# The effect of fibre type in a diet containing fine maize to improve the performance and health of pigs during the final finisher phase

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# Declaration

I, Jan David Huygen Mostert hereby declare that this dissertation, submitted for the MSc (Agric) Animal Science: Animal Nutrition degree at the University of Pretoria, is my own work and has not been submitted by me for a degree at this or any other tertiary institution.

Jan David Huygen Mostert

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# Abstract

The importance of maize grind size in commercial pig rations are oversighted, a substantial amount of nutrients is annually lost due to undigested maize. Pig production could benefit from an increased nutrient availability, without increasing the feed costs. The challenges producers are faced with when feeding a finer feed are firstly; fine feed tend to bridge in the feeding system and secondly; gastric ulcers often develop.

In this study, the effects of using a finer maize (741 µm) particle in finisher pig rations in combination with sunflower meal were investigated to alleviate the risk of gastric ulceration. Finisher pigs of Topigs Norsvin genetics were fed in a commercial set-up, with industry standard rations, after which they were slaughtered at a commercial abattoir.

A total of 288 pigs were used for the study, divided into six treatment groups with six replicates each. The trial was designed with six treatments in a 2 x 3 factorial arrangement, examining the main effects of fibre source (wheat bran and sunflower meal) and maize grind size (720 µm, 741 µm, and 774 µm). Statistical analysis was conducted by ANOVA using SAS software, while blocking was applied to minimise facility effect. The pigs were fed these treatment rations during the finisher phase, from 19 weeks-of-age until slaughter at 22 weeks-of-age, when pigs are most likely to develop gastric ulcers.

Average daily feed intake (ADFI), feed conversion ratio (FCR), average daily gain (ADG), gastric ulceration scores and carcass characteristics were evaluated during this study. Total tract nutrient digestibility was evaluated using chromium dioxide as an indigestible marker. There was no significant difference ($P > 0.05$) in the performance parameters and carcass characteristics of the pigs during this study. Pigs administered sunflower meal as fibre had a significant difference ($P < 0.05$) in digestion of amino acids, crude fibre and starch during the trial. There was no increase in gastric ulcerations all through the study. It was concluded that a diet with medium maize particle sizes of 741 µm on average and with the inclusion of fibre from sunflower meal, enhanced digestibility and did not negatively impact the gastrointestinal tract (GIT) of finisher pigs during this study.

Keywords*: feed efficiency, gastric ulceration, maize grind size, pig nutrition, sunflower meal, wheat bran*

# Contents

# List of abbreviations

| | |
|---|---|
| ADF | acid detergent fibre |
| ADFI | average daily feed intake |
| ADG | average daily gain |
| AID | apparent ileal digestibility |
| ALP | alkaline phosphatases |
| ALT | alanine aminotransferase |
| ANOVA | analysis of variance |
| APS | average particle size |
| Arg | arginine |
| AST | aspartate aminotransferase |
| ASTM | American Society of Testing and Materials |
| ATTD | apparent total tract digestibility |
| CF | crude fibre |
| Cfat | crude fat |
| CP | crude protein |
| $Cr_2O_3$ | chromium oxide |
| CVB | Dutch Feed Evaluation System |
| Cys | cystine |
| DE | digestible energy |
| DNA | deoxyribonucleic acid |
| FDA | Food and Drug Assurance |
| FCR | feed conversion ratio |
| g | gram |
| g/kg | gram per kilogram |
| GC-MS | gas chromatography–mass spectrometry |
| GE | gross energy |
| GIT | gastrointestinal tract |
| GLP-1 | glucogen-like peptide 1 |
| HCl | hydrochloric acid |
| HE | haematoxylin-eosin |
| His | histidine |
| ICP-OES | inductively coupled plasma-optical emission spectrometry |
| Ile | isoleucine |

| | |
|---|---|
| Kg | kilograms |
| kg/m$^2$ | Kilograms per square meter |
| Leu | leucine |
| LCMS | Liquid chromatography mass spectrometry |
| Lys | lysine |
| MDCP | mono-dicalcium phosphate |
| ME | metabolisable energy |
| Met | methionine |
| mg/kg | milligram per kilogram |
| MG1 | maize grind 1 (fine) |
| MG2 | maize grind 2 (medium) |
| MG3 | maize grind 3 (coarse) |
| MJ | megajoules |
| mmol | millimoles |
| MRT | mean retention time |
| NDF | neutral detergent fibre |
| NE | net energy |
| NGR | non-glandular region |
| NIR | near infrared spectrometry |
| NSP | non-starch polysaccharides |
| PAS | Periodic Acid's Schiff Stain |
| pH | potential of hydrogen |
| PPOS | percentage particles on sieve |
| R/kg | South African Rand per kilogram |
| R/ton | South African Rand per ton |
| RNSP | remainder non-starch polysaccharides fraction |
| RPM | revolutions per minute |
| rRNA | ribosomal ribonucleic acid |
| SCFA | short-chain fatty acids |
| SEM | standard error of the mean |
| SID | standardised ileal digestibility |
| SID | standardised ileal digestibility |
| SM1 | sunflower meal with maize grind 1 treatment |
| SM2 | sunflower meal with maize grind 2 treatment |
| SM3 | sunflower meal with maize grind 3 treatment |

| | |
|---|---|
| SMR | sunflower meal ration |
| SOP | standard operation procedures |
| sp. | species |
| Thr | Threonine |
| Trp | tryptophan |
| TTD | total tract digestible |
| Tyr | tyrosine |
| U.S | United States |
| UAS | ulceration average score |
| Val | valine |
| VFP | very fine particles |
| WBR | wheat bran ration |
| WM1 | wheat bran with maize grind 1 treatment |
| WM2 | wheat bran with maize grind 2 treatment |
| WM3 | wheat bran with maize grind 3 treatment |
| µm | Micron |

# List of tables

# List of figures

# List of equations

# Chapter One: Introduction

## 1.1 Introduction

Globally, the swine industry is a large consumer of grains, produced in local market and the global market. Since this industry is competing for resources consumed by human population, it is vital that production is efficient continuously improved. Due to the availability of different raw materials in different markets, there are globally two types of swine rations. The first is a wheat-barley type ration, mainly used in the European markets, with corn-soya rations used in America and South Africa. This corn-soya ration contains between 60 and 70 percent maize. It is therefore important that the use of maize in pigs' rations is utilised as efficient as possible. A study by Kiarie & Mills (2019), suggested that pigs fed a corn-soya ration only digests around 78% of the ration's gross energy (GE), while the rest of this GE is excreted. This suggests that there is room for improvement.

Reduction of particle size leads to better digestibility of nutrients due to an increase surface area that are exposed to the digestive enzymes, which in turn leads to an improved FCR (Vukmirović *et al*., 2017). It has been suggested that for each 100 µm the mean particle size of a ration is decreased and enzyme's access to the starch is increase by 26.8 g/kg total starch, and this then increase the total ileal digestibility of energy (Blasel *et al*., 2006; Vukmirović *et al*., 2017). Fan *et al*. (2017) found that both digestible energy (DE) and metabolisable energy (ME) of wheat can be improved by decreasing the particle size. Similar trails were carried out by DeRouchey *et al*. (2017) and Rojas & Stein (2015), by using maize they and all arrived at a similar conclusion.

The particle size of a material influences factors such as bulk density, cohesive strength, and the angle of repose (AoR) that together with particle size distribution has an impact on flowability. Flowability is the ability of the ration or raw material to flow freely in bulk tanks, silos, feeders, and any other feed handling equipment. Small changes in particle size normally have a significant impact on flowability as it is the most influential factor (Ganesan *et al*., 2008). The issue with feed having low flowability, is that it bridges the feeding system. Bridged silos do not deliver feed in time or in the correct quantities to the animals and is labour intensive to overcome. Flowability is therefore a vital factor to consider when implementing a fine grind size.

Another factor to be considered when reducing particle size is the incidence of gastric ulceration. Jo *et al.* (2021) examined the incidence of gastric ulceration associated with the reduction of ration particle size. Fine feed particles, particularly those rich in insoluble NSPs such as cellulose and hemicellulose, can increase the viscosity of digesta in the gastrointestinal tract. This increased viscosity slows down the movement of digesta and prolongs the retention time of digesta in the stomach and throughout

the GIT. This prolonged exposure to gastric acid and digestive enzymes exacerbate the irritation of the gastric mucosa, leading to gastric ulceration (Hetland *et al.*, 2004). Ulceration decreases production efficiency and could lead to mortalities.

A further negative effect of reducing feed particle size is the potential for slower feed manufacturing. When producers need to change hammer mill screens, the non-productive time of the mill increases, lengthening the time required to produce each metric ton of feed. Using a smaller screen result in a slower throughput of milled products, further contributing to the increased time needed to produce a ton of feed. The longer production times translate to higher costs, as less feed can be produced per day and overall electricity consumption rises.

Implementing changes to enhance the efficient usage of maize should consider the associated negative effects. Reducing particle size should also address the potential increased prevalence of gastric ulceration. It should be noted that very fine particles (VFP) can cause gastric ulceration, which could be mitigated by including the appropriate fibre source (Pluske *et al*., 2003). The chemical composition of fibre affects the nutrient digestibility of a ration, as the degree of lignification plays a role in solubility (Jaworski & Stein, 2017). Soluble fibres are more readily fermented and thus more easily digested than insoluble fibres. The presence of soluble non-starch polysaccharides (NSP) increases the surface area due to their high water-binding capacity, causing the particles to expand and allowing microbes to colonise and degrade the NSP. This soluble dietary fibre may also increase the retention time of digesta, enhancing nutrient absorption (Ngoc *et al*., 2011). Jha & Berrocoso (2016) found that dietary fibre is beneficial for the gut health of finishers and advocate the use of higher fibre content in pig rations (Agyekum & Nyachoti, 2017).

Sunflower meal is a readily available raw material in South Africa, and although it is not only a source of protein, but it also contributes significantly as a fibre source. Sunflower meal can be classified as an insoluble fibre that absorbs water, stimulate intestinal peristalsis, and thereby increase transit time through the GIT (Lannuzel *et al.,* 2022). The inclusion of sunflower meal should therefore decrease the digesta's passage rate trough the GIT, while adding to gut-fill, decrease total feed intake and rendering more nutrients available for absorption.

## 1.2 Problem statement

The research problem involves understanding the complex relationship between dietary fibre intake and the growth performance and health indicators of pigs during the final finisher phase (Lannuzel *et al*., 2022). This includes examining various types and levels of dietary fibre, their digestibility, and their impact on nutrient utilisation and metabolic processes (Ngoc *et al*., 2011). In addition, it is necessary to explore the interactions between dietary fibre, other dietary components, and environmental

factors to develop targeted feeding strategies that optimise both performance and health outcomes in pigs during this critical production phase (Pluske *et al*., 2003).

## 1.3 Justification of the study

In the final finisher phase of pig production, understanding how dietary fibre affects performance and health is essential but not well-studied. Fibre is known to improve gut health and nutrient use in earlier stages, but its specific impact during the final finisher phase on growth, carcass traits, and overall health needs thorough investigation (Vukmirovic *et al*., 2017). Researching this area is crucial for improving pig production efficiency and profitability, as well as ensuring animal welfare and sustainability in the swine industry (Ngoc *et al*., 2011). Gaining a better understanding of how fibre influences pig performance and health in this phase will provide valuable insights for dietary recommendations and management practices, improving productivity and well-being in commercial pig farming.

## 1.4 Aim

The aim of this research was to improve the performance and health of a South African commercial finisher pigs, fed a diet containing a finer maize grind by combining two different fibre sources, wheat bran and sunflower meal.

## 1.5 Objectives

The first objective was to produce, from the same source and batch, maize of different average particle sizes by altering hammer mill screen sizes during milling.

The second objective was to produce finisher feeds containing different maize sizes combined with different ratios of fibre sources (wheat bran and sunflower meal) and evaluate these feeds based on finisher pig' growth performance, development of gastric ulcers and nutrient digestibility.

## 1.6 Hypothesis

H0: Sunflower meal as main source of fibre will have no effect on nutrient digestibility growth performance, or incidence of gastric ulceration typically exacerbated by finely ground maize.

H1: Sunflower meal as main source of fibre will have enhanced nutrient digestibility, growth performance, while reducing the incidence of gastric ulceration typically exacerbated by finely ground maize.

# Chapter Two: Literature review

## 2.1 Introduction

The South African pig industry maintains around 170,000 sows, annually slaughtering approximately 3,500,000 pigs (SAPPO, 2022). Despite its modest global presence, this sector consumes an estimated 993 kilotons of maize meal yearly. Research by Kiarie & Mills (2019) indicates that pigs fed a corn-soya diet utilise only 78% of its gross energy (GE), with the remainder excreted. Consequently, the South African pig herd squanders 218 kilotons of maize annually, impeding production efficiency and profitability.

Reducing the average particle size (APS) of milled maize in pig rations could enhance digestibility and decrease wastage. A finer grind exposes more surface area to digestive enzymes, facilitating nutrient absorption and improving FCR (Vukmirović *et al*., 2017). Studies demonstrated that for every 100 µm reduction in APS, starch accessibility to digestive enzymes increases by 26.8 g/kg, enhancing total ileal digestibility of energy (Blasel *et al.,* 2006; Vukmirović *et al*., 2017).

Fan *et al*. (2017), DeRouchey *et al.* (2017), and Rojas & Stein (2015) observed improved energy content and digestibility by reducing particle size in wheat and maize respectively. Notably, finer particle sizes, below 400 µm, can heighten the risk of gastric ulceration and mortalities (Vukmirović *et al*., 2017). Incorporating suitable fibre sources may mitigate these health risks (Millet *et al*., 2012).

However, finer grinds pose challenges in feed manufacturing, affecting throughput, production time, and costs. Feed bridging in feeding systems emerges as a critical concern for both manufacturers and pig producers. (Hogg & Cho, 2001).

Optimal pig rations should maximise digestibility, minimise health risks like gastric ulceration, be economically viable, and prevent feed bridging. This review aims to explore the impact of particle size and fibre sources on digestion efficiency in growing South African pigs fed corn-soya diets.

## 2.2 Digestion of feed in the pig's gastrointestinal tract

To fully understand the importance and implications of feeding a ration of an altered APS and remodelled fibre profile, the digestive system and the physiology of a pig's digestion should be understood.

Digestion is the process by which feed is converted into usable nutrients, rendering them available for normal body function. Pigs are fed feed, consisting mainly of plant-based feedstuffs such as maize, soya and wheat (mainly so in the southern hemisphere and is commonly referred to as corn-soya

rations), formulated to supply the animal with all its nutrient requirements. This creates a conundrum as nutrients in plant-based feedstuffs are generally protected from the digestive mechanisms of a monogastric animal. To make optimal use of these nutrients supplied, the feed needs to be efficiently utilised by the animal. Efficient utilisation is dependent on the animal's ability to digest and the feed's composition, structure, and form (particle size, mash, and pellets) (Wondra *et al.*, 1995; Ball *et al.*, 2015; Vukmirović *et al.*, 2017).

The pig's digestive system is developed to break-down feedstuffs mechanically, chemically and by microbial activity, with the aim of creating simple compounds that can be absorbed through the mucous membrane. Through raw material processing, grinding to a finer particle and pre-cooking or heat treatment, the digestibility of nutrients can be increased, increasing the contact of acid chyme and the non-glandular gastric mucosa (Cappai *et al.*, 2013). These digested nutrients would later be utilised for the normal body functions, either by being converted into usable energy, into body tissue, such as muscle or stared as fat.

The first section of the pig's digestive system is the mouth, oesophagus, and stomach. The mouth is equipped with incisors, canines, premolars, and molars that enables them to grasp, shear and grind (Laerke & Hedemann, 2012) its feed while it is being lubricated with saliva secreted from three pairs of salivary glands. Saliva contains α-amylase and lysozyme, with mucin, inorganic salt, and water. Although time is limited for the working of α-amylase, this enzyme acts on starch, glycogen and other polysaccharides and oligosaccharides, where it hydrolyses α-(1-4)-glucan bonds (Mc Donald *et al.*, 2011).

The feed bolus is transferred through the oesophagus by peristalsis to the stomach, entering through the pars oesophageal, the non-glandular entrance of the stomach. The activity of α-amylase may continue in this section of the stomach while some microbial fermentation is also possible. The glandular cardia region produces and secretes hydrochloric acid (HCl), pepsinogen, and glycoprotein. Pepsinogen is activated by the acidic condition into pepsin, that hydrolysis protein. HCL denatures protein, exposing its peptide bonds to other proteolytic enzymes. Glycoprotein is the main functional component of mucus, responsible for lubrication and protects the epithelium (Bansil & Turner, 2018).

From here, digesta enters the first segment of the small intestine, the duodenum, through the pyloric region of the stomach. The main function of this segment is the mixing of digesta with digestive enzymes and other secretions before absorption of nutrients in the ileum. Glands of the duodenum secretes mucus that increases the digesta's pH to protect the intestinal wall and contributes to lubrication. Bile secretions enter the duodenum that activates pancreatic lipase and emulsifies fats.

Other pancreatic secretions, including digestive enzymes and insulin, enter the duodenum via the pancreatic duct (Mc Donald *et al.*, 2011).

Finally, after breakdown and absorption of available nutrients, the undigested fraction of the digesta enters the large intestine. These nutrients, carbohydrates, and proteins could be undigested due to entrapment by lignified structures and could include cellulose and hemicellulose that is not digested by the enzymes of the digestive system. The large intestine consisting of ascending, transverse, and descending colon, and the caecum, only secretes mucus. Enzymes found in this section of the digestive system arise from microbial activity or from overflow from the small intestine. Microbial population proliferating in the large intestine alters according to the ration ingredients and the amount and type of nutrients available for them. Commonly this population may include *Lactobacilli, Streptococci, Coliforms, Bacteroides, Clostridia* and yeast. Further digestion of this undigested fraction is dependent on these microorganisms (Mc Donald *et al.*, 2011).

The typical digestive function can be extensively altered by a range of factors and processes regulated by the animal and feed and the properties of feed fed to the animal. Ngoc *et al.* (2011) showed that older pigs had an improved capability of digesting nutrients due to the increased absorption capacity of the small intestine and due to a better colonisation of the large intestine by carbohydrate-degrading microorganisms. This example demonstrates the complex interaction between the animal, its environment and feed characteristics.

