) were also not included in the trial.

3.2 Sows and piglets

3.2.1 Facilities

A high level of biosecurity was maintained at GHB Farms. All persons entering the farm had to go through two control points. The first was a dry shower where clothes were substituted for overalls and gumboots used only on farm. Thereafter a minibus was used to transport workers and visitors to the site where each person had to take a shower and put on a new set of overalls and gumboots. A visitor’s sheet had to be completed to ensure that no person was in contact or had been around other pigs within three days prior to entering the site.

The farrowing houses were environmentally controlled, and sows were individually crated. Each crate was fitted with a water nipple, a single feeder trough and slatted floors. Each crate contained an infrared heating lamp as a heat source that provided a comfortable and warm environment for the piglets. Farrowing houses were cleaned twice a day, and disinfectant footbaths were provided upon entry and throughout the farrowing houses to prevent the spread of any diseases. Workers did not interfere during the farrowing process and only intervened, when necessary, thus providing a calm and natural environment. As piglets were born, the workers applied a disinfectant powder to the piglets to prevent disease and to dry the piglets.

3.2.2 Sows

Pigs used in the trial were offspring of TN60 sows inseminated with TN Tempo semen (Topigs Norsvin SA, Gauteng). Piglets selected for the trial were obtained from second parity sows, from a total of 20 litters. Sows were fed a standard lactation diet from the day of farrowing until weaning at 21 days-of-age.

3.2.3 Selection of piglets

Piglets selected for the trial were weighed individually and tagged within 24 hours of birth. Tags were provided by Topigs Norsvin SA and consisted of two colours, pink and blue. Numbers were printed on the tags to ensure ease of birth weight documentation. Piglets weighing between 0.9-1.2 kg were classified as low-birth-weight and pink tags were assigned, whereas piglets weighing between 1.7-2.0 kg were classified as heavy-birth-weight and blue tags were assigned. The tag number as well as the weight was recorded. Both male and female piglets were selected for the trial as not enough piglets were born of one sex in both birth weight classes. A total of 144 pigs were required for the trial, but more piglets were selected and tagged to account for pre-weaning mortality. After selection, piglets were subject to the management and environment of GHB Farms for the remainder of the lactation period.

3.2.4 Weaning and post-weaning facilities

Piglets were weaned at 21 days-of-age. A day prior to weaning, piglets were marked with two different markers on their backs by the farm workers, as male and female pigs were separated in the weaner houses. On the day of weaning, piglets were transported to the weaner site about 5 km from the breeding site. A high level of biosecurity was maintained at the weaner site of GHB Farms. All persons entering the site were required to shower and dress in overalls and gumboots provided. The pigs were housed in environmentally controlled houses that had fully slatted flooring. The weaner house was divided into two parts by feeders, to split the males and females from one another. Ample water nipples were provided throughout the weaner house. During this period, the pigs were fed commercial diets that consisted of a three-phase feeding regiment. The diets were formulated by a nutritionist and were specific to GHB Farms. As this trial was focused on the growing and finishing phases of production, the LBW and HBW weaner pigs were not treated differently. Therefore, the weaner pigs were subjected to the nutrition, environment, and management of GHB Farms in order to simulate a commercial setting and reduce variation. Generally, pigs would be transferred from the weaner site to the grower site at 70 days-of-age, at this point the growing and finishing phases of production would commence. A day before the transfer, a total of one hundred and forty-four pigs were randomly selected for the trial, consisting of seventy-two with a low-birth-weight and seventy-two pigs with a heavy-birth-weight. Of the seventy-two low-birth-weight pigs, thirty-six were male and thirty-six female. The seventy-two heavy-birth-weight pigs were also equally divided into male and female. The selected pigs were loaded onto a truck and transferred to the experimental farm at the University of Pretoria.

3.3 Trial facilities

The trial commenced on 28 February 2017 and continued until 16 May 2017 at the experimental farm of the University of Pretoria. The pig house contained 58 pens, but only 48 of the 58 pens were used. The pens were 3.5 m^2 and three pigs were placed at a stocking density of 1.17 m^2/pig. Each pen was fitted with a water nipple, a single feeder trough (CAWI feeder) and partially slatted concrete floors. The environment of the pig house was closely controlled, and pigs were protected from the elements in a satisfactory manner. Adequate ventilation of the pig house was maintained by three fans, two smaller fans that remained operational throughout the day and one large fan that turned on automatically when the temperature of the house exceeded 23°C. The house was fitted with windows on each side which remained open during the day and closed at a suitable level during the night. The entire pig house was thoroughly washed and disinfected before the arrival of the pigs.

An adequate level of biosecurity was maintained throughout the trial to ensure a high level of health among the pigs for the duration of the trial. No unauthorised persons were allowed to enter the facility, and all entrances were locked to prevent unwanted entries. Footbaths containing disinfectant was provided upon entry of the facility and throughout the pig house. All persons entering the facility had to change into gumboots provided that were only used in the confines of the house and were forbidden to enter if they have been in contact with domesticated or wild pigs three days prior.

Metal chains were hung between each pen so that pigs could play with the chains to alleviate boredom and prevent negative behaviours like tail biting and aggression.

3.4 Trial animals

One hundred and forty-four pigs were sourced from GHB Farms in Bronkhorstspruit, South Africa. The genetic line used for the trial was obtained by crossing TN60 sows and TN Tempo boars. Pigs were transferred to the experimental farm at 70 days-of-age and continued in the trial for 11 weeks until slaughter at 21 weeks (147 days) of age. Upon arrival pigs were weighed individually and were allocated to a pen based on their 70-day weight, birth weight and sex. Pigs with similar 70-day weights and within the same birth weight group were placed together in a pen. Males and females were not grouped together in a pen; however, males and females were evenly distributed through the facility. Feed and water were provided *ad libitum* and pigs were checked on twice a day. The pens were cleaned three days a week to remove solid waste and the waste draining system was flushed on a weekly basis with clean water. Pigs were weighed and feed intake was determined once a week. A consulting veterinarian was available during the trial to ensure humane treatment of the pigs.

3.5 Experimental design and dietary treatments

A total of 48 pens were used, with three pigs per pen, providing four replicates per treatment. Each pen represented an experimental unit and was allocated to treatments following a complete randomised block design with three feed treatments (control, high SID lysine, and SID low lysine), each combined with either low-birth-weight or heavy-birth-weight pigs, as well as male and female animals. The house was divided into four blocks with one replicate per treatment in each block to account for variation, thereby ensuring that all differences observed were due to differences between treatments.

Three maize-soybean meal based diets were fed during the trial, consisting of a control (CON), high SID lysine (HL) and low SID lysine (LL). The control diet was formulated based on the recommended levels of the Feeding Manual for Topigs Norsvin Finishers (2012), representative of standard commercial diets. The SID lysine levels were either increased (high SID lysine diet) or decreased (low SID lysine diet) with 10% based on the control SID lysine level. The energy level between treatments remained constant within each feeding phase (starter, grower, and finisher). The CON, HL and LL diets within the starter phase had an energy level of 9.87 MJ NE/kg, while the CON, HL and LL diets within the grower phase had an energy level of 9.74 MJ NE/kg and, finally, the energy level of the CON, HL and LL diets within the finisher phase were 9.67 MJ NE/kg. Thus, the diets were iso-caloric for each feeding phase; therefore, SID lysine was the only variable between the three-phase treatment diets. The ratio of the other essential amino acids relative to lysine was kept constant and according to the Feeding Manual for Topigs Norsvin Finishers (2012). The three-phase feeding regiment included a starter phase (Table 3.1), grower phase (Table 3.2) and a finisher phase (Table 3.3). The three-phase diet programme was followed from 70 days-of-age until 147 days-of-age. The starter diet was fed from 70 to 91 days-of-age, the grower was fed from 92 days to 119 days-of-age and the finisher was fed for the remaining days, from 120 to 147 days-of-age. The trial was run for a total of 11 weeks (77 days).

The diets contained no organic acids, antibiotics, or enzymes. All feeds were produced at Simplegrow Agric Services (Knoppieslaagte, Centurion, South Africa) and all feeds were provided in pellet form.

Table 3. 1 Formulated net energy (NE) and standardised ileal digestible (SID) lysine levels and Lys: NE of experimental diets (as fed) during the starter phase

Diet*	NE (MJ/kg)	SID Lysine (g/kg)	SID Lys: NE
CON	9.87	10.60	1.07
HL	9.87	11.66	1.18
LL	9.87	9.54	0.97

***** CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

Table 3. 2 Formulated net energy (NE) and standardised ileal digestible (SID) lysine levels and Lys: NE of experimental diets (as fed) during the grower phase

Diet*	NE (MJ/kg)	SID Lysine (g/kg)	SID Lys: NE
CON	9.74	9.00	0.92
HL	9.74	9.90	1.02
LL	9.74	8.10	0.83

***** CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

Table 3. 3 Formulated net energy (NE) and standardised ileal digestible (SID) lysine levels and Lys: NE of experimental diets (as fed) during the finisher phase

Diet*	NE (MJ/kg)	SID Lysine (g/kg)	SID Lys: NE
CON	9.67	7.60	0.79
HL	9.67	8.36	0.86
LL	9.67	6.84	0.71

***** CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

The complete ingredient list and nutrient composition for the starter, grower and finisher diets can be found in Table 3.4, Table 3.5, and Table 3.6.

Table 3. 4 Formulated raw material and nutrient composition (g/kg on 'as is' basis) of the starter diets

Ingredient (%)	**CON$^{\$}$**	**HL$^{\$}$**	**LL$^{\$}$**
Maize	66.70	62.00	68.80
Soya Oilcake	21.30	25.60	19.60
Soya Oil	1.10	1.50	0.90
Wheat Bran	5.00	5.00	5.00
Sunflower Oilcake	2.00	2.00	2.00
Limestone	1.13	1.13	1.13
Monocalcium Phosphate	1.03	1.00	1.03
Salt	0.42	0.42	0.42
Sodium Bicarbonate	0.10	0.10	0.10
Lysine	0.45	0.44	0.36
Threonine	0.16	0.18	0.12
DL - Methionine	0.15	0.17	0.10
Tryptophan	0.06	0.06	0.04
Premix	0.40	0.40	0.40
Nutrient (g/kg)			
Crude Protein	172.00	189.00	165.00
Crude Fat	35.00	39.00	34.00
Crude Fibre	33.00	33.00	33.00
Sodium	2.00	2.00	2.00
Total Phosphorus	6.30	6.30	6.30
Available Phosphorus	3.00	3.00	3.00
Calcium	7.00	7.00	7.00
Net Energy (MJ/kg)	9.87	9.87	9.87
SID Lysine	10.60	11.66	9.54
SID Lysine/ Net Energy	1.07	1.18	0.97
SID Met	4.00	4.70	3.30
SID Met + Cys	6.30	6.90	5.70
SID Thr	6.80	7.50	6.20
SID Trp	2.10	2.30	1.90
SID Met/ SID Lys	0.35	0.35	0.35
SID Met + Cys/ SID Lys	0.60	0.60	0.60
SID Thr/ SID Lys	0.65	0.65	0.65
SID Trp/ SID Lys	0.20	0.20	0.20

*SID = Standard Ileal Digestible

$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

Table 3. 5 Formulated raw material and nutrient composition (g/kg on ‘as is’ basis) of the grower diets

Ingredient (%)	**CON$^{\$}$**	**HL$^{\$}$**	**LL$^{\$}$**
Maize	71.20	68.40	71.20
Soya Oilcake	12.60	16.10	13.20
Soya Oil	0.50	0.70	0.50
Wheat Bran	7.00	6.00	6.70
Sunflower Oilcake	5.00	5.00	5.00
Limestone	1.05	1.05	1.05
Monocalcium Phosphate	1.00	1.00	1.00
Salt	0.37	0.37	0.37
Sodium Bicarbonate	0.10	0.10	0.10
Lysine	0.46	0.49	0.30
Threonine	0.16	0.19	0.10
DL - Methionine	0.12	0.15	0.06
Tryptophan	0.04	0.05	0.02
Premix	0.40	0.40	0.40
Nutrient (g/kg)			
Crude Protein	150.00	163.00	150.00
Crude Fat	30.00	32.00	30.00
Crude Fibre	39.00	39.00	39.00
Sodium	1.80	1.80	1.80
Total Phosphorus	6.30	6.30	6.30
Available Phosphorus	2.80	2.80	2.80
Calcium	6.50	6.50	6.50
Net Energy (MJ/kg)	9.74	9.74	9.74
SID Lysine	9.00	9.90	8.10
SID Lysine/ Net Energy	0.92	1.02	0.83
SID Met	3.40	4.00	2.80
SID Met + Cys	5.50	6.10	5.00
SID Thr	6.00	6.60	5.40
SID Trp	1.70	1.80	1.50
SID Met/ SID Lys	0.35	0.35	0.35
SID Met + Cys/ SID Lys	0.62	0.62	0.62
SID Thr/ SID Lys	0.67	0.67	0.67
SID Trp/ SID Lys	0.19	0.19	0.19

*SID = Standard Ileal Digestible

$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

Table 3. 6 Formulated raw material and nutrient composition (g/kg on 'as is' basis) of the finisher diets

Ingredient (%)	**CON**$^{\$}$	**HL**$^{\$}$	**LL**$^{\$}$
Maize	70.60	70.70	70.70
Soya Oilcake	9.50	9.10	10.00
Soya Oil	0.50	0.50	0.50
Wheat Bran	11.00	11.10	10.70
Sunflower Oilcake	5.00	5.00	5.00
Limestone	1.02	1.00	1.00
Monocalcium Phosphate	0.90	0.90	0.90
Salt	0.37	0.37	0.37
Sodium Bicarbonate	0.10	0.10	0.10
Lysine	0.37	0.47	0.23
Threonine	0.14	0.20	0.07
DL - Methionine	0.07	0.12	0.02
Tryptophan	0.03	0.04	0.01
Premix	0.40	0.40	0.40
Nutrient (g/kg)			
Crude Protein	140.00	140.00	140.00
Crude Fat	31.00	31.00	31.00
Crude Fibre	42.00	42.00	42.00
Sodium	1.80	1.80	1.80
Total Phosphorus	6.30	6.30	6.30
Available Phosphorus	2.60	2.60	2.60
Calcium	6.00	6.00	6.00
Net Energy (MJ/kg)	9.67	9.67	9.67
SID Lysine	7.60	8.36	6.84
SID Lysine/ Net Energy	0.79	0.86	0.71
SID Met	2.80	3.30	2.30
SID Met + Cys	4.80	5.30	4.40
SID Thr	5.30	5.80	4.70
SID Trp	1.40	1.50	1.30
SID Met/ SID Lys	0.35	0.35	0.35
SID Met + Cys/ SID Lys	0.64	0.64	0.64
SID Thr/ SID Lys	0.70	0.70	0.70
SID Trp/ SID Lys	0.19	0.19	0.19

*SID = Standard Ileal Digestible

$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

3.6 Animal husbandry and data collection

Prior to the arrival of the pigs the feed was weighed out into individual buckets with the respective treatment number labelled on the bucket. The pens were allocated to a specific treatment and the weighed-out feed was then placed into the CAWI feeder within the pen. Each water nipple was thoroughly checked to ensure that the pigs had access to water. Upon arrival at the experimental farm, the pigs were individually weighed to determine the start weight. The animal scale used to weigh the pigs had been calibrated before the arrival of the pigs and was in working order. There was no need to tag pigs, as the tags used during initial selection of the pigs at birth were still in place. After the pigs were allocated to the respective pens, the pigs were left alone in order to minimise any further stress.

Pigs were weighed on a weekly basis which commenced one week after the arrival of the pigs. Body weight gain over the seven-day period was divided by seven to calculate the average daily gain. The weekly feed intake was determined by weighing the left-over feed within the CAWI feeders and subtracting it from the feed made available during the week. The left-over feed was weighed on the same day the pigs were weighed. These figures were used to determine the feed conversion ratio (FCR). Each pen was considered an experimental unit, therefore the growth performance parameters of the three pigs in the pen were averaged and these values were used to determine the results for the experiment.

Feed conversion ratio was calculated per pen (experimental unit) as follow:

$$FCR = \frac{Feed\ (kg)\ consumed\ by\ pen\ for\ week\ x}{Total\ weight\ gain\ (kg)\ of\ pen\ for\ week\ x}$$

Each growth performance parameter (average daily gain, weekly feed intake, and feed conversion ratio) was also determined per phase (starter, grower, and finisher) and over the experimental period.

3.7 Carcass data

Pigs were slaughtered at Eskort Abattoir in Heidelberg, South Africa. Prior to the slaughter of the animals, pigs were slap-marked for carcass identification as the pig heads were removed from the carcasses at the abattoir and the tags would not have been a sufficient form of identification. Pigs were slap-marked on the right buttock using a slap-marker and ink. Each pig was slapped firmly and evenly, ensuring that no harm was done to the pigs in the process. The slap-marker was cleaned thoroughly with soap and water to avoid any contamination between animals. No pins on the characters were incomplete, bent, or damaged.

The data received from the abattoir provided the following information on each carcass:

- Serial number,
- Description (grading of the carcass according to the PORCUS classification system),
- Warm carcass mass in kilograms (WCM),
- Cold carcass mass in kilograms (CCM, calculated at 97% of the WCM),
- Backfat thickness in millimetres (Fat) measured at the point 45 mm lateral from the carcass midline between the 2nd and 3rd last rib with a Hennessey grading probe ®,
- Lean meat % (Meat %) determined by the abattoir using the following equation: *Lean meat percentage = 72.5114 – (0.4618 x fat thickness (mm)) + (0.0547 x muscle thickness) as estimated with the Hennessey grading probe* ® and,
- Gender.

At slaughter, the pigs were stunned using an electric stunner to render the animals unconscious, this ensured that the pigs felt no pain. Thereafter, the throat was cut within 20 seconds to ensure sufficient bleeding. Animals then entered a hot water bath, and thereafter a dehairing machine. Pig heads were then removed, carcasses were washed, and the viscera removed. The warm carcass mass (WCM, kg) was measured on the moving slaughter line with a scale, at the same point where the classifier used the Hennessey grading probe ® to identify the backfat measurements. After the fat (mm) measurements were established, the lean meat % was determined by using the equation stated above. All measurements taken at this point, along with the information stated above were recorded on the computer system. Thereafter, tags were printed containing the serial number along with the description and producer, and these tags were applied to the carcass. Duplicate tags were provided upon which the slap number was written for the trial identification purposes. The carcasses were then moved to the cold room, the cold carcass mass (CCM, kg) was not measured again, as the standard practice at Eskort Abattoir was to deduct 3% from the WCM. The data was received in PDF format from Eskort Abattoir.

3.8 Statistical analysis

The experiment consisted of a 3x2x2 factorial design including three feed treatments (control, high lysine, and low lysine) each combined with low-birth-weight or heavy-birth-weight pigs, as well as male and female animals. Each pen represented an experimental unit and was allocated treatments using a complete randomised block design. The experimental pig house was divided into four equal blocks; therefore, the data was blocked into four blocks. Each block consisted of 12 pens each, thus one replicate per block. There were no significant differences ($P > 0.05$) between the blocks for any of the parameters measured. Data was statistically analysed with the GLM model (Statistical Analysis System, 2019) for the average effects over time. Repeated Measures Analysis of Variance with the GLM model was used for repeated period measures. Means and standard error were calculated and significance of difference ($P<0.05$) between means was determined by Fischer’s test (Samuels, 1989).

The linear model used is described by the following equation:

$$Y_{ijkl} = \mu + T_i + G_j + S_k + B_l + TG_{ij} + TS_{ik} + GS_{jk} + TGS_{ijk} + e_{ijkl}$$

Where Y_{ijkl} = variable studied during the period
μ = overall mean of the population
T_i = effect of the i^{th} treatment (CON, HL, LL)
G_j = effect of the j^{th} the group (Birth Weight)
S_k = effect of the k^{th} the sex (Male and Female)
B_l = effect of the l^{th} the block
TG_{ij} = effect of the ij^{th} interaction between treatment and group
TS_{ik} = effect of the ik^{th} interaction between treatment and sex
GS_{jk} = effect of the jk^{th} interaction between group and sex
TGS_{ijk} = effect of the ijk^{th} the interaction between treatment, group, and sex
e_{ijkl} = error associated with each Y

Chapter 4

Results

4.1 Growth performance parameters and carcass data over the experimental period

There were three mortalities during the trial, and all growth performance data as well as carcass data accounted for the mortalities.

Table 4.1 summarises the effect of birth weight on growth performance parameters and carcass data over the entire grow-finishing period. Birth weight had a significant effect on the start weight of the trial, with heavy-birth-weight (HBW) pigs having higher ($P < 0.05$) start weights compared to low-birth-weight (LBW) pigs. HBW pigs were also significantly heavier ($P < 0.05$) at the end of the trial than LBW pigs. In addition, the average daily gain (ADG) was also significantly higher ($P < 0.05$) in HBW pigs compared to LWB pigs. However, birth weight had no significant ($P > 0.05$) effect on average daily feed intake (ADFI) and feed conversion ratio (FCR). Birth weight had significant effects on warm carcass mass (WCM) and cold carcass mass (CCM), as HBW pigs had significantly ($P < 0.05$) higher WCM and CCM; but birth weight did not have a significant ($P > 0.05$) effect on Lean Meat %. It can be deduced from Table 4.2 that diet (control, high lysine and low lysine) did not have any significant ($P > 0.05$) effect on growth performance parameters and carcass data over the experimental period. Sex had significant effects on ADFI and FCR (Table 4.3), where females had significantly ($P < 0.05$) higher ADFI and FCR compared to males. No other significant ($P > 0.05$) effects were observed between males and females.

Table 4. 1 The effect of birth weight on growth performance parameters and carcass data over the experimental period

	Birth Weight		
	HBW*	LBW$^{\$}$	SEM$^{\#}$
Start weight (70-day weight, kg)	25.26^{a}	19.37^{b}	0.684
End weight (slaughter weight, kg)	109.35^{a}	97.82^{b}	1.402
Average daily gain (ADG, kg/day)	1.09^{a}	1.02^{b}	0.014
Average daily feed intake (ADFI, kg/day)	2.57	2.40	0.060
Feed conversion ratio (FCR)	2.40	2.38	0.044
Warm carcass mass (WCM, kg)	86.36^{a}	76.93^{b}	1.227
Cold carcass mass (CCM, kg)	83.77^{a}	74.63^{b}	1.191
Backfat thickness (mm)	14.02^{a}	13.27^{b}	0.244
Lean meat %	68.48	68.63	0.112

^{ab} Row means with different superscripts differ significantly ($P<0.05$)
*HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth
$^{\$}$LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth
$^{\#}$SEM: Standard error of the mean

Table 4. 2 The effect of feed treatment on growth performance parameters and carcass data over the experimental period

	Feed Treatment*			
	CON	HL	LL	SEM[#]
Start weight (70-day weight, kg)	22.35	21.77	22.82	0.838
End weight (slaughter weight, kg)	104.56	102.85	103.33	1.717
Average daily gain (ADG, kg/day)	1.07	1.05	1.05	0.017
Average daily feed intake (ADFI, kg/day)	2.44	2.52	2.49	0.073
Feed conversion ratio (FCR)	2.33	2.43	2.41	0.054
Warm carcass mass (WCM, kg)	81.88	81.55	81.51	1.503
Cold carcass mass (CCM, kg)	79.42	79.10	79.07	1.459
Backfat thickness (mm)	13.89	13.36	13.68	0.299
Lean meat %	68.47	68.71	68.49	0.138

*****CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

[#]SEM: Standard error of the mean

Table 4. 3 The effect sex on growth performance parameters and carcass data over the experimental period

	Sex		
	Female	Male	SEM[#]
Start weight (70-day weight, kg)	22.43	22.20	0.684
End weight (slaughter weight, kg)	104.01	103.15	1.402
Average daily gain (ADG, kg/day)	1.06	1.05	0.014
Average daily feed intake (ADFI, kg/day)	2.60^{a}	2.37^{b}	0.060
Feed conversion ratio (FCR)	2.49^{a}	2.29^{b}	0.040
Warm carcass mass (WCM, kg)	82.82	80.47	1.227
Cold carcass mass (CCM, kg)	80.34	78.06	1.191
Backfat thickness (mm)	13.93	13.35	0.244
Lean meat %	68.52	68.60	0.112

^{ab} Row means with different superscripts differ significantly ($P<0.05$)

[#]SEM: Standard error of the mean

4.2 Growth performance parameters per period

Growth performance parameters include start weight (70-day weight, kg), end weight (slaughter weight, kg), average daily gain (ADG, kg/day), average daily feed intake (ADFI, kg/day) and feed conversion ratio (FCR). The starter, grower and finisher phases were from 70 to 91 days-of-age (22 to 41 kg live weight), 92 to 119 days-of-age (42 to 71 kg live weight) and 120 to 147 days-of-age (72 to 104 kg live weight), respectively.

4.2.1 The effect of birth weight and feed treatment on growth performance parameters per period

Table 4.4 and Table 4.5 summarise the results of the interaction between birth weight and feed treatment for body weight at the beginning (Table 4.4) and end (Table 4.5) of the starter grower and finisher phases. Furthermore, Table 4.6 to Table 4.8 summarise the results of the interaction between birth weight and feed treatment for ADG (Table 4.6), ADFI (Table 4.7) and FCR (Table 4.8) for each phase (starter, grower, and finisher) and the entire experimental period.

As shown in Table 4.4, there were no significant ($P > 0.05$) differences in body weight at the beginning of the starter, grower, and finisher phases within the HBW and LBW groups. Therefore, feed treatment had no significant ($P > 0.05$) effect within HBW, and LBW groups on body weight at the start of each production phase. However, the HBW group was significantly ($P < 0.05$) heavier than the LBW group at the start of each phase. The heaviest start weight for the LBW group for each phase was observed when the CON diet was fed, whereas the HBW group fed the HL diet experienced the heaviest start weights for the starter phase, and the grower and finisher phases when the LL diet was fed.

It can be deduced from Table 4.5 that the HBW pigs were significantly ($P < 0.05$) heavier than the LBW pigs at the end of the starter, grower, and finisher phases for each feed treatment presented. HBW pigs were therefore significantly ($P < 0.05$) heavier than LBW pigs at the end of the trial. There were no significant ($P > 0.05$) differences in body weight at the end of the starter, grower, and finisher phases within the HBW and LBW groups. Therefore, feed treatment had no effect on body weight at the end of all production phases within the HBW and LBW groups. The heaviest body weights at the end of the experimental period were observed when the LL diet was fed to the HBW pigs. LBW pigs had the heaviest body weights at the end of the experimental period when the CON diet was fed.

It can be concluded from Table 4.4 and Table 4.5 that HBW pigs were significantly ($P < 0.05$) heavier than LBW pigs throughout the trial and that dietary SID lysine concentration of diets had no effect on body weight.