Some of the factors influencing the digestive function will be discussed under the following headings: fibre source, digesta flow rate, fermentation, surface area and the conjunctive effect of these factors.

### 2.2.1 Fibre source

In South African pig industry, the primary fibre source is wheat bran, owing to its availability and cost-effectiveness. Sunflower meal is also utilised as a fibre source, despite its significant contribution to crude protein (CP). South Africa has limited fibre sources, with alternative options including lucerne meal, soya hulls, maize bran, dried distillers' grains, and highly processed fibre additives. The choice of fibre source is primarily determined by availability and cost.

Dietary fibre influences digestive physiology through three main mechanisms: (1) providing structure to the digesta that promotes satiety and regulates feed intake; (2) controlling the flow rate through the GIT, which in turn affects circulating glucose and lipid levels; and (3) serving as an energy source for the microbiota through fermentation (Williams *et al.,* 2019). These effects are a result of the fibre's characteristics, such as solubility, digestibility, and fermentability. Understanding these characteristics aids in comprehending the fibre's impact on digestive physiology.

Fibres can be classified based on their solubility in water into soluble and insoluble fibres. Soluble fibres include hemicelluloses (xyloglucans, galactomannans, and mixed-linkage glucans), pectins, mucilages, and gums. These components allow water molecules to interact and penetrate the fibre, increasing its water-holding capacity and enhancing the viscosity of digesta. This, in turn, prolongs the retention time of digesta in the GIT (Capuano, 2017). Fibre also influences the flow rate, which affects circulating glucose and lipid levels, contributing to the pool of available nutrients (Williams *et al*., 2019).

Insoluble fibres consist of cellulose, lignin, and resistant starch. Cellulose is composed of glucose units linearly linked with β-(1-4) bonds, forming a polymer with strong intermolecular hydrogen bonds, making it indigestible by pigs but fermentable to some extent by micro-organisms. Cellulose can be cross-linked with pectin or hemicellulose, rendering these soluble fractions insoluble as well. Insoluble fibres include starch that is encased by cell walls and remains unavailable until the wall is fermented, referred to as resistant starch (Williams *et al*., 2019). These components exclude water from their chemical structure but absorb water, increasing the bulk of digesta and prolonging digesta transit time (Lattimer & Haub, 2010).

Wheat bran, a by-product of wheat milling, comprises the outer layers of the kernel (the pericarp and aleurone layer) and a fraction of the endosperm. Wheat bran contains approximately 10.7% crude fibre (CF), 45.3% neutral detergent fibre (NDF), and 13.7% acid detergent fibre (ADF) (Feedipedia, 2022). Its non-starch polysaccharide (NSP) content is about 43.15%, with 127 g/kg being insoluble fibre and 18.5 g/kg soluble fibre. Due to its high insoluble fibre content, wheat bran is resistant to fermentation (Williams *et al.,* 2019).

Sunflower meal, a by-product of oil extraction from sunflower seeds, contains approximately 18.1% CF, 36.7% NDF, and 26.7% ADF. Its NSP content is about 39.86%, with 408 g/kg being insoluble fibre and 26 g/kg soluble fibre (Ivanova *et al*., 2012; Stevenson *et al*., 2012; Feedipedia, 2022; CVB diervoeding, 2023). Sunflower meal's high soluble NSP content may decrease the viscosity of digesta (Dadalt *et al*., 2016). Table 2.1 compares wheat bran and sunflower meal in terms of nutrient levels.

Table 2.1 Nutrient comparison between wheat bran and sunflower meal (g/kg) (Ivanova *et al*., 2012; Stevenson *et al*., 2012; Feedipedia, 2022; CVB diervoeding, 2023)

| Nutrients | Wheat bran | Sunflower meal |
|---|---|---|
| **Crude fibre** | 10.70 | 18.10 |
| **Acid detergent fibre** | 13.70 | 26.70 |
| **Neutral detergent fibre** | 45.30 | 36.70 |
| **Soluble fibre** | 18.5 | 26 |
| **Insoluble fibre** | 127 | 408 |
| **Non-starch polysaccharides** | 43.15 | 39.86 |
| **Acid detergent lignin** | 3.41 | 5.77 |
| **Remainder NSP fraction** | -2.15 | 3.16 |
| **Starch (Ewers)** | 16.80 | 3.60 |
| **Bypass starch** | 1.90 | 0.10 |
| **Net energy (MJ/kg)** | 6.13 | 5.85 |
| **Moisture** | 11.70 | 11.00 |
| **Crude protein** | 15.60 | 34.70 |
| **Total lysine** | 0.62 | 1.22 |
| **Total methionine** | 0.25 | 0.76 |
| **Total threonine** | 0.52 | 1.28 |
| **Total tryptophan** | 0.22 | 0.42 |
| **Total valine** | 0.73 | 1.70 |
| **Total histidine** | 0.42 | 0.87 |
| **Total isoleucine** | 0.50 | 1.42 |
| **SID lysine** | 0.43 | 0.96 |
| **SID methionine** | 0.18 | 0.67 |
| **SID threonine** | 0.31 | 1.03 |
| **SID tryptophan** | 0.16 | 0.35 |
| **SID valine** | 0.48 | 1.38 |
| **SID histidine** | 0.33 | 0.71 |
| **SID isoleucine** | 0.67 | 1.17 |

*SID – Standardised ileal digestibility*

### 2.2.2 Digesta flow rate

The movement of digesta along the digestive system is brought about by peristaltic movement of the contracting luminal wall, moving it from one section to another. The time it takes the digesta to relocate is defined as transit time or passage rate, while some researchers refer to it as flow rate or retention time of digesta in a specific section (Wilfart *et al.*, 2007).

Rations with a lower APS will increase the flow rate through the digestive tract and thereby decrease the ration's digestibility as less time is available for digestion and absorption. This is also the main reason why a higher feed intake would cause a decrease in digestibility (Khan *et al.*, 2003). A slow flow rate is therefore needed to allow sufficient time for good digestion.

A fast digesta flow rate will result in digesta that is undigested or only partially digested at the end of the digestive tract. A study done by Wilfart *et al.* (2007) investigated the flow rates of digesta through the stomach, small intestine and through the large intestine where pigs were fed rations that differs in the inclusion rate of wheat bran (wheat bran were used in this study as it is an insoluble fibre). The author reported transit times as mean retention time (MRT) for the solid and liquid phase for each section of the GIT. The average of the liquid and solid phases' MRT were 1 hour, 4 hours and 37 hours for the stomach, small intestine, and large intestine respectively. Total tract MRT of the solids and liquids were 45 hours and 39 hours respectively, therefore average of 42 hours. Wilfart *et al.* (2007) found a linear relation between the total tract MRT (both the solid and liquid phases) and NDF (insoluble fibre content) of the ration. The study produced Equations 2.1 and 2.2 to calculate the MRT.

Equation 2.1 Calculating mean retention time for the solid phase of digest.

$$MRT_{solid} = 70.2 - 99(NDF)$$

Equation 2.2 Calculating mean retention time for the liquid phase of digest.

$$MRT_{liquid} = 77.2 - 173(NDF)$$

These equations suggest that as the NDF content of a ration increases, the transit time through the GIT decreases. Furthermore, fibre content has no effect on MRT in the stomach but does affect the small and large intestines. Research indicated that increasing fibre content in a ration decreases dry matter digestibility and increases indigestible content in the GIT, leading to increased peristaltic movement in the intestines (Zhang *et al.*, 2013). This is related to the water-holding capacity and increased bulk of digesta (Grześkowiak *et al*., 2022). Specifically, fibres with high insoluble lignified cell walls, like wheat bran, significantly reduce MRT and increase faecal bulk due to their low fermentability and physical bulk addition (Hu *et al.*, 2023).

Le Goff *et al.* (2002) is of the opinion that higher digestibility of fibres can be seen if the transit time is low, allowing better fermentation in the large intestine by the microbial flora present.

### 2.2.3 Fermentation

Digesta that pass through the small intestine undigested ends up in the large intestine and will either pass through the rectum and be excreted or could be fermented by microorganisms inhabiting this section of the GIT. The success rate of further digestion, depends on the success of fermentation by the inhabiting population of microorganisms (Williams *et al.*, 2019). Maintaining the population of beneficial microorganisms means that competitive pathogenic organisms are limited and that useful short-chain fatty acids (SCFA) can be produced (Liao & Nyachoti, 2017). Commonly this beneficial microorganism population may include *Lactobacilli, Streptococci, Coliforms, Bacteroides, Clostridia* and yeast, all producing SCFA, while preventing what is known as protein fermentation (Jha & Berrocoso, 2016). Protein fermentation is the breakdown of protein into amino acids and further into ammonia ($NH_3$), indoles, phenols and amines that could be harmful to the GIT. This is brought about when the large intestine is not supplied by fermentable carbohydrates and the microorganisms use protein as energy source.

Dietary fibre provides valuable substrate to these beneficial microorganisms in terms of fermentable carbohydrates that can be converted into SCFA beneficial to gut health, such as acetic, propionic, butyric, and lactic acids (Grześkowiak *et al.*, 2022). Acetic acid consists of two carbon atoms, as product of the fermentation of pectin and xylan, and interacts with the G protein-coupled FFAR2 receptor that works on the inflammation and immune responses of the animal (Ratanpaul *et al.*, 2019). Propionic acid consists of three carbon atoms and is most commonly a metabolite of carbohydrate fermentation, although it can also be metabolised from protein. Most propionic acid is used for gluconeogenesis after being absorbed by the portal vein and metabolised in the liver. Propionic acid is also involved with the immune system through its interaction with the G protein-coupled FFAR2 receptor. Lastly it can down regulate feed intake by stimulating satiety (Ratanpaul *et al.*, 2019). Butyric acid consists of four carbon atoms and the major energy supply for colonocytes that enhances growth and metabolisms of these cells. Butyric acid therefore has an influence on the metabolic pathway of the GIT.

Kiarie & Mills (2019) stated that with a higher concentration of starch in the large intestine, microbes can produce more SCFA that inhibits *Salmonella* and other coliforms to thrive. This starch is then utilised by *Lactobacilli* to produce lactate that is further metabolised to acetate, propionate, and butyrate. These volatile fatty acids decrease the pH in the large intestine making the intestinal environment less suitable for *Salmonella* (Visscher *et al.*, 2009).

The higher concentration of starch supply can also be brought about by feeding rations of larger APS, resulting in the same inhibition of *Salmonella*. The larger APS causes more starch to flow into the caecum as less of the available starch is digested in the small intestine (Vukmirović *et al.*, 2017). Kiarie & Mills (2019) agrees and added that coarser rations also impact the microbial population in the cecum and colon establishing a lager fermentation capacity that produces more SCFA such as propionic and butyric acid. These SCFA prevents harmful bacteria such as *Salmonella* and *E. coli* to thrive, thereby creating an overall healthier GIT. They found that the advantage of feeding coarser rations is that the stomach content's pH is decreased and therefore changes the microbial and physiochemical properties of the stomach. These changes include a more solid content, higher anaerobic bacterial count, and a higher concentration of organic acids. A higher microbial fermentation in the stomach and a slower gastric passage rate results in a higher concentration of undissociated lactic acid, which in turn is associated with the elimination of *Salmonella enterica serovar Typhimurium* DT12.

Yet another alternative to provide the large intestine with a higher concentration of starch is to feed resistant starch. Kiarie & Mills (2019) also found that resistant starch is not degraded by enzymes in the GIT and ends up in the large intestine, where it is then fermented by the microbial population producing SCFA, creating an unfavourable environment for pathogens. The fermentation of resistant starch increases secretion of glucagon-like peptide 1 (GLP-1) and peptide YY, both satiety-stimulating hormones, that influences insulin release when GLP-1 binds to the pancreas' β cells.

### 2.2.4 Surface area

Research shows that an increase in the surface area of a raw material would lead to a better digestibility of nutrients due to an increase surface area exposed to the digestive enzymes, which in turn leads to an improved digestion and improved FCR (Vukmirović *et al.*, 2017). By increasing the surface area, in other words, increases the exposed active sites for enzymes to bind into and exerts its action of degradation, allowing enzymes to degrade more of its substrate in a given time. Some nutrients (substrate for enzymes) in feedstuffs are encapsulated by another structure, commonly an indigestible fibrous covering. Starch is digested in the pig's GIT by the exposure to alpha-amylase; by decreasing the APS of maize, starch degrading enzymes are given a larger surface area and more access to the starch granules and therefore increase the enzyme's starch degrading efficiency. This contrasts with protein degradation, possibly because protein is not as encapsulated by fibre as the starch component of maize (Rojas & Stein, 2015).

Amaral *et al.* (2015) investigated the digestion of starch at three different (550; 700 and 800 µm) APS of maize. The study concluded that even though the smallest APS resulted in a better FCR, no other production parameters were improved. The authors focused on the kinetics behind starch digestion

and found that between the different APS the total digestion in the ileum were similar. They however found that the rate at which digestion happened differs, a different percentage of the total starch were digested in the small intestinal sections anterior to the ileum for each of the different APS. It can therefore be concluded that smaller APS maize gradually influences the rate of starch digestion and alters the glycemic index. Amaral *et al.* (2015) agreed that the reduced APS of maize increased the contact area per weight unit to digestive enzymes that cause the change in digestion rate. According to literature (Maxwell *et al*., 1970) the finer particles additionally cause an increase of HCl production in the stomach as well as an increase in pepsin activity. These two products assist in the catabolism of the protein surrounding the maize's endosperm. Since the endosperm is better exposed after the protein is broken down, digestion of the starch is enhanced. Blasel *et al.* (2006) found that for each 100 µm the mean particle size of a ration is decreased, the starch's access to the digestive enzyme is increase by 26.8 g/kg starch, increasing the total ileal energy digestibility.

Dhital *et al.* (2010) investigated starch digestion *in vitro* and stated that the enzymatic hydrolysis of starch is a process that includes the diffusion of the enzyme through the grain's surface, followed by adsorption before the catalysis of the starch is commenced. For this reason, a smaller granule has a higher hydrolytic rate due to the higher surface area to unit mass ration. Considering a whole grain, enzymes should first diffuse through protein matrices and cell walls before being exposed to the starch portion; this process further delays the rate of hydrolysis. Furthermore, the characteristic of the grain plays a role, much as the surface of starches in the study of Dhital *et al.* (2010) differed, the surface of the grains also differs. Maize starch has a relativity rough surface as it contains pores, channels and cavities allowing enzyme diffusion and adsorption and, in that way, increases the rate of hydrolysis. This contrasts with the surface area of potato starch, for example, that lacks these channels and cavities, decreasing the effective surface area and rate of hydrolysis drastically (Dhital *et al.,* 2010).

### 2.2.5 Conjunctive effect

The factors discussed above seldom act as an entity by itself but rather in conjunction with each other and thereby enlarging the influence they have on the digestive function. To demonstrate this, Ngoc *et al.* (2011) explained that nutrient digestibility is affected by the chemical composition of fibres as the degree of lignification plays a role in the solubility of fibres. Soluble fibres are more readily fermented and therefore easier digested than insoluble fibres. Surface area of the feed component also plays a role in digestibility as this would increase the digestive surface exposed to enzymes and microbes. The presence of soluble NSP increases the surface area due to its high water-binding capacity that causes the particles to expand and allows microbes to colonise and degrade the NSP. This soluble dietary fibre may also increase the retention time of digesta, which enhances nutrient absorption time. Fibre source, digesta flow rate, surface area and fermentation all act together, synergically, or

antagonistically, in influencing the digestive function. By applying these principles correctly, one could create an optimal ration that would be optimally digested.

## 2.3 Optimising digestive function

To optimise a pig's digestive function the factors influencing digestion should be considered in terms of implementation into a practical ration. Fibre sources can seldom be classified as only soluble or insoluble and it is not practical to measure surface area of particles and APS is used instead. Fermentation and digesta flow rate can both be considered, but rations cannot be formulated to drive only one since the net effect of the ration plays a more important and practical role. Both undesirable and desirable effects of the complete ration should be considered in optimising the digestive function of a pig.

### 2.3.1 Starch digestion

Energy utilised from grains can be increased by overcoming limitations in terms of grain characteristics and physiological limitations of the animal. The most notifiable limitation of a grain such as maize is that the cereal's dietary fibre contains cellulose and hemicelluloses (arabinoxylan and mixed-linkage glucans) (Williams *et al.*, 2019). These fibres encapsulate the starch and limits access of enzymes to the active sites (Rojas & Stein, 2015). Cereals with high amylose content are also less digestible than cereals with higher amylopectin content (Black, 2001) due to the different chemical linkages found around starch.

Starch is a polysaccharide made up of glucose molecules that are linked with different biochemical structures. Amylose is a simple linear polysaccharide with α-1,4 links between the glucose molecules, forming a tight helical structure that is relatively inaccessible to enzymes. Amylopectin has branches that are more accessible to enzymes and susceptible to enzymatic cleavage due to its α-1,6 glucose links.

Starch is digested in the small intestine where it is broken down into glucose, while the resistant fraction will pass into the large intestine where it will be fermented to produce SCFA. The production of glucose is more efficient than the production of SCFA, the overall starch digestion will therefore be more efficient if a greater fraction is digested in the small intestine and converted into glucose, rather than fermented (Ratanpaul *et al.*, 2019b).

### 2.3.2 Gastric ulceration

#### *Prevalence and feeding practices*

Intensive pig production systems frequently report occurrences of gastric ulcers, including hyperkeratosis, mucosal erosions, and bleeding ulcers. These conditions are more commonly observed

in pigs fed pelleted rations compared to those fed mash rations (Mößeler *et al.,* 2010; Cappai *et al.,* 2013). Gastric ulceration, particularly in the pars oesophageal region, is common across all pigs. While the incidence in sows is lower at 5%, up to 60% of growing pigs may exhibit lesions at slaughter (Muirhead *et al.,* 2013).

Global studies indicated significant variation in the prevalence of gastric ulceration. For instance, 20.7% of slaughtered pigs in Italy, 30% in Denmark and Australia, 34.8% in Colombia, and 32% in the USA exhibited gastric ulcers (Peralvo-Vidal *et al.,* 2021). In South Africa, data from Bodenstein *et al*. (2023), revealed 93% of slaughter pigs to have some degree of ulceration, with 76% having mild ulceration or keratinisation of the pars oesophageal, and 24% having severe ulceration. Kiarie & Mills (2019), estimated that 1% and 2% of finisher pigs die annually from gastric ulceration.

### *Pathogenesis and risk factors*

Gastric ulceration can lead to death when severe haemorrhage occurs, often resulting in sudden deaths among pigs aged 12 to 24 weeks (Cappai *et al.,* 2013). The early stages of ulceration involve roughening of the pars oesophageal, followed by erosion and eventually ulcer development. Although the cause of ulceration is multifactorial, the physical cause is straightforward. The stomach is largely lined with mucus to protect against its acidic contents; however, the non-glandular portion (pars oesophageal) lacks this lining, making it particularly vulnerable to ulceration (Muirhead *et al.,* 2013; Kiarie & Mills, 2019).

Several factors can contribute to the pathogenesis of gastric ulceration, including the raw materials used in rations, heat treatment during processing, grinding intensity, and the resultant APS. Pelleted feed, which influences maize particle size, is a significant factor. APS greatly affects the passage rate through the GIT; coarser rations slow the passage rate, while finer rations accelerate it, allowing stomach acid to induce keratinisation and erosion of the mucosal wall, leading to ulceration (Kiarie & Mills, 2019).

### *Gastric regions and pH dynamics*

Understanding gastric ulceration necessitates defining the stomach's regions: the non-glandular pars oesophageal, cardial, fundus, and pylorus. Figure 2.1, adapted from Mößeler *et al*. (2014), illustrated the four regions of the stomach. Under normal physiological conditions, the pH is highest in the pars oesophageal and lowest in the fundus, where parietal cells secrete HCl (Engevik *et al.,* 2020; De Witte *et al.,* 2018). Mößeler *et al*. (2014) found that feeding pigs a coarse meal resulted in a pH difference of 2.22 between these regions, with values of 5.16 in the pars oesophageal and 2.96 in the fundus. When pigs were given finely ground pelleted feed, the pH difference decreased to 0.2, with pH values ranging between 4.90 and 4.97 across all stomach regions. The buffering capacity also decreased significantly

from 173 to 93 mmol HCl per pH unit between coarse meal and finely ground pelleted feed, respectively.

Finely ground and pelleted feed increases the liquidity of the stomach's digesta, promoting mixing or reflux between different regions. This movement of low pH digesta to the sensitive pars oesophageal prevents the maintenance of lower pH in the fundus and increases HCl secretion, contributing to ulceration (Mößeler *et al.,* 2014).

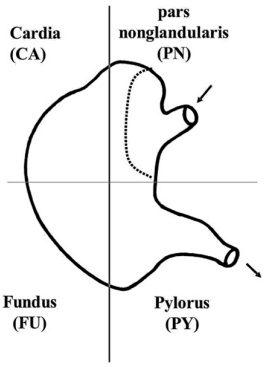


Figure 2.1 Regions of the stomach (Mößeler *et al.*, 2014).

*Optimal particle size and feeding strategies*

Vukmirović *et al.* (2017) concluded that a 600 µm particle size is optimal for stomach morphology, growth performance, nutrient digestion, excretion, and feed mill electricity consumption. However, other studies (Cappai *et al.,* 2013) have reported negative effects on stomach morphology at 600 µm, indicating that APS alone is not a reliable indicator of ulceration risk. The percentage of very fine particles (VFP) below 400 µm in a ration is a critical factor, as coarse particles alone do not mitigate the high ulcerogenic capacity of smaller particles. Rations with less than 29% of particles smaller than 400 µm are considered low-risk for causing ulceration, regardless of the average particle size (Wondra *et al.,* 1995; Cappai *et al.,* 2013; Vukmirović *et al.,* 2017). The optimal particle size for pig rations is believed to be between 500 µm and 1600 µm (Vukmirović *et al.,* 2017).

### 2.3.4 Studying optimal particle size

The impact of particle size on gastric ulceration has been a critical area of study. Vukmirović *et al*. (2017) found that while finer ground feed improves production performance and energy digestibility, it also negatively affects gastrointestinal health. Specifically, decreasing the particle size increased the incidence of pre-ulcerous lesions and ulceration. Serrano *et al*. (2008), confirmed these findings, demonstrating that although reducing particle size can improve digestibility and growth performance, it compromises the mucosal lining of the large intestine and decreases the total weight of the GIT. Additionally, the incidence of gastric ulceration increases when particle size is reduced from 1000 µm

to 400 µm due to increased stomach content viscosity. Feeding a mash form with reduced particle size may also result in higher incidence of respiratory diseases due to more dust created from the feed.

Extensive research has been conducted on the topic of feed particle size in pig rations to determine the optimal size for various production parameters. Studies by Wondra *et al*. (1995), Cappai *et al*. (2013), and Vukmirović *et al*. (2017) have investigated a wide range of APS in rations, each concluding with specific recommendations on the optimal particle sizes tested. Lawrence *et al*. (2003) found that the optimal particle size for pig rations should be between 600 µm and 700 µm to achieve the best growth performance and efficient feed utilisation. Trials conducted on finisher pigs fed maize-based rations indicated that daily gain increased by 8% when pigs were fed a fine ration (with >80% of particles <1200 µm) compared to a coarser ration (with <20% of particles <1200 µm) (Hedde *et al*., 1985).

Total tract digestibility (TTD) of nitrogen and gross energy also improved when particle size was reduced from 1500 µm to 641 µm (Wondra *et al*., 1995). Vukmirović *et al*. (2017) demonstrated that decreasing particle size from 1000 µm to 400 µm reduced the FCR by 8%, increased gross energy digestibility by 7%, decreased faecal nitrogen excretion by 27%, and reduced total dry matter excretion by 26%. Both Wondra *et al*. (1995) and Vukmirović *et al*. (2017) concluded that generally, a decrease of 100 µm in particle size improves feed conversion by 1.3%.

A literature review by Ma *et al*. (2021) confirmed that reducing the particle size of maize enhances the levels of digestible, metabolisable, and gross energy, as well as the apparent ileal digestibility (AID) of starch in pigs at various production stages. These improvements were observed with a reduction in particle size from 865 µm to 339 µm, although Kim *et al*. (2002) recommended an optimal particle size between 640 µm and 650 µm.

Studies that measured feed efficiency in the grower phase, the finisher phase, and the overall grower-to-finisher phase found increases of 8%, 5%, and 7%, respectively, by changing the hammer mill screen from a 6 mm to a 3 mm screen (Callan *et al*., 2007; Vukmirović *et al*., 2017). Despite the benefits of reducing particle size, Vukmirović *et al*. (2017) suggested that the optimal particle size might be larger for older pigs. Specifically, decreasing the particle size of a maize-sorghum ration from 900 µm to 300 µm for weaners led to an increase in energy digestibility.

Particle sizes that are too small negatively affect average daily feed intake. This decrease in feed intake is attributed to reduced palatability, as observed with particle sizes between 400 µm and 360 µm, leading to increased energy consumption per kilogram of feed (Vukmirović *et al*., 2017).

Table 2.2 below summarizes the results of various studies in terms of the particle size investigated and the outcome of each.

Table 2.2 Summary of the effect of particle size on performance and health of grower pigs

| Study Parameter | Outcome |
|---|---|
| **Decrease APS from 1500 µm to 641 µm** | Increase GE and TTD of nitrogen (Vukmirović *et al.*, 2017) |
| **Decrease APS from 1000 µm to 400 µm** | Decrease FCR and increase GE (Wondra *et al.*, 1995) |
| **Decrease APS from 1000 µm to 400 µm** | Higher incidence of gastric ulceration (Wondra *et al.*, 1995) |
| **Decrease APS from 865 µm to 339 µm** | Increase energy and starch AID of maize (Ma *et al.*, 2021) |
| **Decrease APS from 900 µm to 300 µm** | Increase energy digestibility for weaners (Vukmirović *et al.*, 2017) |
| **Feed APS between 640 µm and 650 µm** | Recommended for high energy availability (Ma *et al.*, 2021) |
| **Feed APS between 400 µm and 360 µm** | Decrease palatability and reduce ADFI (Vukmirović *et al.*, 2017) |
| **Feed APS between 600 µm and 700 µm** | Optimal for growth feed utilisation (Lawrence *et al.*, 2003) |
| **Feed APS of 600 µm** | Optimal stomach morphology (Vukmirović *et al.*, 2017) |
| **Particles smaller than 400 µm** | High ulcerogenic capacity (Cappai *et al.*, 2013) |
| **Hammer screen change from 6 mm to 3 mm** | Increase feed efficiency by 7% (Callan *et al.*, 2007) |
| **Every 100 µm APS decreases** | Improves FCR by 1.3% (Blasel *et al.*, 2006) |
| **Less than 29% of particles smaller than 400 µm** | Low ulcerogenic risk (Vukmirović *et al.*, 2017) |

*ASP: average particle size; GE: gross energy; TTD: total tract digestibility; FCR: feed conversion ratio; AID: apparent ileal digestibility; ADFI: average daily feed intake*

## 2.4 Flowability and particle size

Producing feed of a very fine grind has been shown to have negative effects on the animal and its production, leading to economic losses (Vukmirović *et al.*, 2017). It is therefore in the production unit's best interest to find the optimal particle size, but considerations should include the feed mill, its operations and production costs, as a very fine grind could also impact the feed production and feeder system negatively.

### 2.4.1 Optimal particle size

Determining the ideal particle size should take into consideration both the negative and positive effects that grind size has on the animal as well as on the production system, therefore consists of many factors. Factors include the improved digestion of a finer particle, the kinetics of digestion and the negative effects it has on the animal, such as respiratory problems and gastric ulcers. On the feed production side factors includes pellet quality (a finer particle promotes pellet quality), mix-ability

(smaller particle sizes improve mixability as the variability of particles is reduced), energy usage (more energy required for finer grinding) and the reduced flowability with a smaller APS (Amaral *et al.*, 2015).

### 2.4.2 Flowability

The most important of these considerations is to ensure that the ration or raw material can flow freely in bulk tanks, silos, feeders, and any other feed handling equipment (Prescott & Barnum, 2000). This is defined as the flowability of the product and is important as these products will be transferred over a substantial length of systems. Product is constantly being transferred from one component to the next within the manufacturing unit, until it's being loaded into transportation systems and again offloaded into the production unit's feed bins. From these feed bins, the finished feed will further be transported before it ends up in front of the animal. Fine products that do not flow freely will block the system and create a bottle neck, increasing down-time, labour, and maintenance cost, and may ultimately lead to lower feed intake and pig performance (Ganesan *et al.*, 2008).

#### *Influencing factors on flowability*

Flowability of a product is a factor (that determines the flow of the product) of its physical properties such as moisture content, compaction pressure, fat content and particle size (Prescott & Barnum, 2000). Products with higher moisture content will have a lower flowability due to stronger cohesive and adhesion powers, causing the feed not to flow or to bridge. The hygroscopic nature of organic materials and therefore of feed, inclines it to moisture absorption that will increase the cohesive ability of the material due to inter particle liquid bridge formation. The relative humidity in the silo will contribute to the moisture content of the feed (Ganesan *et al.*, 2008) and thereby decrease its flowability.

The compaction of feed or raw materials also causes a decrease in the material's flowability as particles under compaction pressure would have a larger number of contact points between them. More contact points increase the material's inter-particle adhesion and therefore decreases the flowability. Compaction pressure also decrease flowability by increasing the critical arching dimensions, defined as the smallest span that will prevent bridging of a bulk silo (Cannavacciuolo *et al.*, 2009). It is not uncommon for feed and raw materials to be compacted due to the impact of falling material, such as with off-loading into bulk silos and due to vibration caused by transportation (Ganesan *et al.*, 2008).

In summary, the particle size of a material influences factors such as bulk density, cohesive strength, and the angle of repose (AoR) that, together with particle size distribution, has an impact on flowability. Small changes in particle size normally have a significant impact on flowability as it is the most vital factor governing the nature of the material. Finer particle leads to decrease flowability due

to higher compaction and more cohesive powers (Ganesan *et al.*, 2008), all aggravate by a reduced bulk density (Rojas & Stein, 2015) and or an increase in moisture content.

### *Measuring flowability*

The flowability of a material is determined by measuring the maximum slope or angle that the material can sustain as a pile (Lawrence *et al.*, 2003), measured from the horizontal level after it is poured onto a flat surface. This measurement is described as the angle of repose (AoR) and is expressed in degrees of the slope. A higher angle indicates a lower flowability and a lower angle a more flowable material. This test produces a numerical value that can easily be reproduced and adopted as a common assessment of flowability (Craik & Miller, 1958). The physical characteristic of the material influences this angle of repose; as the particles become smaller the AoR becomes greater and the flowability becomes poorer. A material that forms a steep slope with a large AoR therefore has a poor flowability (Groesbeck *et al.*, 2003) as it is influenced by the same factors that would influence flowability (Ganesan *et al.*, 2008).

Groesbeck *et al.* (2003) measured AoR with a tester build with PVC pipes and concluded that with less variation of particle sizes, flowability improved and that by adding fat (they used soya oil) flowability decreased again. Lawrence *et al.* (2003) did flowability tests with solvent-extracted and extruder-expelled soybean meal and found that due to the higher fat content of the extruder soya, the AoR was greater. They have also seen that as the particle size decreased, the AoR increased. With solvent-extracted soya the AoR of the soya was 38.5° while particle size was 444 µm; at 1226 µm the AoR decreased to 30.9°. The extruded soya AoR was 51.9° with a particle size of 639 µm and 44.2° at 965 µm. The complete ration's AoR changed to 53.4°; 53.8°; 55.6° and 52.4°, respectively, for each of the above combinations.

Barbosa-Cánovas & Yan (2013) determined the flowability of materials from its mass flow rate through a conical funnel, using bulk density ($g.cm^{-3}$), orifice diameter D (cm) and the mean particle diameter (d) of the test material (cm). For this calculation, the measuring of bulk density as well as determining the particle size was added steps. The formula used to calculate the mass flow rate ($V_m$) was denoted as per Equation 2.3 below:

Equation 2.3 Calculation of mass flow rate:

$$V_m = \alpha_b(D - \beta d).$$

The external AoR, or the poured AoR, is measured using a conical funnel through which the material is poured onto a flat surface. As the material is poured, the funnel can be lifted as to minimise the effect of falling particles on the height of the heap that is formed. The material should be poured until

the heap reaches a predetermined width. The angle is then calculated by using the inverse tangent rule, the maximum height of the heap of material and the average radius of the flat surface's width (Zhichao, 2011; Beakawi Al-Hashemi & Baghabra Al-Amoudi, 2018). This method required fewer variables and had no need for prior calculations, making this a more robust method for the animal feed industry. Figure 2.2 visualises the processes of measuring AoR practically. Research by Beakawi Al-Hashemi & Baghabra Al-Amoudi (2018) calculated the AoR of different materials that could be used as an indication of what values can be expected in future studies. This research showed that maize flour will have an AoR of between 30° and 40°, while wheat flour would be 45° and whole wheat 27°.

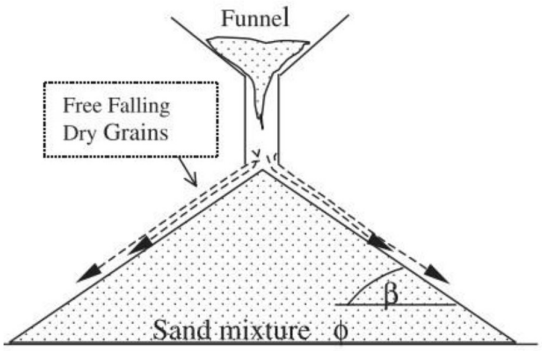


Figure 2.2 Visualising how AoR can practically be measured (Chik & Vallejo, 2005).

## 2.5 Reducing particle size through grinding

Roller mills produce the most uniformity in particle size as particles are pressed and rolled between the rollers, cutting and shearing particles into irregular shapes with many edges. This creates more surface area for digestion. In contrast, hammer mills produce more spherical particles as hammers forces particles through a screen (Wondra *et al.*, 1995; Vukmirović *et al.*, 2017).

Saensukjaroenphon *et al.* (2017) found that the most common way to decrease the particle size of maize meal in a mill is to replace the hammer mill's screen with a screen with a screen that has smaller diameter. This is a time-consuming process that increases the downtime of the mill and therefore decreases productive time. Alternatively, by changing the hammer's tip speed, particle size can be adjusted with minimum downtime. The principle behind this is that the size of the hammer mill's screen determines the maximum size of particle it will produce, but the longer the particle spends in the chamber the smaller it will become, since the frequency of it colliding with the hammers will increase. By increasing the rotation of the hammers (tip speed) the frequency of collision between hammers and the particle will be higher and so the particles will decrease in size even more. Saensukjaroenphon *et al.* (2017) demonstrated this with an interaction found between tip speed and

the size of the screen, as a coarser screen decreased the geometric mean diameter of particles more than a smaller screen, with increase tip speeds.

### 2.5.1 Tip speed

Since the hammer's tip speed is a factor of the revolutions per minute (RPM) of the motor; by adjusting the motor's RPM one can change the particle size produced. To achieve this, the hammer mill's motor should be fitted with a variable frequency drive (VFD). Tip speed can be calculated by using the formula in Equation 2.4 as suggested by Braun *et al*. (2021).

Equation 2.4 Calculating hammer mill's tip speed:

$$Tip\ speed = \frac{\pi \times diameter \times RPM}{60}.$$

In a trail conducted by Saensukjaroenphon *et al.* (2017) maize was milled at three different tip speeds, 52 m/s; 78 m/s and 104 m/s and found that by using the same 2.38 mm screen the geometric mean diameter of particles produced decreased by 233 µm after increasing the tip speed from 52 m/s to 104 m/s. Similarly, the geometric mean decreased by 258 µm and 305 µm using a 3.96 mm and 6.35 mm screen respectively. This illustrated that product of different particle sizes can be produced using a single sieve. For each of these decreases in geometric mean diameters the standard deviation among particles also decreased by 0.31, 0.24 and 0.13 respectively, indicating that the uniformity of particles increased the more contact it had with the hammers. Rojas & Stein (2015) agreed with the better uniformity but said that this was because a screen allows particles up to the size of the screen to pass through as milled particles but also allows smaller particles to pass through. Therefore, by using a smaller size screen, the resulting particles are less variable compared to the resulting particles when using a larger screen.