Table 4. 4 The effect of piglet birth weight and feed treatment on body weight (kg) at the beginning of the starter, grower, and finisher phases (± standard error of the mean)

	Birth Weight*		
Feed Treatment$^{\$}$	HBW	LBW	Mean
Starter Phase (70 days-of-age)			
CON	24.33^{a} (±1.19)	20.38^{b} (±1.19)	22.35 (±0.84)
HL	25.88^{a} (±1.19)	17.67^{b} (±1.19)	21.77 (±0.84)
LL	25.58^{a} (±1.19)	20.06^{b} (±1.19)	22.82 (±0.84)
Mean	25.26^{a} (±0.68)	19.37^{b} (±0.68)	
Grower Phase (92 days-of-age)			
CON	50.60^{a} (±1.90)	45.04^{b} (±1.90)	47.82 (±1.34)
HL	52.71^{a} (±1.90)	41.92^{b} (±1.90)	47.31 (±1.34)
LL	53.00^{a} (±1.90)	43.85^{b} (±1.90)	48.43 (±1.34)
Mean	52.10^{a} (±1.09)	43.60^{b} (±1.09)	
Finisher Phase (120 days-of-age)			
CON	82.75^{a} (±2.14)	75.88^{b} (±2.14)	79.31 (±1.52)
HL	84.79^{a} (±2.14)	72.54^{b} (±2.14)	78.67 (±1.52)
LL	85.17^{a} (±2.14)	72.23^{b} (±2.14)	78.70 (±1.52)
Mean	84.24^{a} (±1.24)	73.55^{b} (±1.24)	

^{ab} Row means with different superscripts differ significantly (P<0.05)

*HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

Table 4. 5 The effect of piglet birth weight and feed treatment on body weight (kg) at the end of the starter, grower, and finisher phases (± standard error of the mean)

	Birth Weight*		
Feed Treatment$^{\$}$	HBW	LBW	Mean
Starter Phase (91 days-of-age)			
CON	50.60^a (±1.90)	45.04^b (±1.90)	47.82 (±1.34)
HL	52.71^a (±1.90)	41.92^b (±1.90)	47.31 (±1.34)
LL	53.00^a (±1.90)	43.85^b (±1.90)	48.43 (±1.34)
Mean	52.10^a (±1.09)	43.60^b (±1.09)	
Grower Phase (119 days-of-age)			
CON	82.75^a (±2.14)	75.88^b (±2.14)	79.31 (±1.52)
HL	84.79^a (±2.14)	72.54^b (±2.14)	78.67 (±1.52)
LL	85.17^a (±2.14)	72.23^b (±2.14)	78.70 (±1.52)
Mean	84.24^a (±1.24)	73.55^b (±1.24)	
Finisher Phase (147 days-of-age)			
CON	108.54^a (±2.43)	100.58^b (±2.43)	104.56 (±1.72)
HL	108.50^a (±2.43)	97.21^b (±2.43)	102.85 (±1.72)
LL	111.00^a (±2.43)	95.67^b (±2.43)	103.33 (±1.72)
Mean	109.34^a (±1.40)	97.82^b (±1.40)	

^{ab} Row means with different superscripts differ significantly (P<0.05)

*HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

The LL feed treatment had a significant ($P < 0.05$) effect on ADG during the starter, grower, and finisher phases between the HBW and LBW groups, where HBW pigs had higher ADGs compared to LBW pigs (Table 4.6). No significant ($P > 0.05$) differences were observed for feed treatments CON and HL on ADG between the HBW and LBW groups during the starter, grower, and finisher phases. HBW pigs had a significantly ($P < 0.05$) higher ADG during the starter and grower phase compared to LBW pigs, however during the finisher phase HBW did not have a significantly ($P > 0.05$) higher ADG than LBW pigs. Throughout the experimental period, HBW that received the LL treatment had significantly ($P < 0.05$) higher ADG compared to LBW pigs that received the LL treatment. The highest ADG was observed for the CON treatment, whereas identical ADGs were observed for the HL and LL treatments. The highest ADG was observed for HBW pigs that were fed the LL treatment. LBW pigs subject to the LL treatment had the lowest ADG, however, LBW pigs experienced the highest ADG when given the CON treatment. HBW pigs had significantly ($P < 0.05$) higher ADGs throughout the experimental period compared to LBW pigs.

Table 4.7 shows the effect of birth weight and feed treatment on daily feed intake (kg/day) for the starter, grower, and finisher phases, as well as the experimental period. During the starter phase, HL and LL feed treatments had significant (*P* < 0.05) effects on DFI between the HBW and LBW groups, where the HBW group had a higher DFI compared to the LBW group. No significant (*P* > 0.05) differences were observed for the CON treatment during the starter phase. HBW pigs had significantly (*P* < 0.05) higher DFI than LBW pigs during the starter phase. During the grower and finisher phases, the LL treatment had significant (*P* < 0.05) effects on DFI, HBW pigs had higher DFIs in comparison to the LBW pigs. In addition, significant (*P* < 0.05) differences within HBW and LBW groups were observed during the finisher phase. HBW pigs consuming the LL treatment had a significantly (*P* < 0.05) higher DFI compared to HBW pigs that were fed the CON treatment. Whereas LBW consuming the LL treatment had a significantly (*P* < 0.05) lower DFI compared to LBW pigs that received the HL treatment. During the experimental period the highest and lowest DFIs were observed for the HL and CON treatments respectively. HBW pigs had the highest DFI when fed the LL treatment, contrarily LBW pigs had the lowest DFI upon receiving the LL treatment. Therefore, the LL treatment had a significant (*P* < 0.05) effect on DFI, as the HBW group had a higher DFI than the LBW group. HBW pigs had higher DFIs compared to LBW pigs during the experimental period.

No significant (*P* > 0.05) differences for FCR were observed during the starter and grower phases (Table 4.8). However, during the finisher phase, significant (*P* < 0.05) differences within the LBW group and between feed treatments were noted. LBW pigs that received the LL feed treatment had significantly (*P* < 0.05) lower FCRs compared to LBW pigs that were fed the HL treatment. Between feed treatments, pigs that were fed the CON treatment had significantly (*P* < 0.05) lower FCRs compared to pigs that received the HL treatment. No significant (*P* > 0.05) differences between birth weight and feed treatment were observed for FCR throughout the entire experimental period. However, the lowest and highest FCRs were observed for the CON and HL treatments respectively. HBW pigs had the lowest FCR when fed the CON diet and the highest FCRs when receiving the LL treatment. In contrast, LBW had the lowest FCR for the LL treatment and experienced the highest FCR when fed the HL treatment. During the experimental period, HBW pigs had higher FCRs compared to LBW pigs.

Table 4. 6 The effect of piglet birth weight and feed treatment on average daily gain (kg/day) for the starter, grower, and finisher phases, and the entire experimental period (± standard error of the mean)

Feed Treatment$^{\$}$	Birth Weight* HBW	LBW	Mean
Starter Phase (70 to 91 days-of-age)			
CON	0.95 (±0.04)	0.87 (±0.04)	0.91 (±0.03)
HL	0.95 (±0.04)	0.84 (±0.04)	0.90 (±0.03)
LL	1.01^{a} (±0.04)	0.84^{b} (±0.04)	0.92 (±0.03)
Mean	0.97^{a} (±0.02)	0.85^{b} (±0.02)	
Grower Phase (92 to 119 days-of-age)			
CON	1.08 (±0.04)	1.03 (±0.04)	1.06 (±0.02)
HL	1.09 (±0.04)	1.03 (±0.04)	1.06 (±0.02)
LL	1.06^{a} (±0.04)	0.98^{b} (±0.04)	1.02 (±0.02)
Mean	1.07^{a} (±0.01)	1.02^{b} (±0.01)	
Finisher Phase (120 to 147 days-of-age)			
CON	1.22 (±0.04)	1.18 (±0.04)	1.12 (±0.03)
HL	1.15 (±0.04)	1.17 (±0.04)	1.16 (±0.03)
LL	1.24^{a} (±0.04)	1.09^{b} (±0.04)	1.17 (±0.03)
Mean	1.20 (±0.02)	1.15 (±0.02)	
Experimental Period (70 to 147 days-of-age)			
CON	1.09 (±0.02)	1.04 (±0.02)	1.07 (±0.02)
HL	1.07 (±0.02)	1.03 (±0.02)	1.05 (±0.02)
LL	1.11^{a} (±0.02)	0.98^{b} (±0.02)	1.05 (±0.02)
Mean	1.09^{a} (±0.01)	1.02^{b} (±0.01)	

[ab] Row means with different superscripts differ significantly ($P<0.05$)

*HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

[$] CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

Table 4. 7 The effect of piglet birth weight and feed treatment on average daily feed intake (kg/day) for the starter, grower, and finisher phases, and the entire experimental period (± standard error of the mean)

	Birth Weight*		
Feed Treatment$^{\$}$	HBW	LBW	Mean
Starter Phase (70 to 91 days-of-age)			
CON	1.67 (±0.09)	1.50 (±0.09)	1.58 (±0.06)
HL	1.67^{a} (±0.09)	1.41^{b} (±0.09)	1.55 (±0.06)
LL	1.81^{a} (±0.09)	1.40^{b} (±0.09)	1.61 (±0.06)
Mean	1.73^{a} (±0.05)	1.44^{b} (±0.05)	
Grower Phase (92 to 119 days-of-age)			
CON	2.35 (±0.11)	2.38 (±0.11)	2.36 (±0.08)
HL	2.39 (±0.11)	2.28 (±0.11)	2.34 (±0.08)
LL	2.55^{a} (±0.11)	2.23^{b} (±0.11)	2.39 (±0.08)
Mean	2.43 (±0.06)	2.30 (±0.06)	
Finisher Phase (120 to 147 days-of-age)			
CON	3.12^{B} (±0.17)	3.21^{AB} (±0.17)	3.17 (±0.12)
HL	3.28^{AB} (±0.17)	3.58^{A} (±0.17)	3.43 (±0.12)
LL	$3.63^{a\,A}$ (±0.17)	$2.89^{b\,B}$ (±0.17)	3.26 (±0.12)
Mean	3.35 (±0.10)	3.23 (±0.10)	
Experimental Period (70 to 147 days-of-age)			
CON	2.45 (±0.10)	2.44 (±0.10)	2.44 (±0.07)
HL	2.53 (±0.10)	2.52 (±0.10)	2.52 (±0.07)
LL	2.75^{a} (±0.10)	2.24^{b} (±0.10)	2.49 (±0.07)
Mean	2.57 (±0.06)	2.40 (±0.06)	

^{ab} Row means with different superscripts differ significantly (P<0.05)

^{AB} Column means with different superscripts differ significantly (P<0.05)

*HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

Table 4. 8 The effect of piglet birth weight and feed treatment on feed conversion ratio for the starter, grower and finisher phases, and the entire experimental period (± standard error of the mean)

	Birth Weight*		
Feed Treatment$^{\$}$	HBW	LBW	Mean
Starter Phase (70 to 91 days-of-age)			
CON	1.75 (±0.07)	1.72 (±0.07)	1.74 (±0.05)
HL	1.80 (±0.07)	1.68 (±0.07)	1.74 (±0.05)
LL	1.78 (±0.07)	1.67 (±0.07)	1.72 (±0.05)
Mean	1.78 (±0.04)	1.69 (±0.04)	
Grower Phase (92 to 119 days-of-age)			
CON	2.25 (±0.09)	2.38 (±0.09)	2.31 (±0.07)
HL	2.27 (±0.09)	2.26 (±0.09)	2.27 (±0.07)
LL	2.49 (±0.09)	2.33 (±0.09)	2.41 (±0.07)
Mean	2.34 (±0.05)	2.32 (±0.05)	
Finisher Phase (120 to 147 days-of-age)			
CON	2.76 (±0.14)	2.84^{AB} (±0.14)	2.80^{B} (±0.10)
HL	3.01 (±0.14)	3.23^{A} (±0.14)	3.12^{A} (±0.10)
LL	3.04 (±0.14)	2.79^{B} (±0.14)	2.91^{AB} (±0.10)
Mean	2.94 (±0.08)	2.95 (±0.08)	
Experimental Period (70 to 147 days-of-age)			
CON	2.30 (±0.08)	2.37 (±0.08)	2.33 (±0.05)
HL	2.41 (±0.08)	2.45 (±0.08)	2.43 (±0.05)
LL	2.50 (±0.08)	2.32 (±0.08)	2.41 (±0.05)
Mean	2.40 (±0.04)	2.38 (±0.04)	

^{AB} Column means with different superscripts differ significantly ($P<0.05$)

*HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

4.2.2 The effect of sex and feed treatment on growth performance parameters per period

Table 4.9 and Table 4.10 summarise the results of the interaction between sex and feed treatment for body weight at the beginning (Table 4.9) and end (Table 4.10) of the starter grower and finisher phases. Furthermore, Table 4.11 to Table 4.13 summarise the results of the interaction between sex and feed treatment for ADG (Table 4.11), ADFI (Table 4.12) and FCR (Table 4.13) for each phase (starter, grower, and finisher) and the entire experimental period.

As shown in Table 4.9 there were no significant (*P* > 0.05) differences within the male and female groups and between feed treatments for body weight at the start of each phase. The body weights at the start of each phase between male and female animals were similar, with females being on average heavier. The heaviest start weights for females during the starter, grower and finisher phases were observed when the CON and LL treatments were fed (*P* > 0.05). Whereas the heaviest body weights at the start of the grower and finisher phases for males were observed when the LL and CON treatments were provided, respectively. No significant (*P* > 0.05) effects within male and females and between treatments were observed for body weights at the end of the starter, grower, and finisher phases (Table 4.10). Females were on average heavier than males at the subsequent growth phases, and at the end of the trial. The heaviest slaughter weight was observed for females fed the LL treatment, whereas the heaviest slaughter weight between treatments was observed for males fed the CON treatment.

Table 4. 9 The effect of sex and feed treatment on body weight (kg) at the beginning of the starter, grower, and finisher phases (± standard error of the mean)

	Sex		
Feed Treatment$^{\$}$	Female	Male	Mean
Starter Phase (70 days-of-age)			
CON	22.96 (±1.19)	21.75 (±1.19)	22.35 (±0.84)
HL	21.75 (±1.19)	21.79 (±1.19)	21.77 (±0.84)
LL	22.58 (±1.19)	23.06 (±1.19)	22.82 (±0.84)
Mean	22.43 (±0.68)	22.20 (±0.68)	
Grower Phase (92 days-of-age)			
CON	48.54 (±1.90)	47.10 (±1.90	47.82 (±1.34)
HL	47.54 (±1.90	47.08 (±1.90	47.31 (±1.34)
LL	49.17 (±1.90	47.69 (±1.90	48.43 (±1.34)
Mean	48.42 (±1.09)	47.29 (±1.09)	
Finisher Phase (120 days-of-age)			
CON	78.96 (±2.14)	79.67 (±2.14)	79.31 (±1.52)
HL	78.21 (±2.14)	79.13 (±2.14)	78.67 (±1.52)
LL	80.46 (±2.14)	76.94 (±2.14)	78.70 (±1.52)
Mean	79.21 (±1.24)	78.58 (±1.24)	

$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

Table 4. 10 The effect of sex and feed treatment on body weight (kg) at the end of the starter, grower, and finisher phases (± standard error of the mean)

Feed Treatment$	Sex		Mean
	Female	Male	
Starter Phase (91 days-of-age)			
CON	48.54 (±1.90)	47.10 (±1.90	47.82 (±1.34)
HL	47.54 (±1.90	47.08 (±1.90	47.31 (±1.34)
LL	49.17 (±1.90	47.69 (±1.90	48.43 (±1.34)
Mean	48.42 (±1.09)	47.29 (±1.09)	
Grower Phase (119 days-of-age)			
CON	78.96 (±2.14)	79.67 (±2.14)	79.31 (±1.52)
HL	78.21 (±2.14)	79.13 (±2.14)	78.67 (±1.52)
LL	80.46 (±2.14)	76.94 (±2.14)	78.70 (±1.52)
Mean	79.21 (±1.24)	78.58 (±1.24)	
Finisher Phase (147 days-of-age)			
CON	103.46 (±2.14)	105.67 (±2.14)	104.56 (±1.72)
HL	102.25 (±2.14)	103.46 (±2.14)	102.85 (±1.72)
LL	106.33 (±2.14)	100.33 (±2.14)	103.33 (±1.72)
Mean	104.01 (±1.40)	103.15 (±1.40)	

$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

As seen in Table 4.11, sex and feed treatment had no significant ($P > 0.05$) effect on ADG for the starter phase, however females had a higher ADG compared to males. Pigs that were fed the LL treatment had a higher ADG compared to the other treatments during the starter phase. The CON treatment displayed significant ($P < 0.05$) effects during the grower and finisher phases, where males had a higher ADG than females; no other differences were observed between sex and feed treatment. During the grower phase, males subject to the LL treatment had significantly ($P < 0.05$) lower ADGs compared to males that were fed the CON and HL treatments. Males fed the CON treatment had significantly ($P < 0.05$) higher ADGs compared to males that received the LL treatment. Throughout the entire grow-finishing period, females had the highest ADG when fed the LL treatment, whereas males had the lowest ADG upon receiving the LL treatment. Therefore, the LL treatment had significant ($P < 0.05$) effects on ADG, females had higher ADGs than males. In addition, males fed the CON treatment had significantly ($P < 0.05$) higher ADGs compared to males that received the LL treatment. During the experimental period, females had higher ADGs than males, and pigs that were subject to the CON treatment had higher ADG compared to the other treatments.

It can be deduced from Table 4.12 that females had a significantly ($P < 0.05$) higher DFI than males during the starter phase. In addition, treatment LL had significant ($P < 0.05$) effects on DFI, as females had higher DFIs compared to males. No significant ($P > 0.05$) effects on DFI for sex and feed treatment were observed during the grower phase, however females did have a higher DFI than males and pigs that were subject to the LL treatment did have higher DFI's compared to the CON and HL treatments. During the finisher phase, LL treatment had significant ($P < 0.05$) effects on DFI, females had higher DFIs than males. Males fed the HL treatment had significantly ($P < 0.05$) higher DFIs compared to males that were presented with the LL treatment. Females had significantly ($P < 0.05$) higher DFIs than males during the finisher phase. During the entire experimental period the highest and lowest DFIs were observed for the HL and CON treatments respectively. Females had the highest DFI when given the LL treatment, contrarily males had the lowest DFI when fed the LL treatment. Therefore, the LL treatment had significant ($P < 0.05$) effects on DFI, where females had higher DFIs than males. Furthermore, males had significantly ($P < 0.05$) lower DFIs than females.

During the starter, grower, and finisher phases, males had significantly ($P < 0.05$) lower FCRs compared to females (Table 4.13). The CON and LL treatments had significant ($P < 0.05$) effects on FCR during the starter phase, where males had better FCRs than females. Furthermore, pigs that were subject to the LL treatment had the best FCR. No significant ($P > 0.05$) effects on FCR for sex and feed treatment were observed during the grower phase, however the best FCR was observed in males that were fed the CON treatment. During the finisher phase, significant ($P < 0.05$) differences were observed between feed treatments, the CON treatment provided a lower FCR compared to the HL treatment, therefore females and males fed the CON treatment had the lowest FCR. During the experimental period females had the highest and lowest FCRs when provided the LL and CON treatments, respectively. Males however, had the highest FCR when subject to the HL treatment, and the lowest FCR when fed the CON treatment. Therefore, the CON treatment had significant ($P < 0.05$) effects on FCR throughout the entire experimental period, as males had lower FCRs than females. The CON treatment provided the lowest FCR compared to other treatments ($P > 0.05$). Furthermore, males had significantly ($P < 0.05$) lower FCRs than females throughout the grow-finishing period.

Table 4. 11 The effect of sex and feed treatment on average daily gain (kg/day) for the starter, grower, and finisher phases, and the entire experimental period (± standard error of the mean)

	Sex		
Feed Treatment$^{\$}$	Female	Male	Mean
Starter Phase (70 to 91 days-of-age)			
CON	0.91 (±0.04)	0.90 (±0.04)	0.91 (±0.03)
HL	0.91 (±0.04)	0.88 (±0.04)	0.90 (±0.03)
LL	0.96 (±0.04)	0.89 (±0.04)	0.92 (±0.03)
Mean	0.93 (±0.02)	0.89 (±0.02)	
Grower Phase (92 to 119 days-of-age)			
CON	1.01^{a} (±0.02)	$1.10^{b\ A}$ (±0.02)	1.06 (±0.02)
HL	1.04 (±0.02)	1.08^{A} (±0.02)	1.06 (±0.02)
LL	1.03 (±0.02)	1.00^{B} (±0.02)	1.02 (±0.02)
Mean	1.03 (±0.01)	1.06 (±0.01)	
Finisher Phase (120 to 147 days-of-age)			
CON	1.18^{a} (±0.04)	$1.22^{b\ A}$ (±0.04)	1.12 (±0.03)
HL	1.15 (±0.04)	1.18^{AB} (±0.04)	1.16 (±0.03)
LL	1.24 (±0.04)	1.09^{B} (±0.04)	1.17 (±0.03)
Mean	1.19 (±0.02)	1.17 (±0.02)	
Experimental Period (70 to 147 days-of-age)			
CON	1.05 (±0.02)	1.09^{A} (±0.02)	1.07 (±0.02)
HL	1.05 (±0.02)	1.06^{AB} (±0.02)	1.05 (±0.02)
LL	1.09^{a} (±0.02)	$1.00^{b\ B}$ (±0.02)	1.05 (±0.02)
Mean	1.06 (±0.01)	1.05 (±0.01)	

^{ab} Row means with different superscripts differ significantly ($P<0.05$)
^{AB} Column means with different superscripts differ significantly ($P<0.05$)
$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

Table 4. 12 The effect of sex and feed treatment on average daily feed intake (kg/day) for the starter, grower and finisher phases, and the entire experimental period (± standard error of the mean)

	Sex		
Feed Treatment[$]	Female	Male	Mean
Starter Phase (70 to 91 days-of-age)			
CON	1.66 (±0.09)	1.50 (±0.09)	1.58 (±0.06)
HL	1.59 (±0.09)	1.52 (±0.09)	1.55 (±0.06)
LL	1.77^{a} (±0.09)	1.45^{b} (±0.09)	1.61 (±0.06)
Mean	1.67^{a} (±0.05)	1.49^{b} (±0.05)	
Grower Phase (92 to 119 days-of-age)			
CON	2.38 (±0.11)	2.35 (±0.11)	2.36 (±0.08)
HL	2.36 (±0.11)	2.31 (±0.11)	2.34 (±0.08)
LL	2.52 (±0.11)	2.26 (±0.11)	2.39 (±0.08)
Mean	2.42 (±0.06)	2.31 (±0.06)	
Finisher Phase (120 to 147 days-of-age)			
CON	3.32 (±0.17)	3.01^{AB} (±0.17)	3.17 (±0.12)
HL	3.46 (±0.17)	3.41^{B} (±0.17)	3.43 (±0.12)
LL	3.66^{a} (±0.17)	$2.87^{b\ A}$ (±0.17)	3.26 (±0.12)
Mean	3.48^{a} (±0.10)	3.10^{b} (±0.10)	
Experimental Period (70 to 147 days-of-age)			
CON	2.53 (±0.10)	2.36 (±0.10)	2.44 (±0.07)
HL	2.55 (±0.10)	2.49 (±0.10)	2.52 (±0.07)
LL	2.73^{a} (±0.10)	2.26^{b} (±0.10)	2.49 (±0.07)
Mean	2.60^{a} (±0.06)	2.37^{b} (±0.06)	

[ab] Row means with different superscripts differ significantly (P<0.05)

[AB] Column means with different superscripts differ significantly (P<0.05)

[$] CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

Table 4. 13 The effect of sex and feed treatment on feed conversion ratio for the starter, grower and finisher phases, and the entire experimental period (± standard error of the mean)

	Sex		
Feed Treatment$^{\$}$	Female	Male	Mean
Starter Phase (70 to 91 days-of-age)			
CON	1.84^{a} (±0.07)	1.63^{b} (±0.07)	1.74 (±0.05)
HL	1.74 (±0.07)	1.74 (±0.07)	1.74 (±0.05)
LL	1.83^{a} (±0.07)	1.62^{b} (±0.07)	1.72 (±0.05)
Mean	1.80^{a} (±0.04)	1.66^{b} (±0.04)	
Grower Phase (92 to 119 days-of-age)			
CON	2.42 (±0.09)	2.21 (±0.09)	2.31 (±0.07)
HL	2.30 (±0.09)	2.23 (±0.09)	2.27 (±0.07)
LL	2.51 (±0.09)	2.32 (±0.09)	2.41 (±0.07)
Mean	2.41^{a} (±0.05)	2.25^{b} (±0.05)	
Finisher Phase (120 to 147 days-of-age)			
CON	2.96 (±0.14)	2.64 (±0.14)	2.80^{B} (±0.10)
HL	3.26 (±0.14)	2.98 (±0.14)	3.12^{A} (±0.10)
LL	3.02 (±0.14)	2.80 (±0.14)	2.91^{AB} (±0.10)
Mean	3.08^{a} (±0.08)	2.81^{b} (±0.08)	
Experimental Period (70 to 147 days-of-age)			
CON	2.46^{a} (±0.08)	2.21^{b} (±0.08)	2.33 (±0.05)
HL	2.50 (±0.08)	2.37 (±0.08)	2.43 (±0.05)
LL	2.51 (±0.08)	2.30 (±0.08)	2.41 (±0.05)
Mean	2.49^{a} (±0.04)	2.29^{b} (±0.04)	

^{ab} Row means with different superscripts differ significantly ($P<0.05$)

^{AB} Column means with different superscripts differ significantly ($P<0.05$)

$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

4.2.3 The effect of birth weight and sex on growth performance parameters per period

Table 4.14 and Table 4.15 summarise the results of the interaction between birth weight and sex for body weight at the beginning (Table 4.14) and end (Table 4.15) of the starter grower and finisher phases. Moreover, Table 4.16 to Table 4.18 summarise the results of the interaction between birth weight and sex for ADG (Table 4.16), ADFI (Table 4.17) and FCR (Table 4.18) for each phase (starter, grower, and finisher) and the entire experimental period.

As shown in Table 4.14, HBW females were significantly ($P < 0.05$) heavier than LBW females at the beginning of the starter, grower, and finisher phases. In addition, HBW males were also significantly ($P < 0.05$) heavier than LBW males at the beginning of each growth phase. Furthermore, no significant ($P > 0.05$) differences were observed between females and males for body weight at the beginning of the starter, grower, and finisher phases, therefore sex had no effect on body weight. At the beginning of the starter and grower phases, HBW females had the heaviest weight, while LBW males were the lightest. However, at the beginning of the finisher phase, HBW males were the heaviest, while LBW males remained the lightest.

It can be deduced from Table 4.15 that HBW females were significantly ($P < 0.05$) heavier than LBW females at the end of the starter, grower, and finisher phases. At the end of each growth phase, HBW males were also significantly ($P < 0.05$) heavier than LBW males. At the end of the starter phase, HBW females were the heaviest, whereas LBW males exhibited the lightest weights. The HBW males were the heaviest and LBW males were the lightest at the end of the grower phase. Furthermore, at the end of the trial HBW males were the heaviest, followed by HBW females, and LBW males were the lightest.