### 2.5.2 Angle of repose

Rojas & Stein (2015) and Saensukjaroenphon *et al.* (2017) both calculated the AoR as a predictor of flowability of the meal produced in their trails. As the particle size decreased, the AoR increased that in turn indicated that the flowability decreased. AoR was calculated using 200 g of samples dispensed onto a flat surface with a diameter of 135 mm and measuring the maximum height of the of the pile created. These measurements were then used as per Equation 2.5 below.

Equation 2.5 Calculating angle of repose (AoR):

$$AoR = \tan^{-1} \frac{maximum\ pile\ height}{platform\ radium}$$

The AoR for ground maize in this trial was 43.9, 41.3 and 38.6 for 2.38 mm, 3.96 mm, and 6.35 mm screen sizes, respectively. The AoR of ground maize were 38.0, 41.4 and 44.3 for tip speeds of 52 m/s, 78 m/s, and 104 m/s, respectively.

### 2.5.3 Pelleting

Normally, a finer particle is used to produce pelleted feed as a coarse particle can contribute to a lower pellet quality. To determine the VFP proportion of a pelleted feed, particle size distribution should be calculated after pelleting as the pelleting process itself contributes to the grinding process. As an alternative, raw materials should be grinded coarser pre-pelleting so that the final pelleted ration's particle size is not too small. The correct way, however, is to do analysis with a wet sieve to determine particle size of pelleted feed for accurate calculation of the VFP size proportion of the ration (Cappai *et al.*, 2013).

## 2.6 Conclusion

Investigating the normal digestion of feed through a pig's digestive tract, the implications of alternating the source of fibre and the effect of feed particle size on the overall system, it is clear that a unidirectional adjustment could incite both positive and negative effects. It is therefore essential for an economically feasible production unit to find the optimal solution, which would not necessarily promote the maximum digestion or flow rate, or the smallest maize particle, but the most cost efficient and practical production solution for all the factors combined. The optimal solution can therefore not be formulated and inserted into any system but should be tailored to the specific system.

From literature the following guidelines should be considered in tailoring a solution:

- The overall formulation of the ration should supply nutrients at the correct levels to the correct section of the GIT.
- Consider the type and inclusion of fibre source to support digestive function, a slower digesta flow rate and better fermentation in the hindgut.
- Enzymatic function is vital and nutrient supply should be correct and in an available structure. This speaks to the surface area and exposure of particles to enzymes.
- The ration's APS should be as low as possible without causing flowability issues and without causing gastric ulceration.

# Chapter Three: Materials and methods

## 3.1 Introduction

The trial was conducted under normal commercial conditions on a commercial farm with feed that was practical to produce.

The experiment was designed in such a way as to collect as much scientific data as possible, while at the same time remain within the constraints of a practical commercial set-up and ensuring the welfare of the animals. Ethical clearance for this experiment was granted by the Faculty of Natural and Agricultural Sciences and the Animal Ethics Committee of the University of Pretoria (NAS179/2019).

## 3.2 Materials

### 3.2.1 Experimental animals

Commercial finisher pigs were used in this study, all supplied from the same origin farm and all F1 progeny bred from Topigs Norsvin (TN) South Africa's F1 female, the TN60. These females get served by Topigs Norsvin's terminal sires, the Tempo. The breeding was done on a commercial farm, Molare (Pty) Ltd, located in Middelburg, Mpumalanga, South Africa. The F1 progeny were raised in the farm's normal commercial setting where pigs are being weaned on 28 days-of-age and moved into a weaner section until 12 weeks-of-age. At the start of 13 weeks, these animals were transferred by truck to the grower section where the experiment was conducted, located on the same farm, but 3 km away from the breeding unit. This transfer induced minimum stress and was done early morning to reduce heat stress; upon arrival pigs had ad libitum access to water and feed. A total of 288 pigs were used for the study, divided into six treatment groups with six replicates each. The trial was designed with six treatments in a 2 x 3 factorial arrangement, examining the main effects of fibre source (wheat bran and sunflower meal) and maize grind size (720 µm, 741 µm, and 774 µm). The specific treatments were as follows: wheat bran with maize ground to 720 µm, wheat bran with maize ground to 741 µm, wheat bran with maize ground to 774 µm, sunflower meal with maize ground to 720 µm, sunflower meal with maize ground to 741 µm, and sunflower meal with maize ground to 774 µm. The pigs were fed these treatment rations from 19 weeks-of-age until slaughter at 22 weeks-of-age. The experiment was conducted during the summer in the month of January.

### 3.2.2 Housing

All the experimental animals were housed in the same grower building, consisting of 36 pens, divided into 2 rows of 18 back-to-back pens and two passages along the outside walls. The pens were 2.6 m by 2.8 m that equals to 7.28 $m^2$ per pen. For the study 8 animals were kept per pen, allowing them 0.91 $m^2$ per pig. This space allowance is within the industry norm, where the SAPPO Pork 360 standard allows for 130 $kg/m^2$ (SAPPO, 2022). The penning was made of iron rods, allowing nose-to-nose contact

between the animals in adjacent pens, two on each side and one behind. The flooring was fully slatted, allowing faeces, urine, and feed wastage to fall through into a flush channel. The buildings' roof was mono-pitched with sheet metal and insulated with polycool, it was an open sided building with adjustable curtains, controlled by a Hotraco Agri Cygnus controller. Temperature inside the building was controlled by regulation of height of the curtain, allowing natural ventilation into the building. Only natural lighting was used in the building.

Feed was supplied through a single pig feeder with a nose operated toggle dispensing mechanism (Cawi, a MS Schipppers product), these feeders allowed the pig access to feed by toggling a metal rod at nose height that in turn dispenses a portion of feed per toggle. During the experiment, feeders were filled by hand using measured bagged feed, specific to each treatment. Pens were regularly inspected to ensure that all equipment was operational, and that water was available throughout the experimental period. Water was supplied *ad libitum* by drinker nipples located in each pen, opposite the feeder and at nose height. Each Cawi feeder had its own water nipple that allowed the pig to drink while eating and could therefore wet its own feed. Water was sourced from the Middelburg municipality that was pumped into a central water reservoir that supplied the building and the rest of the unit; this ensures a constant water supply. Water quality was monitored and complied with the livestock watering regulations (DWAF, 1996).

### 3.2.3 Experimental trail set-up

The building was divided into three blocks with twelve pens per block. Within each block, the twelve pens were each randomly allocated to one of the six treatments. There were six replications of each treatment. A colour card was tied onto each Cawi feeder to indicate the allocated treatment. The treatment specific feed was used to fill-up the Cawi feeder. Feeders were filled-up twice daily to ensure *ad libitum* feeding throughout the experiment.

### 3.2.4 Raw materials and ration preparation

The set of raw materials used for formulating the experimental feed is considered the standard available raw materials commonly used in the South African market. These raw materials consisted of yellow maize, soybean meal, wheat bran and sunflower meal. All other ingredients and additives used in these rations were readily available at the mill and used for standard pig rations. Chromium oxide ($Cr_2O_3$) was used as an indigestible marker; this was the only ingredient that had to be specially procured.

#### *Raw materials*

In preparing the final treatment rations, samples of all available raw materials were collected for proximate analysis using near infrared spectrometry (NIR). The NIR analysis was conducted at CSVet's

feed laboratory in Pretoria, following their standard operating procedures (SOP) with a Perten DA7200, using the current calibrations for each raw material. The results from these scans were used to set the matrix values of the raw materials included in the rations, ensuring the final product was as accurate as practically possible. Table 3.1 presents the nutrient levels of the raw materials obtained from the NIR analysis. These values, along with those from the Dutch Feed Evaluation system (CVB) (CVB diervoeding, 2023), were used to formulate the experimental rations.

Table 3.1 Nutrient composition* of the raw materials used in the experimental feeds (%)

| Raw materials | Moisture | Crude protein | Crude fibre | Crude fat | Starch | Calcium |
|---|---|---|---|---|---|---|
| **Yellow maize meal** | 12.80 | 7.40 | 2.20 | 3.80 | 62.40 | |
| **Soybean meal** | 12.50 | 46.02 | 6.04 | 1.84 | | |
| **Wheat bran** | 11.70 | 15.60 | 10.70 | 3.50 | 16.80 | |
| **Full fat soya** | 11.50 | 35.10 | 5.60 | 19.20 | | |
| **Lucern** | 10.76 | 15.30 | | | | |
| **Sunflower meal** | 8.46 | 34.13 | 23.37 | 2.24 | | |
| **Limestone** | 2.43 | | | | | 24.47 |

**As determined by near infrared spectrometry (NIR)*

### *Basal rations*

First a standard commercial finisher ration was formulated using feed formulation software (BESTMIX®, Adifo Software) according to recommendations of the genetic company, Topigs Norsvin, for finishers between 19 and 22 weeks-of-age and 94 to 104 kg live weight (Topigs Norsvin Feeding Manual, 2015). Table 3.2 shows the nutrient specifications of a finisher ration to be fed to growers between 19 and 22 weeks-of-age and 94 and 104 kg live weight. The net energy (NE) and standard ileal digestibility (SID) of lysine (Lys) specifications had to be adjusted for the inclusion of Ractopamine hydrochloride (Paylean) (Abbas *et al.*, 2022) as specified by the supplier, as this is commonly used in commercial finisher rations in South Africa.

From these specifications, the two basal treatment rations were formulated, one with the inclusion of mainly wheat bran as fibre source (referred to as the wheat bran ration) and the other with a very low inclusion rate of wheat bran, but with a high inclusion rate of sunflower oil cake as the main fibre source (referred to as the sunflower meal ration). Table 3.3 shows the raw material inclusion rates for these rations. The same quantity of maize (630 g/kg) was included for each of the six treatment rations, each with a 4 mg/kg of $Cr_2O_3$ as a marker that enabled digestibility calculations from faecal grab

samples (De Vega & Poppi, 1997). Table 3.4 shows the nutrient specifications of the two different rations

Table 3.2 Specifications for finisher rations (g/kg)

| Nutrients | Topigs Norsvin Manual | Paylean adjusted |
|---|---|---|
| **Net energy (MJ/Kg)** | 9.94 | 9.55 |
| **Standardized ileal digestible lysine** | 7.78 | 9.80 |
| **SID lysine:Net energy** | 0.78 | 1.03 |
| **Crude protein** | | ≥ 160 |
| **Calcium** | 5.92 | |
| **Digestible phosphorous** | 2.82 | |

*Recommended specification for Tempo finisher pigs between 19 and 22 weeks of age and between 94 and 104kg live weight (Topigs Norsvin Feeding Manual, 2015) and adjustments recommended for Paylean inclusion (Abbas et al., 2022).*

Table 3.3 Raw material inclusion levels for each of the two basic treatments (g/kg)

| Raw Materials | Wheat Bran Ration | Sunflower Meal Ration |
|---|---|---|
| **Yellow maize meal** | 630 | 630 |
| **Soya meal** | 130 | 130 |
| **Wheat bran** | 135 | 16 |
| **Full fat soya** | 50 | 65 |
| **Lucern** | 0 | 40 |
| **Sunflower meal** | 20 | 80 |
| **Soya oil** | 0.00 | 5.00 |
| **Limestone** | 2.50 | 2.50 |
| **Monodicalcium phosphate** | 16.11 | 16.18 |
| **Salt** | 6.00 | 6.00 |
| **L-lysine HCL** | 4.40 | 3.96 |
| **DL-methionine** | 0.68 | 0.43 |
| **L-threonine** | 2.07 | 1.65 |
| **L-tryptophan** | 0.40 | 0.33 |
| **Finisher pre-mix** | 2.50 | 2.50 |
| **Paylean** | 0.30 | 0.30 |
| **Chromic oxide** | 0.004 | 0.004 |
| **Total mix** | 1000 | 1000 |

Table 3.4 Formulated nutrient specifications of the basal treatments (g/kg)

| Nutrients | Wheat bran ration | Sunflower meal ration |
|---|---|---|
| **Net energy (MJ/kg)** | 9.48 | 9.43 |
| **Standardized ileal digestible lysine** | 9.41 | 9.41 |
| **SID lysine:Net energy** | 0.99 | 1.00 |
| **Crude protein** | 158.38 | 166.44 |
| **Crude fat** | 41.04 | 46.12 |
| **Crude fibre** | 42.58 | 43.77 |
| **Acid detergent fibre** | 56.40 | 57.30 |
| **Neutral detergent fibre** | 154.13 | 126.76 |
| **Calcium (g/kg)** | 5.45 | 5.49 |
| **Phosphorous** | 8.29 | 7.69 |
| **Digestible phosphorous** | 4.13 | 4.00 |
| **Sodium** | 2.25 | 2.21 |

*Maize grinding*

The experimental rations were all mixed by Molare's on-farm feed mill that mix feed for own use and for that of other pig farm clients. Two hammer mill screens were available, i.e. 3 mm and 4 mm, to create maize meal with different particle sizes and distributions. The finest maize grind (MG1) was created by using only the 3 mm screen, the coarsest maize grind (MG3) by using only the 4 mm screen, both produced by the same hammer mill set to the same RPM. The in-between maize grind (MG2) was a combination of meal milled with the 3 mm and 4 mm screen. The final mean particle size and distribution of particle sizes of each grind were determined by CSVet's feed laboratory, using a 9-tier sieve shaker with different sieve sizes. The mean particle sizes of the different grinds were 720 µm, 741 µm and 774 µm, respectively, with MG1 containing 31% fines (≤425 µm) and 35.7% coarse maize (≥850 µm), MG2 28.2% fines and 37.3% coarse maize and MG3 23.8% fines and 39.8% coarse maize.

*Feed mixing*

Before mixing of the rations started, a macro pack of ingredients with low inclusion levels was created for a 2-ton mixing batch. These ingredients included salt, L-lysine, DL-methionine, L-threonine, L-tryptophan, Paylean, a vitamin and mineral premix pack and the $Cr_2O_3$. At first, 8 g of $Cr_2O_3$ were weighted out into a test tube, while 600 g of Paylean were weighed out into a bucket. The content of the test tube was then added to the bucket and carefully mixed by hand to ensure that the $Cr_2O_3$ was properly mixed into the Paylean. The other ingredients from the list were then weighted out into the

same bucket. The final mixing process was done in the feed mill where raw materials were added to the mixer by means of an electronic operated batch controller, mixing 2 tons of feed per batch. The macro pack ingredients together with limestone and mono-dicalcium phosphate (MDCP) were hand-added to the mixer.

### 3.2.5 Treatments

The trial was designed with six treatments arranged in a 2 x 3 factorial structure, examining the main effects being fibre source (wheat bran and sunflower meal) and maize grind size (MG1, MG2, MG3). Two rations were formulated; a wheat bran ration (WBR) and a sunflower meal ration (SMR), both formulated to a crude fibre (CF) content of 4.3% (Table 3.4). The acid detergent fibre (ADF) content was 5.64% for WBR and 5.73% for SMR, while the neutral detergent fibre (NDF) content was 15.41% for WBR and 12.67% for SMR.

Both rations were mixed with maize meal at three different grind sizes (MG1, MG2, and MG3), maintaining a constant inclusion rate of maize meal across all six treatments. The first treatment was a WBR with maize grind 1 (720 µm) and denoted as WM1. The second treatment was a WBR with maize grind 2 (741 µm), denoted as WM2. The third treatment was WBR with maize grind 3 (774 µm), denoted as WM3. The fourth to sixth treatments were SMR with each of the maize grind sizes as per WBR and denoted as SM1, SM2 and SM3, respectively. Table 3.5 details the six different treatment designations and the compositions corresponding to the various maize grind sizes.

Table 3.5 Mean grind size of maize with detonations of the six experimental treatments used in the study

| | Maize grind size | Wheat Bran Ration | Sunflower Meal Ration |
|---|---|---|---|
| **Maize Mean Grind Size 1** | 720 µm | WM1 | SM1 |
| **Maize Mean Grind Size 2** | 741 µm | WM2 | SM2 |
| **Maize Mean Grind Size 3** | 774 µm | WM3 | SM3 |

*WM1 – wheat bran with maize grind 1 treatment; WM2 - wheat bran with maize grind 2 treatment; WM3 - wheat bran with maize grind 3 treatment; SM1 – sunflower meal with maize grind 1 treatment; SM2 – sunflower meal with maize grind 2 treatment; SM3 – sunflower meal with maize grind 3 treatment*

## 3.3 Methods

### 3.3.1 Animal processing, sample- and data collection

The experimental period started on the Monday of the week that the batch of animal turned 19 weeks-of-age. On this day all animals were weighed, to determine the start weight, and tagged with identification for the pen and treatment group it had been assigned to as well as an individual number

for each pig. Each Cawi feeder was emptied from the previous grower ration and re-filled with the treatment specific ration, all treatment feed added to the feeder was weighed and recorded. All pigs in the experiment were weighed 1, 2 and 3 weeks after this initial weighing to determine growth rate and the final weight before slaughter. The final weighing was therefore done at 22 weeks-of-age.

### *Animal euthanasia*

On the last day of the experimental period, one pig per pen, thus eight pigs per treatment, was individually euthanised, for sample collection. Animals were euthanised under veterinary supervision with a penetrative captive-bolt as per the method described by the Humane Slaughter Association (Captive-Bolt Stunning of Livestock, 2013). One at a time, pigs were moved out of the pen to the adjacent building, where each pig was blocked with a handling board between the board and the pen's wall. A captive-bolt were placed on the crossing point between each ear and the opposite eye before the trigger was pulled (Pig Euthanasia-On Farm Options). Signs of insensibility were observed before further processing continued. The pig was then exsanguinated to ensure euthanasia.

### *Sample collection*

After the animal was euthanised, the gastrointestinal system was eviscerated for evaluation and sample collection. After locating the ileum, two cable-ties were used to close each end of the ileum and then dissected by cutting on the outside of each of the cable-ties. The content of the ileum was transferred into a tube by removing one of the cable-ties and pouring it out. From the rectum a faecal sample was taken by hand and placed in a plastic tub with a screw lid.

All of the samples were kept cool in an insulated box, the ileum samples were frozen to -18°C (Mosenthin *et al.*, 2007) at the end of the day, while the faecal samples were kept in a fridge until further analyses.

### *Gastric ulceration scoring*

Gastric ulceration scores were done by an independent veterinarian with prior experience. The veterinarian evaluated and scored the stomachs for gastric ulceration using a 5-point scale system that were adapted from system used by Ball *et al.* (2015). The system used by Ball *et al.* (2015) scored gastric ulceration using a 4-point scale where keratinisation was characterized by the yellowness of the stomach wall. In the study they gave a zero score if the stomach had no keratinisation, one score where mild keratinisation was found, two for moderate and three for server keratinisation. Details of the scoring system are given on Table 3.6.