Table 4. 14 The effect of piglet birth weight and sex on body weight (kg) at the beginning of the starter, grower, and finisher phases (± standard error of the mean)

	Sex		
Birth Weight*	Female	Male	Mean
Starter Phase (70 days-of-age)			
HBW	25.17^{A} (±0.97)	25.36^{A} (±0.97)	25.26^{A} (±0.68)
LBW	19.69^{B} (±0.97)	19.04^{B} (±0.97)	19.37^{B} (±0.68)
Mean	22.43 (±0.68)	22.20 (±0.68)	
Grower Phase (92 days-of-age)			
HBW	52.47^{A} (±1.55)	51.74^{A} (±1.55)	52.10^{A} (±1.09)
LBW	44.36^{B} (±1.55)	42.85^{B} (±1.55)	43.60^{B} (±1.09)
Mean	48.42 (±1.09)	47.29 (±1.09)	
Finisher Phase (120 days-of-age)			
HBW	84.17^{A} (±1.75)	84.31^{A} (±1.75)	84.24^{A} (±1.24)
LBW	74.25^{B} (±1.75)	72.85^{B} (±1.75)	73.55^{B} (±1.24)
Mean	79.21 (±1.24)	78.58 (±1.24)	

^{ab} Row means with different superscripts differ significantly (P<0.05)
^{AB} Column means with different superscripts differ significantly (P<0.05)
*HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

Table 4. 15 The effect of piglet birth weight and sex on body weight (kg) at the end of the starter, grower, and finisher phases (± standard error of the mean)

	Sex		
Birth Weight*	Female	Male	Mean
Starter Phase (91 days-of-age)			
HBW	52.47^{A} (±1.55)	51.74^{A} (±1.55)	52.10^{A} (±1.09)
LBW	44.36^{B} (±1.55)	42.85^{B} (±1.55)	43.60^{B} (±1.09)
Mean	48.42 (±1.09)	47.29 (±1.09)	
Grower Phase (119 days-of-age)			
HBW	84.17^{A} (±1.75)	84.31^{A} (±1.75)	84.24^{A} (±1.24)
LBW	74.25^{B} (±1.75)	72.85^{B} (±1.75)	73.55^{B} (±1.24)
Mean	79.21 (±1.24)	78.58 (±1.24)	
Finisher Phase (147 days-of-age)			
HBW	108.67^{A} (±1.98)	110.03^{A} (±1.98)	109.34^{A} (±1.40)
LBW	99.36^{B} (±1.98)	96.28^{B} (±1.98)	97.82^{B} (±1.40)
Mean	104.01 (±1.40)	103.15 (±1.40)	

^{ab} Row means with different superscripts differ significantly (P<0.05)
^{AB} Column means with different superscripts differ significantly (P<0.05)
*HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

As shown in Table 4.16 there were no significant ($P > 0.05$) differences for ADG between females and males for the different birth weight groups during the starter, grower, and finisher phases as well as the experimental period. However, during the starter phase significant ($P < 0.05$) differences were observed within female and male groups, where HBW females had higher ADGs ($P < 0.05$) than LBW females and HBW males had higher ADGs ($P < 0.05$) than LBW males. During the grower and finisher phases, significant ($P < 0.05$) differences were observed within the male group, where HBW males had higher ADGs ($P < 0.05$) compared to LBW males. Throughout the experimental period, the only significant ($P < 0.05$) differences were observed within the male group, where HBW males displayed significantly ($P < 0.05$) higher ADGs than LBW males.

Table 4.17 shows the effect of piglet birth weight and sex on average daily feed intake (kg/day) for the starter, grower, and finisher phases, as well as the experimental period. During the starter phase, significant ($P < 0.05$) differences were observed for DFI between females and males within the LBW group, LBW females had higher ($P < 0.05$) average daily feed intakes compared to LBW males. Furthermore, significant ($P < 0.05$) differences were observed between the female and male groups, where HBW females had higher DFIs compared to LBW females and HBW males had higher DFIs than the LBW males. No significant ($P > 0.05$) differences for DFI were observed during the grower phase. However, during the finisher phase, LBW females had significantly ($P < 0.05$) higher DFIs compared to LBW males, and on average females had significantly ($P < 0.05$) higher DFI's compared to males during the finisher phase. Throughout the entire experimental period, significant ($P < 0.05$) differences were observed within the male group, HBW males had higher ($P < 0.05$) DFIs compared to LBW males.

During the starter phase, LBW females had significantly ($P < 0.05$) higher FCRs compared to LBW males (Table 4.18). No significant ($P > 0.05$) differences for FCR were observed for the HBW group between females and males. Furthermore, males had better ($P < 0.05$) FCRs compared to females during the starter phase. Throughout the grower and finisher phases, no significant ($P > 0.05$) differences for FCR were observed between males and females for the HBW and LBW groups, however, on average females had higher ($P < 0.05$) FCRs compared to males. During the entire experimental period, HBW females had higher ($P < 0.05$) FCRs compared to males, and on average males had better ($P < 0.05$) FCRs compared to females. Furthermore, no significant ($P > 0.05$) differences for FCR were observed between males and females for the LBW group.

Table 4. 16 The effect of piglet birth weight and sex on average daily gain (kg/day) for the starter, grower, and finisher phases, and the entire experimental period (± standard error of the mean)

	Sex		
Birth Weight*	Female	Male	Mean
Starter Phase (70 to 91 days-of-age)			
HBW	0.98^{A} (±0.03)	0.95^{A} (±0.03)	0.97^{A} (±0.02)
LBW	0.87^{B} (±0.03)	0.83^{B} (±0.03)	0.85^{B} (±0.02)
Mean	0.93 (±0.02)	0.89 (±0.02)	
Grower Phase (92 to 119 days-of-age)			
HBW	1.06 (±0.02)	1.09^{A} (±0.02)	1.07^{A} (±0.01)
LBW	1.00 (±0.02)	1.02^{B} (±0.02)	1.02^{B} (±0.01)
Mean	1.03 (±0.01)	1.06 (±0.01)	
Finisher Phase (120 to 147 days-of-age)			
HBW	1.19 (±0.03)	1.22^{A} (±0.03)	1.20 (±0.02)
LBW	1.19 (±0.03)	1.11^{B} (±0.03)	1.15 (±0.02)
Mean	1.19 (±0.02)	1.17 (±0.02)	
Experimental Period (70 to 147 days-of-age)			
HBW	1.08 (±0.02)	1.10^{A} (±0.02)	1.09^{A} (±0.01)
LBW	1.03 (±0.02)	1.00^{B} (±0.02)	1.02^{B} (±0.01)
Mean	1.06 (±0.01)	1.05 (±0.01)	

^{ab} Row means with different superscripts differ significantly (P<0.05)
^{AB} Column means with different superscripts differ significantly (P<0.05)
*HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

Table 4. 17 The effect of piglet birth weight and sex on average daily feed intake (kg/day) for the starter, grower, and finisher phases, and the entire experimental period (± standard error of the mean)

	Sex		
Birth Weight*	Female	Male	Mean
Starter Phase (70 to 91 days-of-age)			
HBW	1.81^{A} (±0.07)	1.65^{A} (±0.07)	1.73^{A} (±0.05)
LBW	1.54$^{a\ B}$ (±0.07)	1.33$^{b\ B}$ (±0.07)	1.44^{B} (±0.05)
Mean	1.67^{a} (±0.05)	1.49^{b} (±0.05)	
Grower Phase (92 to 119 days-of-age)			
HBW	2.51 (±0.09)	2.35 (±0.09)	2.43 (±0.06)
LBW	2.33 (±0.09)	2.26 (±0.09)	2.30 (±0.06)
Mean	2.42 (±0.06)	2.31 (±0.06)	
Finisher Phase (120 to 147 days-of-age)			
HBW	3.51 (±0.14)	3.19 (±0.14)	3.35 (±0.10)
LBW	3.45^{a} (±0.14)	3.01^{b} (±0.14)	3.23 (±0.10)
Mean	3.48^{a} (±0.10)	3.10^{b} (±0.10)	
Experimental Period (70 to 147 days-of-age)			
HBW	2.68 (±0.08)	2.46 (±0.08)	2.57 (±0.06)
LBW	2.52^{a} (±0.08)	2.28^{b} (±0.08)	2.40 (±0.06)
Mean	2.60^{a} (±0.06)	2.37^{b} (±0.06)	

^{ab} Row means with different superscripts differ significantly ($P<0.05$)
^{AB} Column means with different superscripts differ significantly ($P<0.05$)
*HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

Table 4. 18 The effect of piglet birth weight and sex on feed conversion ratio for the starter, grower and finisher phases, and the entire experimental period (± standard error of the mean)

	Sex		
Birth Weight*	Female	Male	Mean
Starter Phase (70 to 91 days-of-age)			
HBW	1.83 (±0.05)	1.72 (±0.05)	1.78 (±0.04)
LBW	1.78^{a} (±0.05)	1.60^{b} (±0.05)	1.69 (±0.04)
Mean	1.80^{a} (±0.04)	1.66^{b} (±0.04)	
Grower Phase (92 to 119 days-of-age)			
HBW	2.43 (±0.08)	2.25 (±0.08)	2.34 (±0.05)
LBW	2.39 (±0.08)	2.25 (±0.08)	2.32 (±0.05)
Mean	2.41^{a} (±0.05)	2.25^{b} (±0.05)	
Finisher Phase (120 to 147 days-of-age)			
HBW	3.10 (±0.11)	2.78 (±0.11)	2.94 (±0.08)
LBW	3.06 (±0.11)	2.84 (±0.11)	2.95 (±0.08)
Mean	3.08^{a} (±0.08)	2.81^{b} (±0.08)	
Experimental Period (70 to 147 days-of-age)			
HBW	2.51^{a} (±0.08)	2.30^{b} (±0.08)	2.40 (±0.04)
LBW	2.47 (±0.08)	2.29 (±0.08)	2.38 (±0.04)
Mean	2.49^{a} (±0.04)	2.29^{b} (±0.04)	

^{ab} Row means with different superscripts differ significantly (P<0.05)

^{AB} Column means with different superscripts differ significantly (P<0.05)

*HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

4.2.4 Main and interaction effects

The P-values for all main as well as 2-way and 3-way interaction effects in the study are shown in Table 4.19 to Table 4.23.

As shown in Table 4.19 birth weight had a significant ($P < 0.05$) effect on body weight at the beginning of the starter, grower, and finisher phases; HBW pigs were heavier compared to LBW pigs at the start of each growth phase. Furthermore, birth weight had a significant ($P < 0.05$) effect on body weight at the end of the starter, grower, and finisher phases (Table 4.20). HBW pigs were heavier than LBW pigs at the end of each phase, and therefore at the end of the trial.

Table 4. 19 The P-values for all the main as well as 2-way and 3-way interaction effects for body weight (kg) at the beginning of the starter, grower, and finisher phases

	Phases*		
	Starter	Grower	Finisher
Main Effects			
Feed Treatment$^{\$}$	0.677	0.842	0.944
Birth Weight$^{\#}$	<.0001	<.0001	<.0001
Sex	0.814	0.472	0.720
2-Way Interaction Effects			
Feed Treatment*Birth Weight	0.209	0.381	0.314
Feed Treatment*Sex	0.763	0.955	0.513
Birth Weight*Sex	0.665	0.803	0.663
3-Way Interaction Effects			
Feed Treatment*Birth Weight*Sex	0.947	0.797	0.789

*Starter: Week 0 to Week 3 (70 to 91 days-of age); Grower: Week 4 to Week 7 (92 to 119 days-of age); Finisher: Week 8 to Week 11 (120 to 147 days-of-age)

$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

$^{\#}$HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

Table 4. 20 The P-values for all the main as well as 2-way and 3-way interaction effects for body weight (kg) at the end of the starter, grower, and finisher phases

	Phases*		
	Starter	Grower	Finisher
Main Effects			
Feed Treatment$	0.639	0.942	0.770
Birth Weight#	<.0001	<.0001	<.0001
Sex	0.476	0.875	0.667
2-Way Interaction Effects			
Feed Treatment*Birth Weight	0.379	0.438	0.327
Feed Treatment*Sex	0.980	0.761	0.198
Birth Weight*Sex	0.710	0.660	0.270
3-Way Interaction Effects			
Feed Treatment*Birth Weight*Sex	0.669	0.532	0.533

*Starter: Week 0 to Week 3 (70 to 91 days-of age); Grower: Week 4 to Week 7 (92 to 119 days-of age); Finisher: Week 8 to Week 11 (120 to 147 days-of-age)

$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

#HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

Birth weight had a significant (*P* < 0.05) effect on ADG for the starter and grower phases, where HBW pigs had higher ADGs compared to LBW pigs (Table 4.21). Furthermore, the interaction between feed treatment and sex also had significant (*P* < 0.05) effects on ADG for the grower and finisher phases. As shown in Table 4.22, birth weight had a significant (*P* < 0.05) effect on DFI for the starter phase, where HBW pigs had higher DFIs compared to LBW pigs. Sex also had significant (*P* < 0.05) effect on DFI during the starter and the finisher phases, as females had higher average intakes compared to males. In addition, the interaction between feed treatment and birth weight also had significant (*P* < 0.05) effects on DFI during the finisher phase. During the starter, grower and finisher phases, sex had significant (*P* < 0.05) effects on FCR, as males had better FCRs compared to females during these phases (Table 4.23).

Table 4. 21 The P-values for all the main as well as 2-way and 3-way interaction effects for average daily gain (kg/day) for the starter, grower, and finisher phases

	Phases*		
	Starter	Grower	Finisher
Main Effects			
Feed Treatment$	0.743	0.134	0.620
Birth Weight#	0.000	0.004	0.110
Sex	0.235	0.164	0.529
2-Way Interaction Effects			
Feed Treatment*Birth Weight	0.523	0.743	0.130
Feed Treatment*Sex	0.743	0.050	0.046
Birth Weight*Sex	0.862	0.694	0.124
3-Way Interaction Effects			
Feed Treatment*Birth Weight*Sex	0.299	0.500	0.575

*Starter: Week 0 to Week 3 (70 to 91 days-of age); Grower: Week 4 to Week 7 (92 to 119 days-of age); Finisher: Week 8 to Week 11 (120 to 147 days-of-age)

$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

#HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

Table 4. 22 The P-values for all the main as well as 2-way and 3-way interaction effects for average daily feed intake (kg/day) for the starter, grower, and finisher phases

	Phases*		
	Starter	Grower	Finisher
Main Effects			
Feed Treatment$	0.820	0.888	0.299
Birth Weight#	0.000	0.151	0.403
Sex	0.014	0.213	0.010
2-Way Interaction Effects			
Feed Treatment*Birth Weight	0.390	0.279	0.010
Feed Treatment*Sex	0.352	0.567	0.103
Birth Weight*Sex	0.720	0.677	0.680
3-Way Interaction Effects			
Feed Treatment*Birth Weight*Sex	0.887	0.969	0.816

*Starter: Week 0 to Week 3 (70 to 91 days-of age); Grower: Week 4 to Week 7 (92 to 119 days-of age); Finisher: Week 8 to Week 11 (120 to 147 days-of-age)

$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

#HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

Table 4. 23 The P-values for all the main as well as 2-way and 3-way interaction effects for feed conversion ratio for the starter, grower, and finisher phases

	Phases*		
	Starter	Grower	Finisher
Main Effects			
Feed Treatment$	0.981	0.284	0.079
Birth Weight#	0.114	0.828	0.919
Sex	0.015	0.046	0.022
2-Way Interaction Effects			
Feed Treatment*Birth Weight	0.775	0.333	0.238
Feed Treatment*Sex	0.220	0.665	0.942
Birth Weight*Sex	0.576	0.802	0.699
3-Way Interaction Effects			
Feed Treatment*Birth Weight*Sex	0.317	0.950	0.746

*Starter: Week 0 to Week 3 (70 to 91 days-of age); Grower: Week 4 to Week 7 (92 to 119 days-of age); Finisher: Week 8 to Week 11 (120 to 147 days-of-age)

$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

#HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

4.3 Carcass data

Carcass data collected at the abattoir includes warm carcass mass (WCM, kg), cold carcass mass (CCM, kg), backfat thickness (mm) and lean meat %. Table 4.24 summarise the results of the interaction between birth weight and feed treatment on carcass data, Table 4.25 outlines the results of the interaction between sex and feed treatment on carcass data, and Table 4.26 shows the results of the interaction between birth weight and sex on carcass data. Furthermore, Table 4.27 summarises the P-values for all the main as well as 2-way and 3-way interaction effects for warm carcass mass (WCM, kg), cold carcass mass (CCM, kg), backfat (mm) and lean meat %.

4.3.1 The effect of birth weight and feed treatment on carcass data

The heaviest WCM was observed in the HBW group subject to the LL treatment whereas the lowest WCM was evident in the LBW provided the LL treatment. Therefore, the LL treatment had significant ($P < 0.05$) effects on WCM as the HBW group had heavier WCM compared to the LBW group. There were no significant ($P > 0.05$) effects on WCM for the CON treatment, however the LBW group had the heaviest WCM when provided the CON treatment. The HBW group fed the HL treatment had significantly ($P < 0.05$) heavier WCM compared to the LBW group.

Similar to the WCM findings, the heaviest CCM was observed in the HBW group provided the LL treatment and the lowest CCM was observed in the LBW subject to the LL treatment. The LL treatment thus had significant ($P < 0.05$) effects on CCM as the HBW group had heavier CCM compared to the LBW group. HL treatment had significant ($P < 0.05$) effects on CCM, as HBW pigs had heavier CCM than the LBW pigs. LBW pigs had the heaviest CCM when provided the CON treatment.

The lowest backfat measurement for the HBW group was observed for the CON treatment. Within the HBW group differences were observed between feed treatments for backfat measurements. The HBW group subject to the LL treatment had significantly ($P < 0.05$) higher backfat measurements compared to the HL treatment. Whereas the LBW group displayed the lowest backfat measurement when provided the LL treatment. Therefore, the LL treatment had significant ($P < 0.05$) effects on backfat measurements, as the LBW group had the lowest backfat measurement compared to the HBW group. The LBW group had the highest backfat measurement when subject to the CON treatment.

There were no significant ($P > 0.05$) differences observed for lean meat % between birth weight and feed treatment. The HBW group had the highest and lowest lean meat % when provided the HL and LL treatments respectively. Whereas the LBW group had the highest lean meat % when subject to the LL treatment and the lowest lean meat % when given the CON treatment.

Table 4. 24 The effect of piglet birth weight and feed treatment on warm carcass mass (WCM, kg), cold carcass mass (CCM, kg), backfat (mm) and lean meat %

	Birth Weight		**SEM[#]**
	HBW*	LBW*	
Warm carcass mass (kg)			
CON[$]	84.68	79.07	2.125
HL[$]	86.51^{a}	76.58^{b}	2.125
LL[$]	87.87^{a}	75.16^{b}	2.125
Cold carcass mass (kg)			
CON[$]	82.14	76.70	2.063
HL[$]	83.92^{a}	74.29^{b}	2.063
LL[$]	85.24^{a}	72.90^{b}	2.063
Backfat (mm)			
CON[$]	14.24^{AB}	13.53	0.423
HL[$]	13.26^{A}	13.47	0.423
LL[$]	14.55$^{a\ B}$	12.81^{b}	0.423
Lean meat percentage (%)			
CON[$]	68.33	68.60	0.195
HL[$]	68.82	68.61	0.195
LL[$]	68.29	68.69	0.195

[ab] Row means with different superscripts differ significantly (P<0.05)

[AB] Column means with different superscripts differ significantly (P<0.05)

* HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

[$] CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

[#] SEM: Standard error of the mean

4.3.2 The effect of sex and feed treatment on carcass data

Females had the heaviest WCM when fed the LL treatment, whereas males had the lowest WCM when provided the LL treatment. Therefore, LL treatment had significant ($P < 0.05$) effects on WCM as females had heavier WCM compared to males. Females provided the CON treatment had the lowest WCM, while males given the CON treatment had the heaviest WCM, but no significant ($P > 0.05$) differences were observed.

Males provided the CON treatment had the heaviest CCM, while the lowest CCM was observed for males provided the LL treatment. Contrarily, females fed the LL treatment had the heaviest CCM, while the lowest CCM was observed in females provided the CON treatment. The LL treatment had significant ($P < 0.05$) effects on CCM, as females had heavier CCM compared to males.

The highest and lowest backfat measurements for females were observed for the LL and HL treatments, respectively. Whereas the lowest backfat measurements were observed for males provided the LL treatment. Therefore, the LL treatment had significant ($P < 0.05$) effects on backfat measurements, as females had higher backfat measurements compared to males. Within the male group, differences between feed treatments for backfat was observed. Males fed the CON treatment had significantly ($P < 0.05$) higher backfat measurements compared to males provided the LL treatment.

The lowest lean meat % for females were observed for the LL treatment, whereas the highest lean meat % was observed for males provided the LL treatment. Therefore, the LL treatment had significant ($P < 0.05$) effects on lean meat % between females and males, as females had lower lean meat % compared to males. Within the female group, females provided the HL treatment had significantly ($P < 0.05$) higher lean meat % compared to females given the LL treatment. Males provided the CON treatment had the lowest lean meat %, and therefore males given the LL treatment had significantly ($P < 0.05$) higher lean meat % compared to males subject to the CON treatment.

Table 4. 25 The effect of sex and feed treatment on warm carcass mass (WCM, kg), cold carcass mass (CCM, kg), backfat (mm) and lean meat %

	Sex		SEM[#]
	Female	Male	
Warm carcass mass (kg)			
CON[$]	81.78	81.98	2.126
HL[$]	81.90	81.19	2.126
LL[$]	84.78^{a}	78.24^{b}	2.126
Cold carcass mass (kg)			
CON[$]	79.33	79.52	2.063
HL[$]	79.45	78.76	2.063
LL[$]	82.24^{a}	75.90^{b}	2.063
Backfat (mm)			
CON[$]	13.70	14.08^{A}	0.423
HL[$]	13.45	13.28^{AB}	0.423
LL[$]	14.65^{a}	12.71$^{b\ B}$	0.423
Lean meat percentage (%)			
CON[$]	68.63^{AB}	68.31^{A}	0.195
HL[$]	68.82^{A}	68.61^{AB}	0.195
LL[$]	68.10$^{a\ B}$	68.88$^{b\ B}$	0.195

[ab] Row means with different superscripts differ significantly (P<0.05)

[AB] Column means with different superscripts differ significantly (P<0.05)

[$] CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

[#] SEM: Standard error of the mean

4.3.3 The effect of birth weight and sex on carcass data

The heaviest WCM was observed for females within the HBW group. The HBW females had significantly ($P < 0.05$) heavier WCM compared to LBW females. The same was observed for males, where the HBW males had significantly ($P < 0.05$) heavier WCM compared to males within the LBW group. The lightest WCM was observed for males within the LBW group.

The CCM for females within the HBW group was heavier ($P < 0.05$) compared to females within the LBW group. Males within the LBW group had significantly ($P < 0.05$) lighter CCM in comparison to males within the HBW group. The heaviest CCM was observed for females within the HBW group, whereas the lightest CCM was observed for LBW males.

Significant differences for backfat were observed for males, as LBW males had lower ($P < 0.05$) backfat measurements compared to HBW males. No significant ($P > 0.05$) differences were observed for backfat within the female group. However, HBW females had the highest backfat measurements, whereas LBW males had the lowest backfat measurements.

No significant differences ($P > 0.05$) were observed for lean meat % between males and females or within HBW and LBW groups.

Table 4. 26 The effect of piglet birth weight and sex on warm carcass mass (WCM, kg), cold carcass mass (CCM, kg), backfat (mm) and lean meat %

	Birth Weight		**SEM#**
	HBW*	LBW*	
Warm carcass mass (kg)			
Female	86.64^{a}	79.00^{b}	1.735
Male	86.03^{a}	74.87^{b}	1.735
Cold carcass mass (kg)			
Female	84.05^{a}	76.63^{b}	1.684
Male	83.49^{a}	72.63^{b}	1.684
Backfat (mm)			
Female	14.17	13.70	0.346
Male	13.87^{a}	12.84^{b}	0.346
Lean meat percentage (%)			
Female	68.56	68.48	0.159
Male	68.41	68.78	0.159

^{ab} Row means with different superscripts differ significantly (P<0.05)

^{AB} Column means with different superscripts differ significantly (P<0.05)

* HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

$^{\#}$SEM: Standard error of the mean

4.3.4 Main and interaction effects

As shown in Table 4.27, birth weight had a significant ($P < 0.05$) effect on WCM, CCM and backfat. HBW pigs had a heavier WCM and CCM compared to LBW pigs, furthermore, HBW pigs also had higher backfat measurements compared to LBW pigs. Significant ($P < 0.05$) interactions between feed treatment and sex were observed for backfat and lean meat %. Significant ($P < 0.05$) 3-way interactions for backfat and lean meat % were observed.

Table 4. 27 The P-values for all the main as well as 2-way and 3-way interaction effects for warm carcass mass (WCM, kg), cold carcass mass (CCM, kg), backfat (mm) and lean meat %

	Warm carcass mass (kg)	**Cold carcass mass (kg)**	**Backfat (mm)**	**Lean meat percentage (%)**
Main Effects				
Feed Treatment$^{\$}$	0.982	0.982	0.467	0.384
Birth Weight$^{\#}$	<.0001	<.0001	0.034	0.355
Sex	0.185	0.185	0.102	0.625
2-Way Interaction Effects				
Feed Treatment*Birth Weight	0.257	0.257	0.085	0.270
Feed Treatment*Sex	0.243	0.243	0.026	0.015
Birth Weight*Sex	0.312	0.314	0.423	0.168
3-Way Interaction Effects				
Feed Treatment*Birth Weight*Sex	0.401	0.400	0.045	0.047

*Starter: Week 0 to Week 3 (70 to 91 days-of age); Grower: Week 4 to Week 7 (92 to 119 days-of-age); Finisher: Week 8 to Week 11 (120 to 147 days-of-age)

$^{\$}$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

$^{\#}$HBW: Heavy birth weight pigs weighed between 1.7-2.0kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2kg at birth

4.4 Economic analysis

The trial focused on birth weight as determining factor for optimal nutrient concentration in grower and finisher diets, therefore the cost of the feeding strategy based on birth weight subject to different feed treatments was investigated to determine the economic feasibility (Table 4.28). The economic feasibility was ultimately determined by considering the feed cost per kg gain and the income over feed cost (IOFC) during the grow-finishing period. The feed cost per unit of gain is applied when comparing nutritional programs where there is an expected change in feed efficiency without a change in growth rate (Menegat *et al*., 2019). However, the IOFC is an accurate method to determine the economic value of a feed program and is applied when systems run on a fixed-time basis, and for comparing feed programs when there is an expected change in both feed efficiency and growth rate (Menegat *et al*., 2019). The calculations used to determine the economic feasibility are explained below.

The total amount of feed used per phase (starter, grower, and finisher) for each treatment and birth weight group was calculated from weekly feed intake data collected during the trial. The diet cost (R/kg) was calculated by using fixed prices for raw materials and other ingredients (maize R2.70/ kg, soya oilcake R2.45/ kg, soya oil R10.74/ kg, wheat bran R2.75/ kg, sunflower oilcake R4.90/ kg, limestone R0.68/ kg, monocalcium phosphate R8.42/ kg, salt R1.82/ kg, sodium bicarbonate R5.98/ kg, lysine R23.00/ kg, threonine R24.30/ kg, DL-methionine R44.00/ kg, tryptophan R160.00/ kg and premix R40.00/ kg). The feed cost (R/kg) per phase for each treatment and birth weight group was calculated by multiplying the total amount of feed used per phase by the diet cost (R/kg). Thereafter the feed cost per pig (R/pig) for each phase was calculated by dividing the feed cost (R/kg) by the total amount of pigs used within the feed treatment and birth weight group. The total feed cost (R/pig) for the experimental period was determined by adding the feed cost of each phase (starter, grower, and finisher). The carcass value (revenue) for each treatment and birth weight group was calculated by multiplying the WCM by R25.00/ kg (fixed price).

The cost per kg gained during the grow-finishing period was calculated by using the following formulae:

$$Feed\ cost\ per\ kg\ gain = \frac{Total\ feed\ cost\ per\ pig\ for\ the\ experimental\ period\ (R\ per\ pig)}{End\ weight\ (Slaughter\ weight, kg) - Start\ weight\ (70\ day\ weight, kg)}$$

The income over feed cost was determined by using the following formulae:

$$\begin{gathered} Income\ over\ feed\ cost\ (IOFC) = \\ carcass\ value\ (R\ per\ pig) - total\ feed\ cost\ per\ pig\ for\ the\ experimental\ period\ (R\ per\ pig) \end{gathered}$$

The calculations were based on gross income values of carcasses slaughtered, as no other expenses were considered.