Table 3.6 Score 0 to 5 allocated according to the severity of gastric ulceration

| Description of ulceration detected | Score |
|---|---|
| No keratinisation occurs in the stomach | 0 |
| Mild to moderate keratinisation | 1 |
| Marked keratinisation | 2 |
| Marked keratinisation with ulceration | 4 |
| Diffuse ulceration occurs | 5 |

### 3.3.2 Feed sample analysis

500 g samples of each of the treatment rations were taken after the final mixing. These samples were placed in a plastic zip lock bag and sent to independent laboratories for analysis.

*Near infrared spectrometry*

All final feed samples were analysed by NIR at CSVet's feed laboratory in Pretoria, following their standard operating procedures (SOP) with a Perten DA7200, using current calibrations for pig rations. Evonik, South Africa, Midrand, analysed feed samples for the amino acid profile using their AminoNIR®, this spectrometry technology is calibrated and validated specifically for detecting the amino acid profiles in feed. These results were only used to verify result produced by the Food and Drug Assurance (FDA) laboratory and no further analysis were done on these results.

*Particle size and distribution*

CSVet's feed laboratory did sieve tests on the maize meal and on the final feeds. The sieve tests were conducted using a 9-tier sieve shaker according to the laboratory's in-house method and the average particle size was calculated from these results. Prior to conducting the sieve test, all sieves were individually weighed and recorded. The sieve test method used 500 g of final feed for 5 minutes, while 300 g of maize meal was used for 7 minutes to ensure proper separation of particles. The sieves were stacked with the largest sieve aperture on top, decreasing apertures down the stack to the smallest sieve aperture at the bottom. A collection pan was added to the bottom of the tower. The correct weight of sample was weighted out and added to the top sieve in the tower. The lid of the shaker was closed, and the timer set to correct time before it was started. After the time elapsed, the lid was opened, and the top sieve carefully taken down and placed on a scale. The weight of the sieve with the remaining particles ($w$ = scaled weight) was recorded before the sieve was cleaned for the next use. This process was repeated for each of the sieves and the collection pan. The percentage particle on each sieve (PPOS) was determined by deducting these scaled weights ($w$) individually from the

empty sieve weights (*s*) and then calculating the percentage of product from the total weight of product recovered from the sample tested. This calculation is shown in Equation 3.1.

Equation 3.1 Calculating percentage particle on sieve (PPOS):

$$PPOS = 100 \times \left[ (w_n - s_n) \Big/ \sum_{n=sieve}^{10} (w_n - s_n) \right]$$

Where *n* = the different sieves; *w* = scaled weight; *s* = sieve weight

A further calculation was done on the 2500 µm and 2000 µm fractions of each of the treatment ration samples to determine what proportion of each of these fractions was made up of maize. After the sieve test, the product left on each of these sieves (2500 µm and 2000 µm sieve) were individually spread out on the table, by hand all the maize particles were moved aside, recollected, and weighted. This weight was then recorded as a percentage of the total weight of that fraction.

A particle size was allocated to each treatment ration and to each of the maize grind sizes; the allocated particle size was calculated to infer an average particle size (APS) for each sample. In calculating the APS, each sieve's aperture was used to obtain an assumed collected particle size of particles that each sieve would entrap according to the aperture of the previous or following sieve. Table 3.7 shows the sequence of sieves in the tier used each sieve's aperture and the corresponding collected particle size. This collected particle size was calculated from half the difference between the sieve's aperture and the following sieve's aperture and then adding the sieve's own aperture.

Table 3.7 Sieves and their apertures used for average particle size (APS) calculation

| Position in tier | Sieve aperture (µm) | Collected particle size (µm) |
|---|---|---|
| **Top sieve** | 2500 | 2750 |
| **Second sieve** | 2000 | 2500 |
| **Third sieve** | 1000 | 1075 |
| **Fourth sieve** | 850 | 925 |
| **Fifth sieve** | 710 | 780 |
| **Sixth sieve** | 600 | 655 |
| **Seventh sieve** | 500 | 550 |
| **Eighth sieve** | 425 | 463 |
| **Ninth sieve** | 355 | 390 |
| **Bottom collection pan** | 0 | 178 |

APS was then calculated as the sum of each sieve's contribution, calculated by multiplying the PPOS with the collected particle size as in Table 3.6 Equation 3.2 visualizes this mathematically.

Equation 3.2 Calculating average particle size (APS) from sieve test analysis:

$$APS = \sum_{n=sieve}^{10} (PPOS_n \times CPS_n)$$

*Wet chemistry analysis*

Feed samples were duplicated to be sent out to the different laboratories. A feed sample from each treatment was sent to the Food and Drug Association Laboratory in Pretoria to analyse for the amino acid profile. Liquid Chromatography Mass Spectrometry (LCMS) method was used for this analysis (method nr LCMS-074). This analysis was important to establish the correct amino level of each treatment for digestibility determinations. One of the duplicated feed samples of each treatment was sent to Nvirotek Laboratories in Hartebeespoort to analyse for the concentration of $Cr_2O_3$ by means of Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) (IFRA, 2016) that was later used to calculate the digestibility of nutrients. Analysis for dry matter (DM) (AOAC 934.01; 105°C for 4 hours), CF (ANKOM, AOCS Ba 6a-05), ADF (ANKOM method ADF 01/02) and NDF (ANKOM method NDF 01/02) was also conducted as this laboratory according to their standard methods.

### 3.3.3 Slaughtering of animals at abattoir

From the total of 288 animals, only 48 were euthanised on farm, while the remaining animals were loaded at 22-weeks-of-age for slaughter at Rica abattoir in Randfontein. These 240 animals were loaded on two separate loads, 120 per load and 20 animals from each of the six treatments. The trip to the abattoir was 240 km and took about two hours thirty minutes; the pigs were all slaughtered the day after arrival, after spending the night in the abattoir's lairage. There were no dead-on-arrival pigs, nor were there any carcass or partial condemnations. On the slaughter line each carcass was individually identified using the ear tag number given to each on the first day of the experiment. Using this number, slaughter data were correlated to individuals and back to each animal's treatment group and block within treatment. Warm- and cold-carcass mass, meat millimetres and percentage, fat percentage, sex and grading were measured and recorded for each carcass. Weight measures were taken with hanging carcasses from a hook on an overhead track rail scale and recorded electronically to a software program. Grading measures were taken with the Hennessy Grading system probe (Hennessy Technology: Grading) that were also recorded electronically to a software program.

### 3.3.4 Faecal and ileal digesta sample analysis

The ileum content samples were analysed by Nvirotek Laboratories for its amino acid profile, $Cr_2O_3$ and DM content (Dadalt *et al.*, 2016). AID was calculated for each amino acid according to Equation 3.3.

Equation 3.3 Calculating apparent ileal digestibility (AID):

$$AID_{AA} = \frac{[Cr_2O_3]_{Feed}}{[Cr_2O_3]_{Ileal\ digesta}} \times \frac{AA_{Ileal\ digesta}}{AA_{Feed}}$$

Where AA = amino acid calculated for (g/100g)

Similar to the feed, faecal samples of each of the individual animals were analysed by Nvirotek Laboratories for $Cr_2O_3$ by ICP-OES. These samples were analysed for DM, CF, ADF, NDF and starch (AOAC 996.11) according to the laboratory's standard methods. These nutrients were used in the calculation of TTD (Wang & Adeola, 2017) with Equation 3.4.

Equation 3.4 Calculating total tract digestibility (TTD):

$$TTD_{CF} = \frac{[Cr_2O_3]_{Feed}}{[Cr_2O_3]_{faecal}} \times \frac{CF_{faecal}}{CF_{Feed}}$$

Where CF (%) was replaced for each of the other nutrients calculated.

### 3.3.5 Statistical analysis of data

Data collected during this trail was analysed by ANOVA according to a 2 x 3 factorial design, using SAS software. Blocking was applied to minimise facility effect; all interactions were investigated. The euthanised pigs were each evaluated as an experimental unit. Each sample collected was therefore used as an individual data point, while the feed and weight data were evaluated per pen. Analysis of the feed samples was done per treatment.

Gastric ulceration average score (UAS) was calculated by using the number of animals per score group, multiplying it with the score and then dividing it by the total number of animals in that treatment or group. The equation that was used is described in Equation 3.5. This data was statistically analysed with Chi-Square and interactions were run between treatments, grind sizes and basal rations.

Equation 3.5 Calculating average ulceration score (UAS):

$$UAS = \sum \frac{\text{Ulceration score} \times \text{number animals}}{Total\ number\ animals}$$

# Chapter Four: Results and discussion

## 4.1 Feed

### 4.1.1 Nutrient composition

Although efforts were directed to match formulation values with actual feed mixed, the results of the analysis of the final mixed feeds showed that there were some deviations which was significant ($P < 0.05$). These findings are normal as variation within a raw material sample is expected. The feed mill aims to mix feed in such a way to ensure that every sample of final feed is identical in composition. Over-all this has been achieved in that the composition of all samples and bags of feed were similar, it can therefore be stated that feed was all mixed homogeneously. Since raw materials were scanned with a NIR to determine nutrient composition, the results were only an estimation of the actual nutrient content. It was deemed unnecessary to do wet chemistry analysis on the raw materials, as those samples would not have differed notably from those used in the final feed. Generally, it is accepted that a 5% variance in specifications due to testing methods and raw material variance can occur.

In Table 4.1, the difference between each treatment ration and its basic formulation can be seen. The WBR and SMR rations were formulated to a 9.48 MJ/kg NE and 9.44 MJ/kg NE, respectively. The WBR energy was found to be an average of 7.3% higher than the formulated value. WM1 were 9.5% higher, where WM2 was 6.4% higher and WM3 7.1% higher. The SMR were close to target and on average 4% higher in NE, with SM3 that varied the most from its formulation being 4.9% higher in NE. On average the SMR NE value was 9.81 MJ, while the WBR NE value were 4% higher at 10.21 MJ. It is therefore accepted that the SMR were as formulated, while the WBR were higher in NE. This may be due to an underestimation of the wheat bran's energy contribution.

The crude protein content of the treatment rations was within the allowable 5% variance, besides that of WM3 and SM3 that varied with 5.1% and 5.2% respectively. SM3 had a CP content of 17.96% while it was formulated to be 17.07% and therefore within the acceptable range. The total lysine analysed in these rations was all very close to the formulated values, with only numerical differences. The crude fibre fraction of all rations was much lower than formulated, while the starch content was all higher. The ADF and NDF fractions of the WBR were lower than formulated while the SMR rations' ADF and NDF were all higher than formulated. This all points to the incorrect calculation of these nutrients or that the matrix values used for raw materials for these fractions that was not set correctly for the different fibre sources. The difference between treatments within the same ration is relatively small, it can therefore be concluded that the homogeneity between treatments was acceptable.

Table 4.1 Formulated versus actual nutrient composition of the basal rations (%)

| Nutrients | Wheat bran ration | | | | Sunflower meal ration | | | |
|---|---|---|---|---|---|---|---|---|
| | Formulated | Maize grind 1 | Maize grind 2 | Maize grind 3 | Formulated | Maize grind 1 | Maize grind 2 | Maize grind 3 |
| **Dry matter** | | 88.38 | 88.59 | 88.53 | | 88.72 | 88.72 | 88.84 |
| **Net energy (MJ/kg)** | 9.48 | 10.38 | 10.09 | 10.16 | 9.44 | 9.70 | 9.84 | 9.91 |
| **Total lysine** | 10.67 | 10.58 | 10.78 | 10.35 | 10.95 | 10.97 | 10.18 | 11.03 |
| **Crude protein** | 15.83 | 16.36 | 16.50 | 16.63 | 17.07 | 17.51 | 17.35 | 17.96 |
| **Crude fibre** | 4.36 | 2.60 | 3.70 | 3.10 | 4.79 | 4.40 | 4.30 | 4.30 |
| **Acid detergent fibre** | 5.64 | 3.80 | 5.10 | 4.40 | 5.73 | 6.30 | 6.30 | 6.10 |
| **Neutral detergent fibre** | 15.41 | 9.80 | 12.70 | 11.00 | 12.68 | 13.60 | 13.20 | 13.00 |
| **Starch** | 41.96 | 48.80 | 45.30 | 46.20 | 40.28 | 43.50 | 43.90 | 42.70 |
| **Phosphorous** | 8.29 | 5.73 | 5.32 | 5.75 | 7.69 | 6.30 | 5.92 | 6.16 |

*Maize grind 1 – fine grind; Maize grind 2 – medium grind; Maize grind 3 – coarse grind*

### 4.1.2 Particle size

The sieve test on the three different maize grinds and the six treatment rations, shows the calculated average particle size of each, and the particle distribution between 2500 µm and 355 µm sieves and the last fraction collected in the pan (Table 4.2).

The finest maize grind (MG1) was calculated to 720 µm average particle size with 0.5% of the particles found on the 2500 µm sieve and a further 2.7% on the 2000 µm sieve. These two fractions therefore accounted for 3.2% of the total maize, followed by 24.5% on the 1000 µm sieve. The VFP collected in the pan, accounted for 18.6% of the maize while 65.8% of particle were found between 1000 µm and 500 µm. The slightly coarser grind's (MG2) average particle size was 742 µm and had 3.4% of particles in the 2500 µm and 2000 µm sieves, 0.6% and 2.8% respectively. The collection pan accounted for 15.9% of milled maize and 68.4% of particles were found between the 1000 µm and 500 µm sieves. It can be concluded that the slightly coarser particles of MG2 were not due to more VFP nor due to more very coarse particle, but rather due to a higher percentage of particles between 1000 µm and 500 µm. This is a positive finding meaning that the distribution of particles was normal. The coarsest maize grind (MG3) average particle size was calculated to 774 µm; 3.8% of the particles were found on the 2500 µm and 2000 µm sieves, both sieves collected slightly more particles, total of 0.8% on the 2500 µm and 3.0% on the 2000 µm sieve. The fraction collected in the pan were less than any of the other two with 11.8% and 72.3% of particles that were found between the 1000 µm and 500 µm sieves, respectively. Although MG3 had more of the 2500 µm and 2000 µm particles (3.8% vs 3.2% on MG1 and 3.4% on MG2) and less collected in the pan, the main driver for a coarse average particle size is the shift of particles into the 1000 µm fraction. Figure 4.1 illustrates the differences between the different maize grind size fractions.

Table 4.2 The average particle size and particle size distribution of the maize and the six treatment rations (%)

| Test Sample | 2500 µm | 2000 µm | 1000 µm | 850 µm | 710 µm | 600 µm | 500 µm | 425 µm | 355 µm | Pan | Average particle size (µm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **MG1** | 0.5 | 2.7 | 24.5 | 8.0 | 11.7 | 6.9 | 14.7 | 5.3 | 7.1 | 18.6 | 720 |
| **MG2** | 0.6 | 2.8 | 25.6 | 8.3 | 11.1 | 7.1 | 16.3 | 5.2 | 7.1 | 15.9 | 741 |
| **MG3** | 0.8 | 3.0 | 27.3 | 8.7 | 10.2 | 7.4 | 18.7 | 5.0 | 7.0 | 11.8 | 774 |
| **WM1** | 1.1 | 0.9 | 21.6 | 8.0 | 10.9 | 5.5 | 8.1 | 10.9 | 3.2 | 29.8 | 640 |
| **SM1** | 1.3 | 1.0 | 20.5 | 8.3 | 10.9 | 6.0 | 7.7 | 10.8 | 3.4 | 30.2 | 639 |
| **WM2** | 1.0 | 1.0 | 22.1 | 8.1 | 11.1 | 5.8 | 7.7 | 10.7 | 3.7 | 28.8 | 647 |
| **SM2** | 1.3 | 1.0 | 21.5 | 8.5 | 10.7 | 5.2 | 7.8 | 10.3 | 3.5 | 30.1 | 647 |
| **WM3** | 1.3 | 2.7 | 27.9 | 8.1 | 9.8 | 5.3 | 6.2 | 9.6 | 2.7 | 26.3 | 725 |
| **SM3** | 3.5 | 3.2 | 26.5 | 7.5 | 9.1 | 4.8 | 5.6 | 9.5 | 3.0 | 27.4 | 769 |

*MG1 – Fine maize grind 1; MG2 – Medium maize grind 2; MG3 – Coarse maize grind 3; WM1 – wheat bran with maize grind 1 treatment; WM2 - wheat bran with maize grind 2 treatment; WM3 - wheat bran with maize grind 3 treatment; SM1 – sunflower meal with maize grind 1 treatment; SM2 – sunflower meal with maize grind 2 treatment; SM3 – sunflower meal with maize grind 3 treatment*

### 4.1.3 Grinding of maize

Lyu *et al.* (2020) investigated different milling types and concluded that the hammer mill's reduction ratio (the average input particle size divided by the average of the size of the output particle sizes) was the highest among miller types. It was also found that the hammer mill consumes the most energy during grinding among the different milling types and produced more dust and fine particles when compared to the product produced by a roller mill. Apart from varying screen sizes, tip speed and moisture content of product; loading can also influence the resulting particle size and distribution of particles produced (Lyu *et al.*, 2020). With this information the milling of maize could have been better controlled so to produce more ideal particles since only the sieve size were adjusted in the current study, not tip speed nor loading were measured or adjusted during the trail's milling process. The

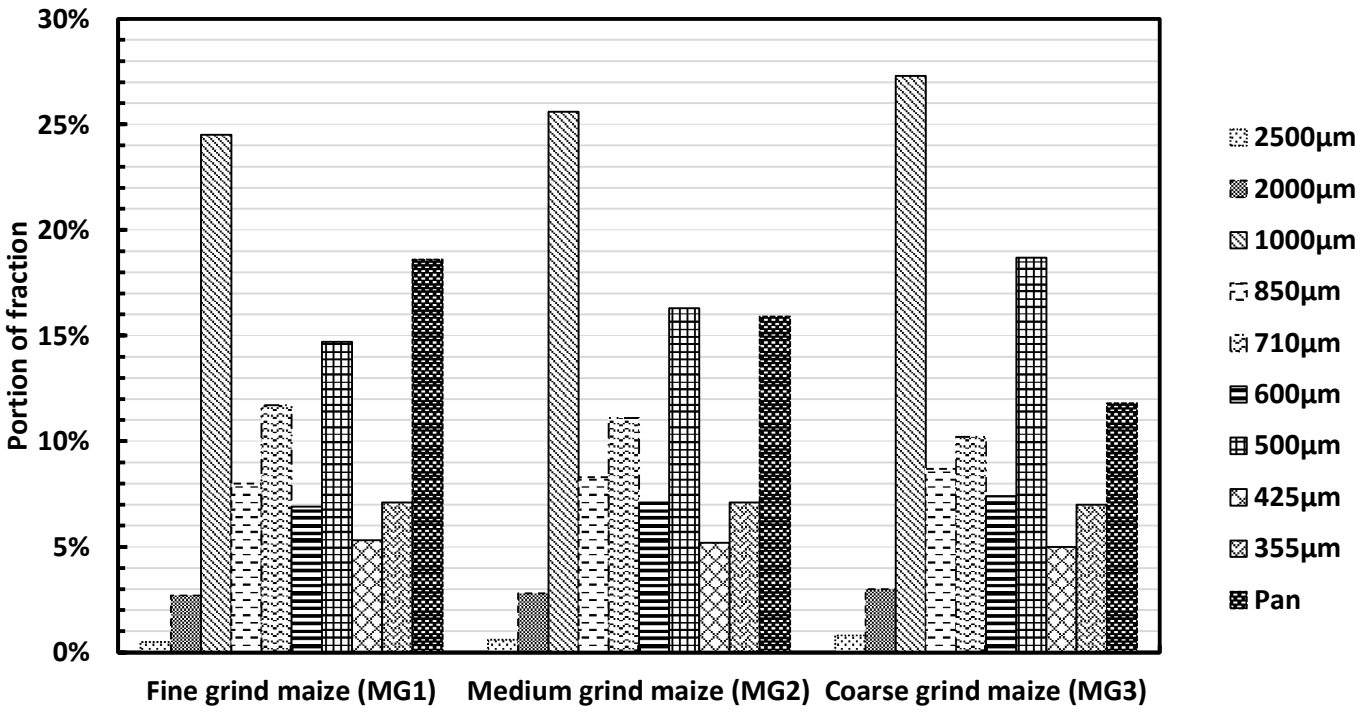


Figure 4.1 Sieve tests results of maize grinds

results obtained, however, showcase what can be produced in the industry without much intervention and limited control over the milling procedures.