Table 4. 28 The calculated economic feasibility of birth weight and feed treatment for the experimental period

Birth Weight	**HBW***			**LBW***		
Feed Treatment	**CON$**	**HL$**	**LL$**	**CON$**	**HL$**	**LL$**
Total number of pigs	22.00	23.00	24.00	24.00	24.00	23.00
Start weight (70-day weight, kg)	24.33	25.88	25.58	20.38	17.67	20.06
End weight (slaughter weight, kg)	108.54	108.50	111.00	100.58	97.20	95.67
Body weight gain (kg)	84.21	82.62	85.42	80.20	79.53	75.61
Warm carcass mass (WCM, kg)	84.68	86.51	87.87	79.07	76.58	75.16
Total feed used for the starter phase (kg)	841.28	856.71	914.41	755.27	709.19	706.59
Total feed used for the grower phase (kg)	1577.95	1604.90	1716.57	1599.14	1534.10	1495.81
Total feed used for the finisher phase (kg)	2098.50	2205.20	2441.65	2157.96	2406.85	1944.49
Diet cost for the starter phase (R/kg)	3.21	3.24	3.14	3.21	3.24	3.14
Diet cost for the grower phase (R/kg)	3.23	3.27	3.14	3.23	3.27	3.14
Diet cost for the finisher phase (R/kg)	3.19	3.25	3.10	3.19	3.25	3.10
Feed cost per pig for the starter phase (R/pig)	122.91	126.15	130.41	110.35	104.43	100.77
Feed cost per pig for the grower phase (R/pig)	231.41	238.29	244.81	234.51	227.78	213.33
Feed cost per pig for the finisher phase (R/pig)	304.29	325.86	344.23	312.91	355.66	274.14
Total feed cost per pig for the experimental period (R/pig)	658.60	690.31	719.45	657.77	687.87	588.23
Carcass value (R/carcass)	2117.00	2162.75	2196.75	1976.75	1914.50	1879.00
Feed cost per kg gain	7.82	8.36	8.42	8.20	8.65	7.78
Income over feed cost (IOFC)	1458.40	1472.44	1477.30	1318.98	1226.63	1290.77

$CON (control): Diet formulated based on Topigs Norsvin Feed Manual for Finishers; HL (high lysine):10% higher SID lysine than control; LL (low lysine): 10% lower SID lysine than control. The ratio between other essential amino acids relative to lysine remained constant between treatments

* HBW: Heavy birth weight pigs weighed between 1.7-2.0 kg at birth; LBW: Low birth weight pigs weighed between 0.9-1.2 kg at birth

The most expensive feed treatment for the HBW group was the LL treatment, which had a total feed cost of R719.45 per pig in comparison to the CON treatment, which was the cheapest at R658.60 per pig. Therefore, the lowest feed cost per kg gain was for the CON treatment at R7.82. For the LBW group, the most expensive feed treatment was the HL treatment which had a feed cost of 687.87 per pig and the cheapest feed cost was for the LL treatment at R588.23 which also had the lowest feed cost per kg gain at R7.78. When considering the IOFC, which is the most accurate method to determine the economic value of a feed program, the highest value for the HBW group was for the LL treatment and the lowest was for the CON treatment (R1477.30 vs. R1458.40). The highest IOFC for the LBW group was for the CON treatment (R1318.98) and the lowest value was obtained for the LL treatment (R1290.77).

Chapter 5

Discussion

5.1 Birth weight

5.1.1 Growth performance parameters

Birth weight affects postnatal growth rates in pigs and numerous studies have shown that low-birth-weight pigs are at a disadvantage compared to heavier littermates, as they grow slower and therefore do not obtain slaughter weights comparable to heavier birth weight pigs (Gondret *et al*., 2005; Rehfeldt & Kuhn, 2006; Beaulieu *et al*., 2010; Smith *et al*., 2007; Václavková *et al*., 2012; Nevrkla *et al*., 2017; Zotti *et al*., 2017; Lanferdini *et al.*, 2018). Birth weight had significant effects on weights at the start and end of each growth phase, as HBW pigs were significantly heavier at each phase compared to LBW pigs. This is in line with the findings of Václavková *et al*. (2012), where pigs with low-birth-weights grew slower and were lighter at all growth stages. The data presented in this trial is consistent with previous studies showing that light birth weight pigs require a greater number of days to reach the same slaughter weight compared to heavier littermates (Gondret *et al*., 2005), as the average slaughter weight difference between HBW pigs and LBW pigs were 11.53 kg at the end of the trial. At the start of the trial, HBW pigs were significantly heavier than LBW pigs for each feed treatment presented. At the start of the grower and finisher phases, LBW pigs remained significantly lighter compared to HBW pigs. There were no significant differences within the LBW group for slaughter weights at the end of the trial, indicating that the HL feed treatment did not improve slaughter weights as expected. Therefore, low-birth-weight pigs remained significantly lighter throughout growth stages, irrespective of SID lysine level. Douglas *et al*. (2014) performed a study to determine if a high specification diet (higher lysine: energy ratio) fed to low-birth-weight pigs would result in increased growth performance. The results of the study indicated that low-birth-weight pigs given access to a high specification diet did not show improved performance. Similar results were observed in this study, as LBW pigs provided with the HL treatment did not display significant improvements in growth performance (start and end weights, ADG, DFI and FCR) compared to the CON and LL treatments provided. Even though not significant, LBW pigs obtained the heaviest slaughter weights when presented with the CON treatment. Whereas HBW pigs fed the LL treatment had the heaviest slaughter weights compared to the CON and HL treatments, indicating that growth in HBW pigs was not limited to low SID lysine levels.

During the starter and grower phases, LBW pigs had on average significantly lower ADGs compared to HBW pigs. However, during the finisher phase, no significant difference was observed. Similar findings were observed in the study carried out by Gondret *et al*. (2005) where ADG in the finishing period were similar between birth weight groups. Albeit the ADG for the grow-finishing period differed significantly between birth weight groups, as HBW pigs had significantly higher ADGs compared to LBW pigs. Findings by Alvarenga *et al*. (2012) and Nevrkla *et al*. (2017) support this, as they found that heavy-birth-weight pigs are associated with higher daily gains. A possible explanation for lower growth rates in LBW pigs was posed by Handel & Stickland (1987), as piglets born light have a lower muscle fibre number which restrict the potential for postnatal growth. During the grow-finishing period, LL treatment had significant effects on ADG, as HBW pigs had higher ADGs compared to LBW pigs. During the entire experimental period, although not significant, HBW pigs that consumed the LL treatment had the highest ADG compared to other treatments, while LBW pigs had the lowest ADGs when given the LL treatment compared to other treatments.

Growing pigs can adjust their feed intake over a wide range of dietary energy concentrations to achieve a constant daily energy intake (NRC, 1998). In this study, the NE levels of the feed treatments were kept constant within each phase (starter, grower, and finisher), however the SID lysine levels of the feed treatments were different. Schiavon *et al*. (2018) found that a reduction of SID lysine level resulted in pigs increasing their feed intake. This was observed in HBW pigs as they had the highest DFI for the LL treatment during the starter, grower, and finisher phases, this was however not significant. During the finisher phase, HBW pigs consuming the LL treatment had significantly higher DFIs compared to the CON treatment. The LL treatment had significant effects on DFI throughout the grow-finishing period, as HBW pigs consumed significantly more feed in comparison to LBW pigs. As the LL treatment contained a lower SID lysine level, pigs had to consume more feed to meet their nutritional requirements. Contradictorily, even though not significant, LBW pigs consumed the least amount of feed when given the LL treatment which can explain the low ADG observed. A possible explanation for the low DFI of the LL treatment by the LBW pigs could be environmental temperature. High environmental temperatures cause a reduction in feed intake as pigs rely on reducing their metabolic heat production to maintain a comfortable body temperature (Renaudeau *et al*., 2011). In addition to environmental temperature, the LL treatment contained high levels of dietary fibre. Diets that are bulky due to the addition of fibre can cause depressed feed intake due to gut fill (Agyekum & Nyachoti, 2017). Although not significant, HBW pigs had higher DFIs compared to LBW pigs during the grow-finishing period. Aymerich *et al*. (2020) concluded that growth rate and feed efficiency might be improved by providing diets containing higher lysine levels to small pigs to compensate for their lower feed intake capacity. However, LBW pigs provided with the HL treatments had significantly higher DFIs and FCRs during the finisher phase compared to the other treatments provided.

During the grow-finishing period, no significant differences were observed for FCR between birth weight groups and feed treatments provided. However, significant effects within the LBW group for feed treatment was observed during the finisher phase. The LBW group that was provided with the LL treatment had a significantly better FCR in comparison to the HL treatment, due to LBW pigs consuming more of the HL treatment in comparison to the LL treatment. Montoro *et al*. (2020) performed a study to investigate the effect of birth weight and weaning weight on performance indicators in the growing phase and found that FCR was similar between groups (small and big pigs at birth). These findings are in line with data obtained in this trial, as the FCR between LBW and HBW groups were similar. Even though no significant differences for FCR were observed during the entire experimental period, LBW pigs had better FCRs compared to HBW pigs.

5.1.2 Carcass data

Rehfeldt & Kuhn (2014) and Madsen & Bee (2015) concluded that carcass weights and lean meat percentages were lower and fat content higher in low-birth-weight pigs. A possible reason as explained by Rehfeldt & Kuhn (2014) could be because low-birth-weight pigs reach the plateau for muscle fibre growth earlier; therefore, feed energy can no longer be used to deposit protein but is mainly used for fat deposition. In this study, feed treatment had significant effects on WCM and CCM of LBW and HBW groups. Carcasses from the HBW group and the HL and LL treatments had significantly heavier WCM and CCM compared to carcasses from the LBW group. Although not significant, the LL treatment yielded the heaviest carcasses within the HBW group, whereas CON treatment yielded the heaviest carcasses for the LBW group. The CON treatment did not yield any significant differences between the HBW and LBW groups for the WCM and CCM. Feed treatment also had a significant effect on backfat measurements of the carcasses within the HBW group. Carcasses from the LL treatment had significantly higher backfat measurements compared to the HL treatment, causing backfat to be higher in low SID lysine diets. Similar results were obtained in the study done by Li *et al*. (2012), that found backfat thickness to increase as the SID Lys: ME ratio decreased. Carcasses of the HBW group and LL treatment had significantly higher backfat thickness compared to the LBW group. In this study, the results indicated that the backfat levels decreased as the SID lysine content of the diet increased for the HBW group. However, contradictory results were obtained for the LBW group, the lowest backfat thickness was observed for the low lysine treatment. Whilst not significant, the LBW pigs that received the LL treatment were the lightest at slaughter compared to all the other groups, which can explain the low backfat thickness. Furthermore, between the CON and HL treatment for the LBW carcasses, the carcasses from the HL treatment had the lowest backfat thickness. Schiavon *et al*. (2018) found that as the amino acid content of diets increases, the backfat content of carcasses decreased, which is consistent with the results obtained in this study. Pigs born light are more likely to have fatter carcasses compared to heavy-birth-weight pigs (Gondret *et al*., 2005; Bee, 2007). In this study, even though not significant, carcasses from HBW pigs had increased backfat content compared to the LBW group. A possible explanation for this can be due to the HBW group yielding heavier carcasses. Kim & Kim (2017) found a strong positive correlation between carcass weight and backfat thickness, therefore as the carcass weight increases the backfat thickness also increases. In this current study, although not significant, the LL treatment yielded the highest lean meat % within the HBW group, and the CON treatment within the LBW group. There were no significant differences between birth weight groups and feed treatments for lean meat % as the lean meat percentage was similar between birth weight groups and feed treatment. Lower backfat content will result in increased return on investment, as producers are paid more for leaner carcasses. Although the HL and LL treatments yielded lower backfat measurements for the HBW and LBW groups respectively, the carcasses were smaller compared to the other treatments. Therefore, less kilograms of meat will be sold per pig; hence it would be beneficial to the producer to consider SID lysine levels that will produce lean carcasses whilst still yielding bigger carcasses to maximise the return per pig. Furthermore, all the treatments in this study produced carcasses for HBW and LBW groups that fall within the P&O class of the PORCUS classification system of South Africa, hence any treatment would be a viable option for pork producers.

5.2 Sex

5.2.1 Growth performance parameters

The focus of the trial was to determine the optimal nutrient density of diets to be fed to pigs during the grow-finishing phase based on pig birth weight, however employing the data obtained in this trial for sex will provide insight to the expected outcomes in a commercial setting. Males and females experienced non-significant differences in start and end weights throughout the trial, with females being heavier compared to males. Females were heavier than males at slaughter, but not significantly, and this is in line with the findings of Bocian *et al*. (2012), where females achieved a higher body weight at slaughter compared to males. Contradictory results were found in previous studies that reported females being lighter at slaughter in comparison to males (Quiniou *et al*., 2010; Aymerich *et al*., 2021). Whilst not significant, the heaviest slaughter weights for females were achieved on the LL treatment, while males had the heaviest slaughter weights on the CON treatment. Boars exhibit a greater potential for growth compared to gilts from 40 to 70 kg body weight until slaughter (Aymerich *et al*., 2020). In this study significant differences for ADG were observed during the grower (42 to 71 kg body weight) and finisher phases (72 to 104 kg body weight). Males had significantly higher ADGs compared to females for the CON treatment. Furthermore, within the male group significant differences were observed between feed treatments, as males had significantly lower ADGs when provided with the LL treatment compared to the CON and HL treatments. During the finisher phase, even though not significant, males had higher ADGs compared to females for the CON treatment and within the male group higher ADGs were observed for the CON treatment in comparison to the LL treatment. Throughout the experiment, females had significantly higher ADGs than males for the LL treatment, as females had the highest ADG for the LL treatment while males experienced the lowest ADG for the LL treatment. Aymerich *et al*. (2020) found that boars had greater average daily gains when higher levels of SID Lys were presented within diets. This is in accordance with the results found in this trial as boars had significantly higher ADGs when provided with the CON treatment, compared to the LL treatment. Males experienced small differences for ADG between the CON and HL treatments. Boars may require more SID Lys to reach their potential for growth and protein deposition, thus a response to a higher SID lysine level can be explained.

Throughout the experiment significant differences were observed between males and females for DFI. Females had significantly higher DFI compared to males, this is contradictory to results found in previous studies that state there is no difference between the intakes of males and females (Newell & Bowland,1972; Aymerich *et al*., 2020). Females fed the LL treatment had significantly higher intakes than males which explains the higher ADG for females compared to males provided with the LL treatment. Aymerich *et al*. (2020) performed a study to establish if gilts and boars respond differently to SID Lys: NE ratio in terms of growth performance. The study found that gilts have lower ADG and higher FCR compared to boars, while no differences were observed for DFI. During this trial, males had significantly better FCRs compared to females as well as significantly lower DFIs whilst still obtaining similar ADGs compared to females.

5.2.2 Carcass data

Warriss *et al*. (1993) determined that boars produced carcasses that were 1.5kg lighter for hot carcass weight compared to females. In this study, the WCM and CCM of carcasses from females were about 6 kg significantly heavier for the LL treatment compared to males. For the other treatments, carcasses from females and males had similar WCM and CCM, with no significant differences. Although not significant, the LL treatment yielded the heaviest carcasses within the female group, whereas CON treatment yielded the heaviest carcasses within the male group. Gispert *et al*. (2010) found that the fat content of males was higher than that of females, whereas Warriss *et al*. (1993) established that males had lower P_2 levels compared to females. In this study, males had significantly lower backfat content for the LL treatment compared to females. However, the carcasses from females and the LL treatment were significantly heavier compared to that of males. Carcasses from males that were subject to the LL treatment had significantly lower backfat thickness compared to male carcasses and the CON treatment. Even though not significant, the HL treatment yielded female carcasses with the lowest backfat thickness, whereas the LL treatment yielded male carcasses with significantly lower backfat thickness compared to the CON treatment. However, the carcasses produced with lower backfat thickness also had lower yield compared to carcasses with higher backfat content. Feed treatment had significant effects on lean meat % within the female and male groups. Female carcasses for the LL treatment had significantly lower lean meat % compared to the HL treatment. Whereas male carcasses had significantly higher lean meat % for the LL treatment compared to the CON treatment. The LL feed treatment had significant effects on lean meat % between males and female carcasses, where female carcasses had significantly lower lean meat % compared to male carcasses for the LL treatment. Commercial grading and classification systems are based on backfat measurements in combination with carcass weight (Hugo & Roodt, 2007). In this study, it can be concluded that the lightest carcasses of males and females were associated with the lowest backfat measurements and therefore the highest lean meat yield. However, pork producers are compensated financially per kilogram pork produced, hence carcasses with the lowest backfat content and highest lean meat % might not produce the greatest returns on investment. Furthermore, it is important that pork producers consider SID lysine levels in diets that will produce a heavy carcass with an acceptable backfat thickness. However, all the treatments in this study produced carcasses for males and females that fall within the P&O class of the PORCUS classification system of South Africa, hence any treatment would be a viable option for pork producers.

5.3 Birth weight and sex

5.3.1 Growth performance parameters

In this trial, no significant differences were observed for start and end weights throughout the growth phases between females and males within the HBW and LBW groups. However, significant differences were observed within the female and male groups; as HBW females were significantly heavier throughout the trial compared to LBW females, and HBW males were significantly heavier at the start and end of each growth phase compared to LBW males. At the end of the trial, whilst not significant, HBW males exhibited the heaviest slaughter weights, which is in line with the findings of Vázquez-Gómez *et al*. (2020), where heavy-birth-weight males were heaviest at slaughter compared to heavy-birth-weight females and low-birth-weight males and females. Based on the results of the interaction between birth weight and sex, it can be concluded that birth weight had the greatest effect on body weights throughout the trial compared to sex, as no significant differences were observed between males and females for body weight, however HBW pigs were consistently significantly heavier at each growth phase compared to LBW pigs. Throughout the experimental period, males within the HBW group had significantly higher ADGs compared to males within the LBW group (1.10 kg/day vs. 1.00 kg/day). Although not significant, the HBW females also experienced higher ADGs compared to the LBW females (1.08 kg/day vs. 1.03 kg/day). However, non-significantly, HBW females had poorer FCRs compared to LBW females, possibly due to higher DFIs. Bérard *et al*. (2010) found similar results, where high-birth-weight females had higher gain to feed ratios compared to low-birth-weight females. HBW males had significantly better FCRs compared to HBW females, whereas no significant differences were observed for FCR between LBW males and females.

5.3.2 Carcass data

Carcasses from the HBW females had significantly heavier WCM and CCM compared to the LBW females, in addition HBW males also had significantly heavier WCM and CCM in comparison the LBW males. Although not significant, the heaviest WCM and CCM was observed for the HBW female carcasses, whereas the lowest WCM and CCM was observed for LBW male carcasses. This is in contrast with the findings of Vázquez-Gómez *et al*. (2020), where LBW females had the lightest carcass weights at slaughter. Carcasses of HBW males had significantly higher backfat thickness compared to LBW males, whereas no significant differences were observed between HBW and LBW female carcasses. Whilst not significant, the lowest backfat thickness was observed for the LBW male carcasses, while the highest backfat thickness was evident in HBW females. The carcasses with the lowest backfat thickness produced the highest lean meat yield. Even though not significant, HBW carcasses within the female group produced higher lean meat % compared to LBW female carcasses. These observations are in accordance with that of Rehfeldt *et al*. (2008), as heavy-birth-weight females exhibited a higher lean meat yield compared to low-birth-weight females.

5.4 Economic feasibility

For a feed treatment to be economically viable, the price of feeding the diet must be offset by the gain in body weight or improved feed utilisation (Douglas *et al*., 2014). The highest body weight gain and ADG for the HBW group was observed for the LL treatment and the lowest for the HL treatment (85.42 vs. 82.62 and 1.11 vs 1.07). Whereas the best FCR was observed for the CON treatment and the lowest for the HL treatment. For the LBW group, the highest body weight gain was observed for the CON treatment whereas the lowest gain was for the HL treatment (80.20 vs. 75.61). The ADG was lowest for the LL treatment while the highest ADG was observed for the CON treatment (0.98 vs. 1.04). When considering only the growth performance, it can be concluded that the LL treatment would be best suited for the HBW pigs and the CON treatment for the LBW pigs. However, to make an accurate conclusion, the feed cost per kg gain as well as the IOFC should also be considered (Table 4.28). HBW pigs had the lowest feed cost per kg gain for the CON treatment, but the lowest IOFC was also observed for the CON treatment. Whereas the highest feed cost per kg gain and IOFC was observed for the LL treatment. The LBW group fed the LL treatment had the lowest feed cost per kg gain and the lowest IOFC, whereas the highest IOFC was observed for the CON treatment with the highest feed cost per kg gain. The carcass data obtained showed that any feed treatment used resulted in carcasses within the P&O class. Therefore, it can be concluded that the highest value for the HBW pigs will be obtained when these pigs are fed a low SID lysine diet (LL), whereas a standard SID lysine diet (CON) will yield the highest value for LBW pigs.

Chapter 6

Conclusion

The selection for improved sow productivity has led to an increase in litter size as well as an increase in the number of low-birth-weight piglets born. Low-birth-weight pigs are associated with slower growth rates, lighter slaughter weights and carcasses as well as decreased pork quality compared to heavy-birth-weight pigs. Consequently, as the birth weight of a pig decreases, the feasibility of a pig being full value at market equally declines. Therefore, low-birth-weight pigs pose management challenges and may have negative economic implications for pork producers. To develop a more precise feeding regime based on birth weight, it is important that pig producers as well as nutritionists understand the growth limitations posed by low-birth-weight pigs as well as their genetic potential for growth. Low-birth-weight pigs have a lower number of muscle fibres in comparison to heavy-birth weight-pigs, and therefore display decreased potential for lean growth, thus depositing more fat. The nutrient requirements suggested for grow-finishing pigs might therefore not be applicable to low-birth-weight pigs.

The *aim* of the study was to determine the optimal nutrient concentration of grow-finishing diets based on birth weight and the effects of different nutrient dense diets on the growth performance and carcass quality of low-birth-weight pigs compared to heavy-birth-weight pigs subject to the same diets. Low-birth-weight pigs were significantly ($P < 0.05$) lighter compared to heavy-birth-weight pigs throughout the trial, irrespective of feed treatment provided. Although no treatment significantly ($P > 0.05$) increased the liveweight of the low-birth-weight pigs, the heaviest end weights at the starter, grower and finisher phases were achieved with the standard SID lysine level (10.60 g/kg, 9.00 g/kg, and 7.60 g/kg). For the heavy-birth-weight pigs, treatment had no significant ($P > 0.05$) effect on weights at the end of the starter, grower, and finisher phases; however, the heaviest weights were achieved with the low SID lysine level (9.54 g/kg, 8.10 g/kg, and 6.84 g/kg). Feed treatment had no significant ($P > 0.05$) effect on ADG for the low-birth-weight and heavy birth weight pigs, but it was clear that the standard SID lysine level and the low SID lysine level allowed for the greatest ADG for the low-birth-weight and heavy-birth-weight pigs, respectively. Feed treatment had significant ($P < 0.05$) effect on FCR throughout the finisher phase. The SID lysine level required to optimise FCR from 120 to 147 days of age was found to be 7.60 g/kg. Feed treatment had significant ($P < 0.05$) effect on backfat deposition within the heavy-birth-weight group, as lower backfat measurements were observed for the high SID lysine treatment compared to the low SID lysine treatment. The lowest backfat thickness for the heavy-birth-weight carcasses was observed for the high SID lysine treatment, however lower carcass weights were observed for this treatment. The low-birth-weight group had the lowest backfat measurements for the low SID lysine level, but the lightest carcasses was observed for this treatment in comparison to the standard SID lysine and high SID lysine treatments. Each treatment yielded carcasses within the acceptable classes (P&O) of the pork classification system used in South Africa. In addition, the income over feed costs for the different feed treatments and birth weight groups were investigated to determine the economical viability. The low SID lysine treatment yielded the highest income over feed cost for the heavy-birth-weight pigs, while the standard SID lysine level delivered the highest income over feed cost for the low-birth-weight pigs.

In conclusion, improvements in growth performance and feed efficiency were observed for the standard SID lysine level and the low SID lysine level in low-birth-weight and heavy-birth-weight pigs, respectively. The highest income over feed cost was also observed for the beforementioned feed treatments and birth weight groups. This study therefore showed that both heavy-birth-weight and low-birth-weight pigs did not benefit from receiving diets with high SID lysine levels.

The null hypothesis (H_0) of this study, stating that the high SID lysine regime will not provide the necessary support for improved growth performance and carcass quality to the low-birth-weight pigs, was accepted.

Chapter 7

Critical Evaluation

This chapter aims to evaluate the shortcomings of the trial.

7.1 Diet formulation

The significance of diet formulation is to optimise diets with the raw materials available to provide the animal with the exact nutrients required for maintenance and growth. The diet price is a factor that must be considered; diets should be price competitive whilst supporting optimal growth. Expensive diets will negatively impact farm profitability as production costs will be excessively high. In addition to price, factors like raw material quality will influence the diet quality as well. Due to variability in the quality of raw materials the diets formulated are dissimilar to the final product fed to the animal which can cause conflicting results. Manufacturing and analysis of diets before they are fed to the animals during the trial can be a sound method to control the abovementioned variables; ensuring that specifically formulated diets correspond to the final product fed to the experimental animals. This will guarantee that conclusions made based on trial results are sound.

7.2 Analysis

The feed manufactured for the trial was not analysed to determine the chemical composition. Therefore, the conclusion could not be made that the formulated specifications correspond to that of the manufactured feed. The feed could have been analysed to ensure that the feed manufactured corresponded to the formulations, which could have solidified the conclusions made in the trial.

7.3 Environmental influences

The trial was conducted at the research facility of the University of Pretoria, South Africa. The facility was not environmentally controlled and could therefore not control temperature effectively. The trial was performed during the summer months which led to hot temperatures throughout the day, and low temperatures at night. These differences in minimum and maximum temperature could have influenced animal performance.

7.4 Sample size and sex

Due to the nature of the trial, sample size was limited and both males and females had to be used. During the selection of piglets at birth the number of males born into the low-birth-weight category was not sufficient and females had to be selected as well. A larger sample size could have been used to mimic commercial conditions and increase the number of replicates per treatment.

Furthermore, the use of a single sex could have reduced the number of variables that had to be considered during the trial.

7.5 Slaughtering process

The loading process was stressful due to warm temperatures and the ineffective loading platform. The animals were without water for a long time and only received water once they arrived at the abattoir. As instructed by the abattoir, the pigs were only slaughtered the day after arrival, therefore the pigs were without feed for about twelve hours. The stress caused by the loading process, travelling and the night spent at the abattoir might have influenced the carcass data obtained.

7.6 Weaner period

During the 7-week weaner period (21 days-of-age to 70 days-of-age) the weaner pigs remained on the commercial farm, GHB Farms. The weaner pigs were subject to the environment and nutrition of the farm, thus low-birth-weight and heavy-birth-weight pigs were not treated or fed differently during this 7-week period. This period is a crucial time in the development of the pig and treating the low-birth-weight and heavy-birth-weight pigs the same could have had a potential effect on the outcome of the trial. However, as stated in the aim and objectives, the trial was focused on the growing and finishing period (70 days-of-age to 147 days-of-age) and for this reason weaner pigs were not treated differently. For future trials, it can be considered to rather feed the low-birth-weight and heavy-birth-weight pigs differently from weaning until slaughter, this will ensure that the entire growth period is monitored closely and will guarantee that conclusions made based on trial results are sound.

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