### 4.1.4 Particle size distribution

The variation in particle distribution could be considered another variable in the experiment, although we accept that this variation is normal during maize grinding. From the MG1 grind to the MG3 grind, the proportion of coarse particles (between 2500 µm and 500 µm) increased, while the proportion of finer particles decreased. It is less than ideal that the MG1 grind produced any particles larger than 2500 µm, and the proportion of particles in the 2000 µm fraction could have been reduced. The 2500 µm fraction was acceptable in the MG2 grind, but a smaller proportion of the 2000 µm fraction was expected. The APS calculated for each grind did not differ as much as anticipated. These findings reflect the practical conditions, although the average maize grind was aligned with the experimental protocol; the presence of coarser particles could have been mitigated. Nonetheless, the objective of maize grinding for these experimental conditions was achieved.

The study conducted by Gao *et al*. (2020) reported comparable sieve test results, although the finer fractions were more precisely characterised. In their research, over 70% of particles in the fine grind were smaller than 400 µm, while the coarser grind still contained 48% of these fine particles. There was a distinct shift from coarse particles to very fine particles when attempting to reduce the APS. However, the study by Gao *et al*. (2020) did not address the incidence of gastric ulceration, which could

have been a significant drawback given the high percentage of particles below 400 µm, the fraction identified as VFP.

In the final rations, the average particle size decreased within each of the basal treatment rations due to the maize grind. Specifically, the APS for SM3 was 769 µm, for SM2 it was 647 µm, and for SM1 it was 640 µm. Similarly, WM3 had a finer average particle size of 725 µm compared to SM3, with WM2 at 648 µm and WM1 at 641 µm. The treatments' sieve test results are illustrated in Figure 4.2.

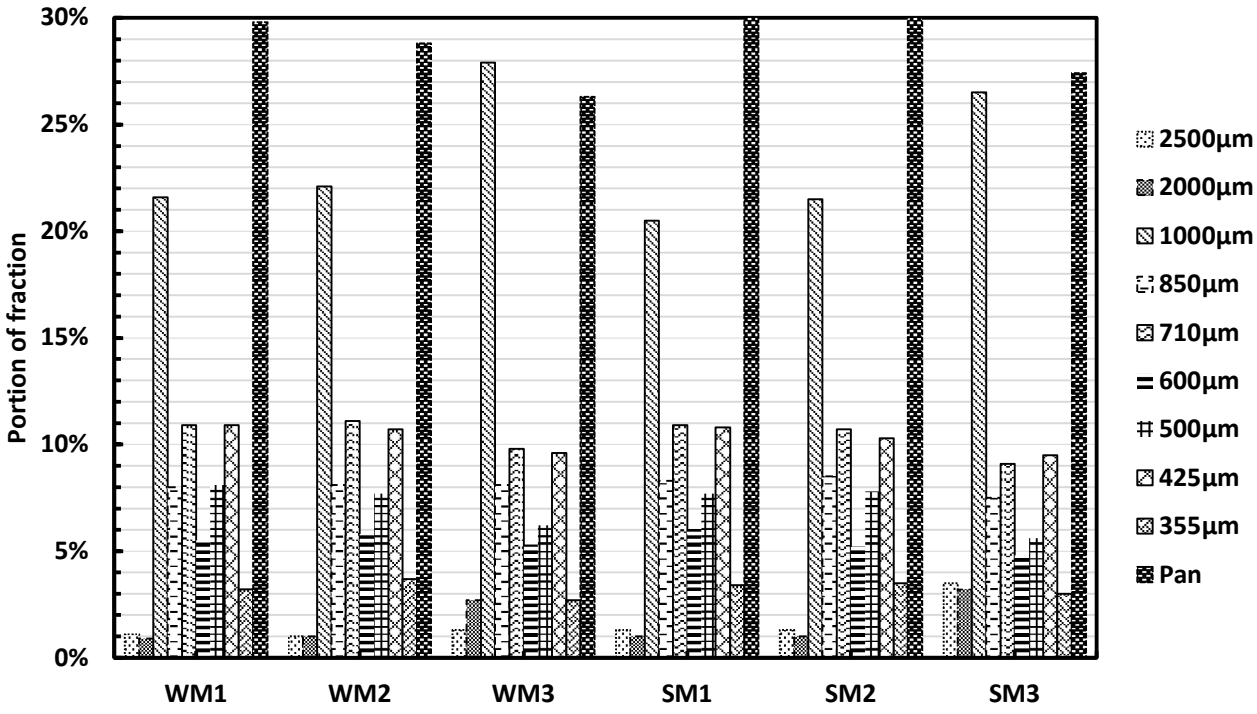


Figure 4.2 Sieve test results of treatment rations

The particle distribution of SM2 and WM2, as well as SM1 and WM1, was very similar, with minimal differences in the measured fractions, resulting in comparable averages. The fractions of SM3 and WM3 between 1000 µm and the pan were also very similar, although the coarse fractions differed. For SM3, the 2500 µm fraction constituted 3.5%, and the 2000 µm fraction was 3.2%, whereas for WM3, these fractions were 1.3% and 2.7%, respectively. The higher APS of SM3 was primarily due to these two fractions. In the study by Gao *et al*. (2020), the fine ration had a higher proportion of particles in the 1-2 mm range, while the coarser ration showed a decrease in particles within this range. These findings could have influenced the study's outcome; however, in the current study, the distribution is more uniform. The percentages of maize in the 2500 µm and 2000 µm fractions were calculated to identify the cause of the observed differences; the results are presented in Table 4.3.

Table 4.3 Maize in 2500 µm and 2000 µm fractions (%)

| Test Sample | Maize in 2500 µm fraction | Maize in 2000 µm fraction | Total maize in the 2500 µm and 2000 µm fractions |
|---|---|---|---|
| **WM1** | 0.90 | 23.11 | 9.86 |
| **SM1** | 0.24 | 20.07 | 8.42 |
| **WM2** | 0.30 | 18.02 | 9.15 |
| **SM2** | 1.44 | 17.92 | 8.58 |
| **WM3** | 33.42 | 68.84 | 57.42 |
| **SM3** | 8.56 | 40.83 | 23.84 |

*WM1 – wheat bran with maize grind 1 (fine) treatment; WM2 - wheat bran with maize grind 2 (medium) treatment; WM3 - wheat bran with maize grind 3 (coarse) treatment; SM1 – sunflower meal with maize grind 1 (fine) treatment; SM2 – sunflower meal with maize grind 2 (medium) treatment; SM3 – sunflower meal with maize grind 3 (coarse) treatment*

The 2500 µm and 2000 µm fraction of WM3 contained more maize particles than SM3 with the same maize grind. This can be interpreted that, although the total particles on these two sieves for the WM3 sample were less than those of SM3, the maize fraction of the WM3 were still more than SM3. The total maize recovered in these two fractions for SM2 and WM2 were similar, although SM2's 2500 µm fraction were higher than the same fraction of WM2. The percentages of both fractions were similar for SM1 and WM1.

### 4.1.5 Very fine particles

Previous research (Millet *et al*., 2012; Vukmirović *et al*., 2017; Kiarie & Mills, 2019) concluded that the VFP in a ration, defined as particles smaller than 400 µm, increased the risk of gastric ulceration. For comparison with the current study, Table 4.4 summarises the maize grinds and the treatment rations' fractions smaller than 400 µm, classified as VFP. It should be noted that only the 355 µm fraction and the particles collected in the pan were used to calculate the total percentage of VFP. The next measured fraction during sieve testing was 425 µm, so some particles may not have been accounted for in this calculation. The finer grind of maize did contribute to the VFP, although not excessively. The VFP percentages for WM1, WM2, SM1, and SM2 exceeded 29%, while WM3 and SM3 were close to that mark. This suggests that all treatment rations, except WM3 and SM3, had a higher risk of causing gastric ulceration.

For the trail, it was important to see a decreasing average particle size from SM3 to SM2 and SM1, similarly from WM3 to WM2 and WM1, which was achieved. The difference between these larger fractions of WM3 and SM3 is not ideal and could have contributed to unexpected experimental variation.

Table 4.4 Smallest sieve test fractions and combined very fine particles (VFP) fraction of treatments and milled maize (%)

| Sample Tested | 355 µm | Pan | VFP |
|---|---|---|---|
| **MG1** | 7.1 | 18.6 | 25.7 |
| **MG2** | 7.1 | 15.9 | 23.0 |
| **MG3** | 7.0 | 11.8 | 18.8 |
| **WM1** | 3.2 | 29.8 | 33.0 |
| **SM1** | 3.4 | 30.2 | 33.6 |
| **WM2** | 3.7 | 28.8 | 32.5 |
| **SM2** | 3.5 | 30.1 | 33.6 |
| **WM3** | 2.7 | 26.3 | 29.0 |
| **SM3** | 3.0 | 27.4 | 30.4 |

*VFP was calculated as the sum of the 355 µm fraction and the fraction left in the pan. MG1 – Fine maize grind 1; MG2 – Medium maize grind 2; MG3 – Coarse maize grind 3; WM1 – wheat bran with maize grind 1 treatment; WM2 - wheat bran with maize grind 2 treatment; WM3 - wheat bran with maize grind 3 treatment; SM1 – sunflower meal with maize grind 1 treatment; SM2 – sunflower meal with maize grind 2 treatment; SM3 – sunflower meal with maize grind 3 treatment*

## 4.2 Animal performance

### 4.2.1 Feed intake

Table 4.5 shows the pig's feed intakes, weights data, ADG and FCR for the experimental period. In the current study, pigs had an ADFI ranging from 3.30 kg to 3.37 kg per pig per day across different treatment groups, with no statistically significant differences ($P > 0.05$) observed. Pigs on the SM3 treatment had the highest ADFI of 3.46 kg/day, while those on WM1 and SM1 treatments had the lowest ADFI at 3.30 kg/day and 3.32 kg/day, respectively. Total energy consumption per day, calculated using the ADFI and the formulated NE for each ration, did not differ significantly ($P > 0.05$) between age groups.

In a study by Callan *et al.* (2007), the ADFI of finisher pigs on finer grind rations was significantly lower than those fed coarser rations. The fine grind ration used a 3 mm hammer mill screen, while the coarse grind ration used a 6 mm screen, resulting in ADFIs of 2.66 kg/day and 2.76 kg/day, respectively.

Table 4.5 Animal weights, average daily gains and feed conversion ratio of all six treatment groups (± standard error of the mean)

| Production Parameter | Wheat bran Ration | | | Sunflower meal Ration | | | *p*-value | |
|---|---|---|---|---|---|---|---|---|
| | Maize Grind 1 | Maize Grind 2 | Maize Grind 3 | Maize Grind 1 | Maize Grind 2 | Maize Grind 3 | Fibre source | Grind Size |
| **Start weight (kg)** | 84.99 (±2.37) | 87.27 (±2.46) | 87.82 (±2.43) | 84.47 (±2.43) | 84.16 (±2.37) | 88.41 (±2.33) | 0.60 | 0.36 |
| **Weight end of week 1 (kg)** | 92.78 (±2.56) | 96.17 (±2.66) | 96.67 (±2.62) | 94.00 (±2.62) | 93.23 (±2.56) | 97.90 (±2.52) | 0.94 | 0.32 |
| **Weight end of week 2 (kg)** | 101.06 (±2.59) | 103.77 (±2.69) | 103.68 (±2.66) | 101.64 (±2.65) | 101.88 (±2.59) | 105.79 (±2.55) | 0.90 | 0.44 |
| **Weight end of experimental period (kg)** | 104.55 (±0.76) | 105.42 (±0.80) | 104.66 (±0.79) | 104.89 (±0.78) | 106.84 (±0.76) | 104.64 (±0.77) | 0.79 | 0.38 |
| **Average daily gain (week 1) (kg/day)** | 1.11 (±0.08) | 1.27 (±0.09) | 1.26 (±0.09) | 1.36 (±0.09) | 1.30 (±0.08) | 1.36 (±0.08) | 0.09 | 0.70 |
| **Average daily gain (week 2) (kg/day)** | 1.18 (±0.07) | 1.09 (±0.07) | 1.00 (±0.07) | 1.09 (±0.07) | 1.24 (±0.07) | 1.13 (±0.07) | 0.29 | 0.38 |
| **Average daily gain end of experimental period (kg/day)** | 0.74 (±0.13) | 0.99 (±0.13) | 0.85 (±0.13) | 0.55 (±0.13) | 0.88 (±0.13) | 0.46 (±0.12) | 0.36 | 0.12 |
| **Average daily gain for the experimental period (kg/day)** | 1.06 (±0.04) | 1.11 (±0.04) | 1.07 (±0.04) | 1.08 (±0.04) | 1.18 (±0.04) | 1.07 (±0.04) | 0.38 | 0.12 |
| **Average daily feed intake per pig (kg)** | 3.30 (±0.10) | 3.37 (±0.10) | 3.34 (±0.10) | 3.32 (±0.10) | 3.37 (±0.10) | 3.46 (±0.09) | 0.55 | 0.67 |
| **Feed conversion ratio for the experimental period** | 3.11 (±0.14) | 3.04 (±0.14) | 3.12 (±0.14) | $3.07^{AB}$ (±0.14) | $2.86^{B}$ (±0.14) | $3.23^{A}$ (±0.13) | 0.88 | 0.12 |

*$^{A,B}$ means within a row of the same fibre source without a common superscript differ significantly ($P < 0.05$)*
*Maize grind 1 – fine grind; Maize grind 2 – medium grind; Maize grind 3 – coarse grind*

Nemechek *et al*. (2016) also observed a decreased ADFI with decreasing particle size of maize grind, with the finest grind having the lowest palatability. Yun *et al*. (2019) found that ADFI increased as maize grind size increased from 200 µm to 800 µm. Souza *et al.* (2023) reported ADFIs of 3.74 kg/day and 3.47 kg/day for finishers on different corn-soy rations. Xie *et al.* (2022) measured ADFI between 3.17 kg/day and 3.47 kg/day with various rations, including fermented soybean meal.

### 4.2.2 Body weight and average daily gain

Figure 4.3 illustrated the weights of the pigs during the experimental period. At the start of the experimental period, the finisher pigs weighed between 84 and 88 kg (Table 4.6), in line with genetic guidelines (Topigs Norsvin Feeding Manual, 2015). Initial weights showed no statistically significant differences ($P > 0.05$) between treatment groups. Over the first week, pigs gained between 1.11 kg/day and 1.36 kg/day, resulting in body weights of 94 kg to 97 kg. In the second week, gains ranged from 1.00 kg/day to 1.24 kg/day, with weights reaching 101 kg to 105 kg. The final week saw a drop in ADG, ending with final body weights between 104 kg and 106 kg. Figure 4.3 illustrated the weights of pigs during the experimental period.

Souza *et al*. (2023) reported ADGs of 1.21 kg/day and 1.25 kg/day for pigs on corn-soy rations. Xie *et al.* (2022) observed an ADG of 0.88 kg/day for the control group, increasing to 1.09 kg/day with fermented soybean meal. The ADG in the current study aligns with these findings, demonstrating expected performance from a well-managed production system.

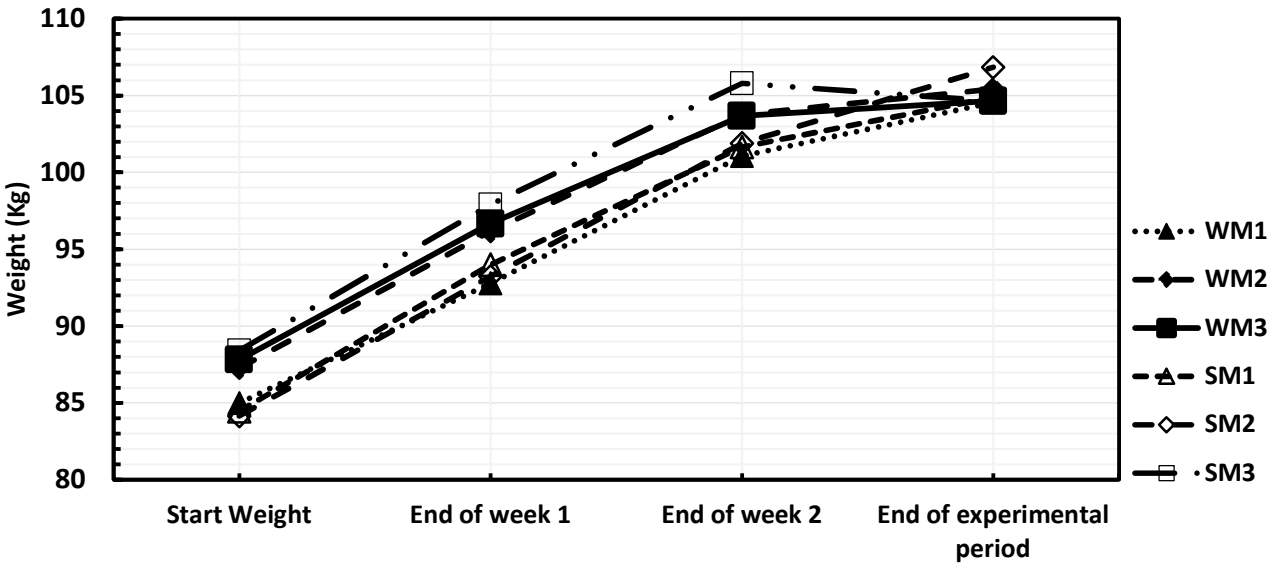


Figure 4.3 Average weekly pig weights per treatment

### 4.2.3 Feed conversion ratio

The FCR for the entire experimental period (Table 4.5) showed a significant difference ($P < 0.05$) between the SM2 and SM3 groups. SM2 had the best FCR at 2.86, while SM3 had the worst at 3.23. The other treatments had FCRs of around 3.1. The high FCR found for in SM3 treatment might be explained by the coarse grinding of maize and having the highest ADFI and resulting in the poorest FCR.

Callan *et al.* (2007) found that the FCR for finer grind rations was significantly lower than for coarser grind rations, with values of 3.00 and 3.18, respectively. Nemechek *et al.* (2016) noted similar trends, with FCRs improving as particle size decreased. Yun *et al.* (2019) observed that finer grinds improved nutrient digestibility, potentially impacting FCR. Souza *et al*. (2023) reported FCRs of 3.09 and 2.77, while Xie *et al.* (2022) found FCRs between 3.2 and 3.3.

### 4.2.4 Impact of maize grind

The current study indicated that the maize grind size significantly impacts feed intake and conversion. Pigs fed the finer maize grind (WM1 and SM1) had numerically lower energy intakes compared to those fed coarser grinds (WM3 and SM3). The high FCR of pigs on the SM3 treatment could be attributed to the high percentage of maize in the 2500 µm and 2000 µm fractions (Table 4.3), leading to lower nutrient absorption.

Callan *et al.* (2007) demonstrated that finer grind rations led to lower ADFI and better FCR. Nemechek *et al.* (2016) suggested that decreased ADFI with finer grinds might be due to reduced palatability. Yun *et al.* (2019) highlighted increased ADFI with coarser grinds, despite higher nutrient digestibility with finer grinds. The findings from the current study are consistent with these results, emphasizing the importance of optimizing particle size for improving feed efficiency and nutrient utilization.

## 4.3 Carcass traits

Carcass traits of animals slaughtered from each of the six treatment groups are summarised in Table 4.6.

### 4.3.1 Back fat

Carcass traits for the six treatment groups are summarised in Table 4.6. The current study demonstrated a statistically significant difference ($P < 0.05$) in backfat measurements between the SM2 and SM3 treatments, with pigs fed these treatments producing backfat of 15.66 mm and 14.40 mm, respectively. A similar trend was observed between WM2 and WM3; although the finer grind of WM2 resulted in more backfat than the coarser grind of WM3, this difference was not statistically significant ($P > 0.05$). It can be inferred that the coarser maize grind in both SM3 and WM3 likely reduced the pigs' energy digestion, resulting in lower nutrient availability for fat deposition. Conversely, the finer maize grind treatments (SM2 and WM2) provided more digestible energy, leading to increased backfat measurements. Callan *et al.* (2007) found no significant difference in backfat between fine and coarse grinds using 3 mm and 6 mm hammer mill screens, respectively. The backfat measurements in their study ranged from 12 mm to 13 mm for fine treatments and from 11.5 mm to 12.9 mm for coarse treatments.

Table 4.6 Carcass analysis of each treatment group (± standard error of the mean)

| Carcass Traits | Wheat bran Ration | | | Sunflower meal Ration | | | *p*-value | |
|---|---|---|---|---|---|---|---|---|
| | Maize Grind 1 | Maize Grind 2 | Maize Grind 3 | Maize Grind 1 | Maize Grind 2 | Maize Grind 3 | Fibre source | Grind Size |
| **Backfat** | 15.34 (±0.43) | 15.77 (±0.43) | 15.63 (±0.48) | 14.97$^{AB}$ (±0.49) | 15.66$^{A}$ (±0.44) | 14.40$^{B}$ (±0.43) | 0.12 | 0.23 |
| **Warm carcass weight (kg)** | 86.01 (±0.89) | 86.92 (±0.88) | 87.57 (±1.03) | 86.63 (±0.88) | 87.95 (±0.89) | 86.61 (±0.86) | 0.76 | 0.42 |
| **Cold carcass weight (kg)** | 83.47 (±0.85) | 84.32 (±0.84) | 84.80 (±0.98) | 84.03 (±0.84) | 85.76 (±0.85) | 83.93 (±0.82) | 0.60 | 0.29 |
| **Driploss (%)** | 3.00 (±0.01) | 3.00 (±0.01) | 2.99 (±0.01) | 3.00 (±0.01) | 3.00 (±0.01) | 3.00 (±0.01) | 0.71 | 0.34 |
| **Meat_mm** | 101.72 (±1.05) | 101.90 (±1.04) | 100.70 (±1.21) | 101.44$^{A}$ (±1.04) | 101.71$^{A}$ (±1.05) | 97.69$^{B}$ (±1.02) | 0.20 | 0.04 |
| **Carcass yield (%)** | 67.20 (±0.56) | 68.10 (±0.56) | 68.01 (±0.64) | 68.58 (±0.56) | 68.18 (±0.56) | 68.54 (±0.54) | 0.17 | 0.78 |

*$^{A,B}$ means within a row of the same fibre source without a common superscript differ significantly ($P < 0.05$)*
*Maize grind 1 – fine grind; Maize grind 2 – medium grind; Maize grind 3 – coarse grind*

### 4.3.2 Carcass mass

In the current study, warm carcass masses ranged from 86 kg to 88 kg across all treatment groups (Table 4.6), with no statistically significant differences ($P > 0.05$) observed. The standardised 3% drip loss at the abattoir resulted in cold carcass weights between 83 kg and 86 kg, which similarly showed no significant differences ($P > 0.05$) between treatments. Carcass yield in the current study ranged between 67% and 69% across all treatments, with no statistically significant differences ($P > 0.05$) observed. The decrease in meat millimetres in the SM3 treatment group, which produced only 97.69 mm of meat compared to 101.44 mm and 101.71 mm in SM1 and SM2, respectively, suggests that less energy utilisation from the ration impacts the protein-to-energy ratio. This imbalance results in a higher SID Lys:NE ratio, leading to less available energy for fat deposition and protein synthesis, ultimately resulting in a leaner carcass with lower meat yield. The WBR treatments consistently produced carcasses with 100 mm to 101 mm of meat.

## 4.3 Nutrient digestibility

### 4.3.1 Apparent ileal digestibility

The results from the current study, presented in Table 4.7, highlight the mean values of the AID of various amino acids for the different fibre sources and grind sizes. The SMR demonstrated significantly higher AID for most amino acids compared to the WBR. Specifically, lysine's AID is 95.15% in SMR

versus 93.60% in WBR, methionine's AID is 94.39% in SMR versus 93.07% in WBR, and threonine's AID is 94.57% in SMR versus 92.64% in WBR ($P < 0.05$).

Other noteworthy findings include the AID of valine (90.36% in SMR vs. 86.46% in WBR) and arginine (96.82% in SMR vs. 93.79% in WBR), which also show significantly higher digestibility ($P < 0.05$) in SMR. Proline, glutamic acid, and glycine showed no statistically significant difference ($P > 0.05$) between the fibre sources, although their AID values were numerically higher in SMR.

The inclusion of sunflower meal in the diet reduces digesta transit time through the GIT. This reduction may be due to an ileal or colonic brake mechanism, where undigested nutrients and fibre reaching the ileum or large intestine slow transit times, providing more time for enzymatic action. Consequently, this can enhance satiety and reduce feed intake (Rantanpaul *et at*., 2019).

### 4.3.2 Total tract digestibility

Table 4.7 also reveals that the TTD of CF, NDF, and starch is significantly higher ($P < 0.05$) in the SMR compared to the WBR. Specifically, TTD for CF is 89.12% in SMR versus 78.76% in WBR; for NDF, it is 95.70% in SMR versus 91.37% in WBR; and for starch, it is 99.92% in SMR versus 99.82% in WBR. The TTD of ADF shows no significant difference ($P > 0.05$), with values of 94.42% for SMR and 89.15% for WBR. Table 4.8 presents the TTD of CF, ADF, NDF and starch for each treatment. It becomes evident that the SMR treatments had a better fibre digestibility when comparing each grind size to the WBR counterpart. The WM1's fibres digested significantly better ($P < 0.05$) than the WM2's fibres, but it is unexpected that the WM3 digested statistically comparable to WM1.

Sunflower meal's higher NSP content increases the surface area for enzymatic colonisation and digestion. Its high water-binding capacity expands digesta particles, promoting microbial colonisation and SCFA production, which contributes to the diet's energy content. Additionally, the SMR's higher CF and CP content likely delivers more fibre and starch to the hindgut, enhancing microbial digestion and nutrient extraction.

### 4.3.3 Effect of grind size

The impact of grind size on amino acid digestibility showed limited significant differences. Only methionine, threonine, and histidine exhibited statistically significant variations ($P < 0.05$) among grind sizes, with MG1 displaying the highest AID. Specifically, for methionine, MG1 had an AID of 94.83%, compared to 93.73% for MG2 and 92.63% for MG3. Notably, while significant differences were observed between MG1 and MG3, no significant disparities were found between MG1 and MG2, nor between MG3 and MG2 ($P > 0.05$). Threonine's AID was 94.26% for MG1 and 94.10% for MG2, while MG3 exhibited a significantly lower AID of 92.45%. Regarding histidine, MG1 displayed an AID of

Table 4.7 Amino acid, fibre and starch digestibility of fibre source and grind size as main effects (%)

| | Fibre source | | | Grind size | | | |
|---|---|---|---|---|---|---|---|
| | **Wheat bran** | **Sunflower meal** | **SEM** | **MG1** | **MG2** | **MG3** | **SEM** |
| **AID Lysine** | 93.60$^{B}$ | 95.15$^{A}$ | 0.43 | 94.48 | 94.76 | 93.88 | 0.53 |
| **AID Methionine** | 93.07$^{B}$ | 94.39$^{A}$ | 0.40 | 94.83$^{a}$ | 93.73$^{ab}$ | 92.63$^{b}$ | 0.50 |
| **AID Threonine** | 92.64$^{B}$ | 94.57$^{A}$ | 0.46 | 94.26$^{a}$ | 94.10$^{a}$ | 92.45$^{b}$ | 0.56 |
| **AID Valine** | 86.46$^{B}$ | 90.36$^{A}$ | 0.78 | 88.11 | 89.48 | 87.63 | 0.96 |
| **AID Histidine** | 92.45$^{B}$ | 94.55$^{A}$ | 0.41 | 94.33$^{a}$ | 93.61$^{ab}$ | 92.56$^{b}$ | 0.50 |
| **AID Leucine & Isoleucine** | 91.71$^{B}$ | 93.48$^{A}$ | 0.51 | 93.01 | 92.49 | 92.28 | 0.62 |
| **AID Proline** | 91.74 | 93.21 | 0.53 | 93.30$^{a}$ | 92.89$^{ab}$ | 91.23$^{b}$ | 0.65 |
| **AID Phenylalanine** | 91.12$^{B}$ | 93.48$^{A}$ | 0.64 | 92.81 | 92.94 | 91.15 | 0.78 |
| **AID Alanine** | 89.66$^{B}$ | 92.76$^{A}$ | 0.56 | 91.93 | 91.36 | 90.35 | 0.69 |
| **AID Aspartic acid** | 92.46$^{B}$ | 95.05$^{A}$ | 0.38 | 94.01 | 93.52 | 93.74 | 0.46 |
| **AID Glutamic acid** | 91.78 | 92.81 | 0.66 | 93.15 | 92.84 | 90.90 | 0.81 |
| **AID Cysteine** | 93.60$^{B}$ | 95.86$^{A}$ | 0.38 | 95.14 | 94.92 | 94.13 | 0.47 |
| **AID Glycine** | 87.02 | 88.61 | 1.13 | 88.37 | 89.18 | 85.90 | 1.38 |
| **AID Serine** | 91.87$^{B}$ | 93.66$^{A}$ | 0.50 | 93.14 | 93.2 | 91.95 | 0.62 |
| **AID Arginine** | 93.79$^{B}$ | 96.82$^{A}$ | 0.31 | 95.43 | 95.31 | 95.17 | 0.38 |
| **TTD Crude fibre** | 78.76$^{B}$ | 89.12$^{A}$ | 0.70 | 84.90 | 81.22 | 85.70 | 0.86 |
| **TTD Acid detergent fibre** | 89.15 | 94.42 | 0.40 | 92.06$^{a}$ | 90.28$^{b}$ | 93.02$^{a}$ | 0.49 |
| **TTD Neutral detergent fibre** | 91.37$^{B}$ | 95.70$^{A}$ | 0.33 | 93.73$^{a}$ | 92.54$^{b}$ | 94.33$^{a}$ | 0.41 |
| **TTD Starch** | 99.82$^{B}$ | 99.92$^{A}$ | 0.01 | 99.88$^{a}$ | 99.84$^{b}$ | 99.89$^{a}$ | 0.01 |

*$^{A,B}$ means within a row of the same fibre source without a common superscript differ significantly (P < 0.05)*
*$^{a,b}$ means within a row of the same grind size without a common superscript differ significantly (P < 0.05)*
*MG1 – fine maize grind; MG2 – medium maize grind 2; MG3 – coarse maize grind*
*AID - Apparent Ileal Digestible*
*TTD - Total Tract Digestible*

Table 4.8 Amino acids, fibre and starch digestibility in the different treatment groups (%)

| | Wheat bran | | | | Sunflower meal | | | | *p*-value | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Maize Grind 1 | Maize Grind 2 | Maize Grind 3 | SEM | Maize Grind 1 | Maize Grind 2 | Maize Grind 3 | SEM | Fibre source | Grind Size | Fibre source x Grind size |
| **AID Lysine** | 93.13$^{b}$ | 93.91 | 93.75 | 0.74 | 95.84$^{a}$ | 95.62 | 94.00 | 0.74 | 0.014 | 0.485 | 0.263 |
| **AID Methionine** | 93.69$^{b}$ | 92.47$^{b}$ | 93.06 | 0.70 | 95.97$^{aA}$ | 94.99$^{aA}$ | 92.20$^{B}$ | 0.07 | 0.027 | 0.012 | 0.035 |
| **AID Threonine** | 93.06$^{b}$ | 92.88$^{b}$ | 91.96 | 0.79 | 95.46$^{aA}$ | 95.33$^{aA}$ | 92.94$^{B}$ | 0.79 | 0.005 | 0.050 | 0.575 |
| **AID Valine** | 86.04$^{b}$ | 87.46$^{b}$ | 85.87 | 1.36 | 90.18$^{a}$ | 91.50$^{a}$ | 89.40 | 1.36 | 0.001 | 0.379 | 0.971 |
| **AID Histidine** | 92.68$^{b}$ | 92.91 | 91.77 | 0.71 | 95.97$^{aA}$ | 94.32$^{AB}$ | 93.36$^{B}$ | 0.71 | 0.001 | 0.055 | 0.355 |
| **AID Leucine & Isoleucine** | 91.58$^{b}$ | 91.31 | 92.23 | 0.88 | 94.44$^{a}$ | 93.68 | 92.33 | 0.88 | 0.018 | 0.700 | 0.260 |
| **AID Proline** | 91.84$^{b}$ | 91.71 | 91.66 | 0.91 | 94.76$^{aA}$ | 94.06$^{A}$ | 90.80$^{B}$ | 0.91 | 0.055 | 0.067 | 0.096 |
| **AID Phenylalanine** | 90.80$^{b}$ | 91.97 | 90.59 | 1.11 | 94.83$^{a}$ | 93.90 | 91.71 | 1.11 | 0.013 | 0.211 | 0.409 |
| **AID Alanine** | 90.16$^{b}$ | 89.40$^{b}$ | 89.43 | 0.97 | 93.69$^{a}$ | 93.33$^{a}$ | 91.28 | 0.97 | 0.0003 | 0.272 | 0.529 |
| **AID Aspartic acid** | 92.41$^{b}$ | 91.72$^{b}$ | 93.25 | 0.65 | 95.60$^{a}$ | 95.33$^{a}$ | 94.22 | 0.65 | <0.0001 | 0.759 | 0.105 |
| **AID Glutamic acid** | 90.87$^{b}$ | 92.80 | 91.66 | 1.15 | 95.42$^{aA}$ | 92.87$^{AB}$ | 90.15$^{B}$ | 1.15 | 0.275 | 0.119 | 0.032 |
| **AID Cysteine** | 93.89$^{b}$ | 93.80 | 93.11$^{b}$ | 0.66 | 96.38$^{a}$ | 96.04 | 95.16$^{a}$ | 0.66 | 0.0001 | 0.289 | 0.946 |
| **AID Glycine** | 86.14 | 87.65 | 87.28 | 1.95 | 90.60$^{A}$ | 90.71$^{A}$ | 84.52$^{B}$ | 1.95 | 0.324 | 0.226 | 0.158 |
| **AID Serine** | 91.83$^{b}$ | 92.45 | 91.32 | 0.87 | 94.44$^{a}$ | 93.94 | 92.59 | 0.87 | 0.016 | 0.285 | 0.714 |
| **AID Arginine** | 93.42$^{b}$ | 93.67$^{b}$ | 94.28$^{b}$ | 0.53 | 97.44$^{a}$ | 96.96$^{a}$ | 96.07$^{a}$ | 0.53 | <0.0001 | 0.891 | 0.115 |
| **TTD Crude fibre** | 80.70$^{bA}$ | 72.89$^{bB}$ | 82.68$^{bA}$ | 1.21 | 89.10$^{a}$ | 89.55$^{a}$ | 88.71$^{a}$ | 1.21 | <0.0001 | 0.001 | 0.0002 |
| **TTD Acid detergent fibre** | 90.04$^{bA}$ | 86.54$^{bB}$ | 90.87$^{bA}$ | 0.70 | 94.09$^{a}$ | 94.02$^{a}$ | 95.16$^{a}$ | 0.70 | <0.0001 | 0.001 | 0.032 |
| **TTD Neutral detergent fibre** | 92.02$^{bA}$ | 89.17$^{bB}$ | 92.92$^{bA}$ | 0.58 | 95.45$^{a}$ | 95.91$^{a}$ | 95.75$^{a}$ | 0.58 | <0.0001 | 0.012 | 0.003 |
| **TTD Starch** | 99.84$^{b}$ | 99.79$^{b}$ | 99.84$^{b}$ | 0.02 | 99.93$^{a}$ | 99.89$^{a}$ | 99.94$^{a}$ | 0.02 | <0.0001 | 0.019 | 0.989 |

*$^{A,B}$ means within a row of the same fibre source without a common superscript differ significantly (P < 0.05)*
*Maize grind 1 – fine grind; Maize grind 2 – medium grind; Maize grind 3 – coarse grind*
*AID - Apparent Ileal Digestible*
*TTD - Total Tract Digestible*

94.33%, MG2 93.61%, and MG3 92.56%. MG2 showed similarity to both MG1 and MG3, with significant differences ($P < 0.05$) observed between MG1 and MG3.

Table 4.8 highlight the mean values of the AID of various amino acids for the different treatment groups. The comparisons between sunflower meal and wheat bran across different maize grind sizes reveal several significant findings. For the SM1 and WM1 groups, the SM1 consistently showed significantly higher AID all amino acids compared to the WM1. Specifically, lysine's AID was 95.84% in SM1 versus 93.13% in WM1 ($P < 0.05$), methionine's AID was 95.97% in SM1 versus 93.69% in WM1 ($P < 0.05$), and threonine's AID was 95.46% in SM1 versus 93.06% in WM1 ($P < 0.05$).

Between the SM2 and WM2 groups, several amino acids showed significant differences in AID. Methionine's AID was 94.99% in SM2 versus 92.47% in WM2 ($P < 0.05$), threonine's AID was 95.33% in SM2 versus 92.88% in WM2 ($P < 0.05$), valine's AID was 91.50% in SM2 compared to 87.46% in WM2 ($P < 0.05$), and histidine's AID was 94.32% in SM2 versus 92.91% in WM2 ($P < 0.05$). Other amino acids such as alanine, aspartic acid and arginine also showed a significant higher digestibility in SM2 compared to WM2. The SM3 and WM3 groups, only showed significant differences ($P < 0.05$) for cysteine and arginine (95.16% in SM3 vs. 93.11% in WM3 and 96.07% in SM3 vs. 94.28% in WM3, respectively).

Although only methionine, threonine, and histidine showed significant variations across grind sizes, MG1 consistently demonstrated superior digestibility compared to MG2 and MG3, with certain variations between the latter two grind sizes also evident.

While CF digestibility shows no statistically significant differences ($P > 0.05$) among grind sizes, ADF, NDF, and starch digestibility are significantly higher ($P < 0.05$) in MG1 and MG3 compared to MG2. Specifically, TTD for ADF is 92.06% for MG1, 90.28% for MG2, and 93.02% for MG3. For NDF, TTD is 93.73% for MG1, 92.54% for MG2, and 94.33% for MG3. Starch digestibility is 99.88% for MG1, 99.84% for MG2, and 99.89% for MG3.

Finer grinding of maize increased the surface area for enzymatic action, breaking down the protein encapsulation of maize endosperm and enhancing starch and protein digestion. This finer grind also increases HCl production, activating more pepsin, and further improving protein digestion.

The study's findings align with previous research, confirming that finer maize grind sizes improve digestion efficiency for both energy and amino acids. The medium grind (MG2) shows better digestibility than the coarse grind (MG3), but not as effectively as the finest grind (MG1). Gao *et al*. (2020) found no additional benefit in nutrient utilisation when maize was ground finer than 682 µm, suggesting an optimal particle size slightly below 700 µm. This study's results support this finding,

indicating that enzyme availability may limit further improvements in digestibility. The addition of enzymes, not accounted for in this study, might enhance the efficiency of grinding maize below 700 µm, as suggested by Gao *et al*. (2020).

## 4.4 Gastric ulceration

Evaluation of the gastric mucosa was conducted on all experimental pigs, both on the farm and at the slaughter line. Data from these evaluations indicated that 81.6% of the animals exhibited some degree of gastric ulceration, while 18.4% showed no ulceration. Most ulceration was classified as keratinisation of the gastric mucosa, accounting for 68.1% of the animals. For the remaining 13.5%, ulcerations were visible, with 2.9% exhibiting diffuse ulceration of the gastric mucosa.

Gastric ulceration average scores (UAS) were used to measure each treatment's ulceration severity and were calculated as per Equation 3.5. The various UAS measurements (Table 4.9) ranged from 1.32 to 1.77, with a numerical increase from 1.48 to 1.63 for MG3 to MG1. Pigs receiving WBR had a lower UAS compared to those fed SMR, with values of 1.49 and 1.60, respectively. Notably, pigs fed WBR exhibited a lower incidence of gastric ulceration than those fed SMR. Additionally, there was a trend indicating that a finer maize grind size was associated with a higher incidence of gastric ulceration compared to a coarser grind.

Table 4.9 Ulceration average score (UAS) for treatments, grind sizes and ration types

| **Parameter** | ***UAS** |
|---|---|
| MG1 | 1.63 |
| MG2 | 1.52 |
| MG3 | 1.48 |
| Wheat bran treatments | 1.49 |
| Sunflower meal treatments | 1.60 |
| WM1 | 1.52 |
| WM2 | 1.71 |
| WM3 | 1.54 |
| SM1 | 1.77 |
| SM2 | 1.32 |
| SM3 | 1.43 |

**No significant difference; MG1 – Fine maize grind 1; MG2 – Medium maize grind 2; MG3 – Coarse maize grind 3; WM1 – wheat bran with maize grind 1 treatment; WM2 - wheat bran with maize grind 2 treatment; WM3 - wheat bran with maize grind 3 treatment; SM1 – sunflower meal with maize grind 1 treatment; SM2 – sunflower meal with maize grind 2 treatment; SM3 – sunflower meal with maize grind 3 treatment*

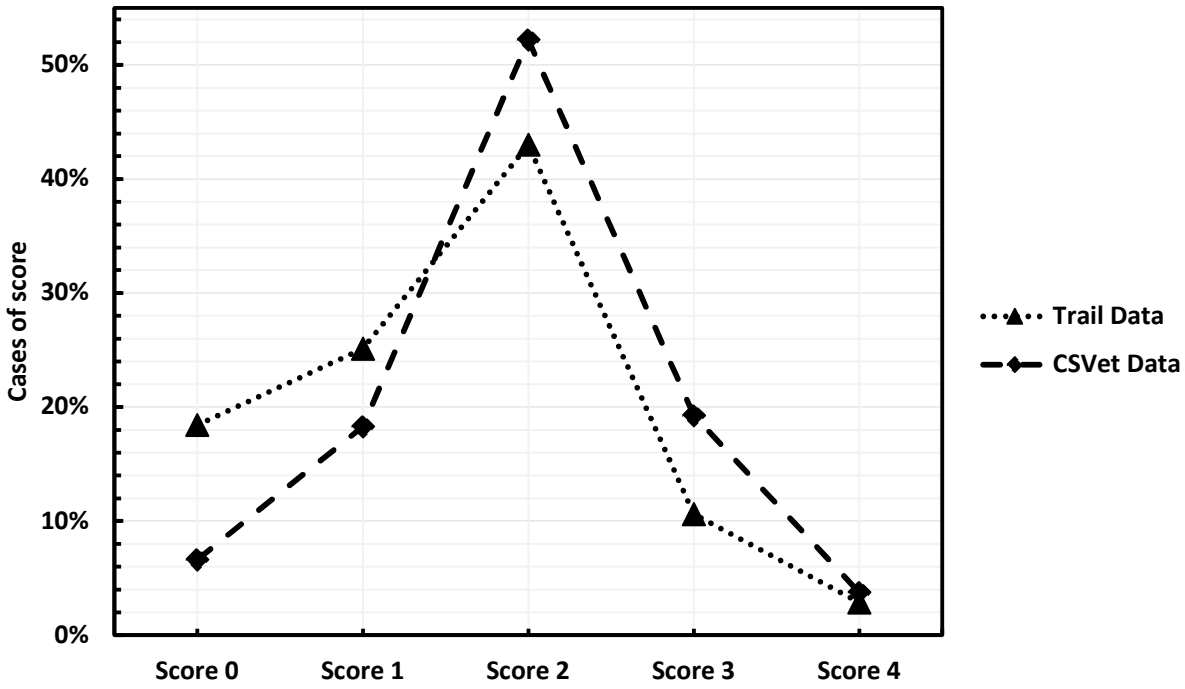


Figure 4.5 Gastric ulceration scores percentage of cases.

The combined UAS for all trial animals was calculated at 1.54, indicative of moderate keratinisation of the gastric mucosa. For comparison, the calculated UAS from the CSVet database is 1.95, demonstrating a similar distribution pattern to that observed in this study. Figure 4.5 compares the distribution of UAS between the CSVet database and the data collected in this study, presented as a percentage of cases in this study encompassed all animals as a single batch, whereas the cases in the CSVet data were calculated based on evaluations conducted in 50-animal batches.

Commercial gastric ulceration data have been collected since 2016 by an independent swine company, CSVet (Bodenstein *et al.*, 2023), through routine gastric ulceration evaluations on the slaughter line. This database includes 18 production units across South Africa, with varying genetics, health statuses, feed suppliers, and ration types. For this study, 314 slaughter groups were evaluated; from each slaughter group, 50 stomachs were randomly selected, evaluated, and recorded. This data provides a representative overview of the general trend and severity of gastric ulceration in South African slaughter pigs. The CSVet database suggests that 93% of slaughter pigs have some degree of gastric ulceration, much higher than the 60% suggested by Muirhead *et al.* (2013).

The incidence of ulceration in this study was lower than some studies would suggest. Millet *et al.* (2012) tested high and low fibre inclusions with a fine and coarse grind of around 400 µm and 700 µm, respectively, using a 0-5 gastric ulceration score. They found that most experimental pigs had severe

keratosis without any erosions. No significant difference was observed among most treatment groups, but the high fibre and coarse grind ration had a lower ulceration score.

## 4.5 Financial analysis

Raw material prices fluctuate rapidly, while the mixing and milling cost of a feed mill tend to fluctuate less, cost also moves as the financial climate changes. This makes feed price comparisons difficult and somewhat irrelevant as prices cannot be compared after a trail was concluded. It is however relevant to do a comparison of the trail's current rations and their costs in relation to one another. For future analysis or cost comparisons, current feed prices should be used to calculate the cost of production, while using the same animal parameters.

Table 4.10 gives a cost comparison between the six treatments in terms of cost of gain. Cost of gain was calculated by multiplying the FCR per treatment with the feed price for each treatment. This calculated cost of gain gives the production result a financial value, so that the net economic benefit can be compared between groups. Table 4.10 repeats the ADG, ADFI and FCR form Table 4.6, before supplying the feed price and the calculated cost of gain. Form this table, within the same fibre source, the MG2 were the most economically efficient treatments, while the MG3 were the most inefficient. Treatment SM2 were slightly more economically efficient then treatment WM2, although the feed price was higher, therefore only due to the better FCR. The situation can change in the future as the cost of wheat bran and sunflower meal fluctuates.

Table 4.10 Cost of gain for each treatment

| Parameter | Wheat bran ration | | | Sunflower meal ration | | |
|---|---|---|---|---|---|---|
| | WM1 | WM2 | WM3 | SM1 | SM2 | SM3 |
| **Average daily gain (kg/day)** | 1.06 | 1.11 | 1.07 | 1.08 | 1.18 | 1.07 |
| **Average daily feed intake (kg)** | 3.30 | 3.37 | 3.34 | 3.32 | 3.37 | 3.46 |
| **Feed conversion ratio** | 3.11 | 3.04 | 3.12 | 3.07 | 2.86 | 3.23 |
| **Feed price (R/ton)** | R 3 356.76 | R 3 356.76 | R 3 356.76 | R 3 550.64 | R 3 550.64 | R 3 550.64 |
| **Cost of gain (R/kg)** | R 10.44 | R 10.20 | R 10.47 | R 10.90 | R 10.15 | R 11.47 |

*WM1 – wheat bran with maize grind 1 (fine) treatment; WM2 - wheat bran with maize grind 2 (medium) treatment; WM3 - wheat bran with maize grind 3 (coarse) treatment; SM1 – sunflower meal with maize grind 1 (fine) treatment; SM2 – sunflower meal with maize grind 2 (medium) treatment; SM3 – sunflower meal with maize grind 3 (coarse) treatment*

# Chapter Five: Conclusion and recommendations

## 5.1 Conclusion

In this study the medium maize grind (741 µm) positively impacted the digestibility and production efficiency of animals, compared to a coarser and finer grind, despite the small differences in average particle size. The average particle size difference between the fine maize grind (720 µm) and the coarse grind (774 µm) was 54 µm, achieved by changing the hammer mill screen from 4 mm to 3 mm. This screen changes primarily affected the fraction collected on the 1000 µm sieve, indicating that optimisation of a finer grind should not only target average particle size but also adjust the very coarse fractions. Reducing coarse particles may only slightly lower the average particle size but could enhance production efficiency. The proportion of very fine particles in the fine and medium grind treatment rations was approximately 33%, compared to 30% in the coarse grind treatment rations. Notably, the incidence of gastric ulcers was lower than typically observed in commercial pigs in South Africa, even though the fine maize grind exceeded the recommended 29% of very fine particles.

The wheat bran ration had the slightly (but not significantly) lower ulceration average score compared to the sunflower meal ration. The inclusion of sunflower meal however significantly promoted digestion in most amino acids tested, while crude fibre and starch were all better digested in these rations. Sunflower meal might have caused a decrease in the digesta's transit time through the gastrointestinal tract, creating more time for normal digestive function, and the time for enzymes to act on its substrates. Sunflower meal provided enough non-starch polysaccharides to increase the substrate's surface area and in turn allowed enzymes to colonise it. Microbes were able to colonise the digesta due to the high water-binding capacity of sunflower meal, promoting microbial digestion and therefore the production of short-chain fatty acids. Feed intakes decreased due to better gut-fill which further decreased the transit time through the gastrointestinal tract. The inclusion of sunflower meal potentially influenced the microbial population positively, allowing more nutrients to be extracted from the digesta.

The most efficient feed conversion ratio was observed in the treatment group receiving sunflower meal combined with maize ground to a particle size of 741 µm, achieving a feed conversion ratio of 2.86 over the experimental period. This result significantly differed from the group fed sunflower meal with maize ground to 774 µm, which had a feed conversion ratio of 3.23. No other significant differences were observed in feed conversion ratio, average daily feed intake, or cold carcass weights among the remaining treatments. Furthermore, these two treatments exhibited significant differences in lean meat measurements (101.71 mm and 97.69 mm, respectively) and backfat thickness (15.66 mm and

14.40 mm, respectively) on the carcasses. The treatment group with sunflower meal and maize ground to 741 µm displayed the thickest meat and the highest backfat. This suggested that when nutrients are more readily digestible, animals can utilise a greater proportion of nutrients from the feed, thereby meeting their nutritional requirements with a lower daily feed intake. Animals that received the treatments with fine maize grind (720 µm) did not show further significant improvements; in some instances, they had the same performance than the medium grind and in other the same as the coarse grind treatment groups.

The financial analysis of the experimental results showed that feed conversion ratio drives profitability as a lower feed conversion ratio reduces the cost of gain. Although sunflower meal ration treatments' feed cost was higher than the wheat bran ration's, the lower feed conversion ratio tends to reduce cost of gain for these treatments. This trail's cost of gain was lowest for the sunflower meal with maize grind of 741 µm treatment, closely followed by the wheat bran with maize grind of 741 µm treatment. The coarse grind treatments' cost of gain was the highest.

By reducing the average particle size of milled maize, the producer can benefit from better digestion of the ration fed, reducing feed conversion ratio and improving overall productivity. The inclusion of sunflower meal is recommended along with wheat bran to mitigate the possibility of gastric ulceration while increasing the flowability of the ration. Sunflower meal further aids in the digestion process, accommodating the finer maize grind. It should be noted that a finer maize grind can simply be produced by changing the hammer mill screen and the small changes to the average particle size could produce significant results.

## 5.2 Shortcomings of the current research

Raw material and final feed testing should have been conducted more accurately using chemical analytical procedures instead of near-infrared spectrometry. Variation between the two fibre source rations introduced uncertainty in interpreting the study's results.

Incorporating a negative control treatment would have highlighted the detrimental effects of a very fine maize grind. If maize were ground to approximately 300 µm, flowability issues could have arisen, and the incidence and severity of gastric ulceration might have increased. These effects could have been more pronounced in the wheat bran ration compared to the sunflower meal ration. However, as the trial was conducted in a commercial setting, this was not feasible.

No analysis of crude protein was done, although focuses tend to move away from crude protein toward amino acids, hence crude protein should not be discarded.

Flowability measurements of the experimental rations and processed raw materials would have provided producers with a reference for the physical characteristics of the rations and an indication of their performance in the feeding system.

## 5.3 Recommendation for future research

Future research should focus more on the nutrient analysis of sunflower meal so that a better definition of the raw material can be made.

In future research, the grind size of maize should not exceed 700 µm. Using a very fine grind of approximately 500 µm is expected to produce significant results.

The inclusion of specific enzymes should be clearly defined, and their contribution to digestibility should be thoroughly investigated. Enzymes are expected to significantly enhance digestibility when used with finely ground raw materials.

Development equipment for on-site or in-laboratory flowability test would allow for flowability testing before a plan of finer grinds are implemented.

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