Prediction of gut capacity of weaner and finishing pigs using physicochemical measurements of bulkiness of fibrous feeds

By

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A dissertation submitted in fulfilment of the requirements for the degree of

MASTER OF SCIENCE IN AGRICULTURE (ANIMAL SCIENCE)

in the

Discipline of Animal and Poultry Science

College of Agriculture, Engineering and Science

School of Agricultural, Earth and Environmental Science

University of KwaZulu-Natal

March 2012

Pietermaritzburg, South Africa

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Abstract

Physicochemical properties of different fibrous ingredients were used to determine the influence of feed bulk on voluntary feed intake and gut capacity in weaner and finishing pigs. Physicochemical measures of bulkiness determined on feed ingredients were DM, crude protein (CP), ether extract, ash, water holding capacity (WHC), bulk density, crude fibre (CF), neutral detergent fibre (NDF) and acid detergent fibre (ADF). Among the fibre sources, maize stover had the highest WHC, followed by veld grass, then lucerne hay, maize cob, sunflower husks, groundnut haulms, rice bran and saw dust. The greatest bulk densities (1.4 g DM/ml) were observed in lucerne hay and saw dust, whilst sunflower husk had the lowest (0.7 g DM/ml) ($P < 0.001$). Rice bran, maize cob and groundnut haulms were the most fermentable fibrous ingredients ($P < 0.05$).

Based on differences in physicochemical properties, six fibres namely lucerne hay, maize cob, maize stover, veld grass, saw dust and sunflower husk were selected and used in formulating fibrous diets fed to growing pigs based on wideness in ranges of their bulk properties. Thirty-one complete diets were formulated by dilution of a conventional weaner feed with increment levels of each fibre source at 0, 80, 160, 240, 320 and 400 g/kg. Each of the diets was offered *ad libitum* to four of 124 pigs weighing 18.1 (s.d. 1.37) kg body weight, in individual pens, for four weeks. There was a linear decrease in scaled feed intake (SFI) ($P < 0.001$) as bulk density of the feeds increased. There was a quadratic relationship between SFI and WHC, NDF and ADF, respectively, whereby SFI increased up to a point when it reached its maximum and then started to decrease as bulkiness increased ($P < 0.001$). By use of the broken stick model, the maximum SFI marking the gut capacity of pigs was attained when WHC = 4.5 ± 1.25 g water/g DM ($P <$

0.001), NDF = 367 ± 29 g/kg DM ($P < 0.001$) and ADF = 138 ± 77 g/kg DM ($P < 0.01$), respectively. The SFI decreased linearly with an increase in bulk density of the feeds ($P < 0.001$).

Four of 84 finishing pigs in individual pens, at 65 (s.d. 1.37) kg body weight were given, *ad libitum* to each of 21 diets containing graded levels of lucerne, maize cobs, saw dust and sunflower husk. There was a linear decrease in SFI ($P < 0.001$) as WHC increased. There was a quadratic decrease in SFI as CF ($P < 0.001$) and NDF ($P < 0.01$) increased. As CP increased, there was a quadratic increase in SFI ($P < 0.01$). In weaner pigs, an increase in WHC, NDF, ADF and bulk density constrains feed intake, thereby providing relationships that can be used to predict gut capacity. Conversely, measurements of feed bulk cannot provide relationships with intake that can be used to predict gut capacity in finishing pigs.

Key words: bulkiness; bulk density; feed intake; fermentation; growing pigs; gut capacity; neutral detergent fibre; water holding capacity.

Acknowledgements

I am delighted to have the opportunity to record thanks to my supervisors, Professor Michael Chimonyo and Professor Rob Mervyn Gous, who unsparingly criticized parts of the thesis and made suggestions that ensured that this document is very much better than it otherwise might have been. These are interesting guys to work with. I also acknowledge the financial support from the University of KwaZulu-Natal competitive grant and the South African Pig Producers Organisation for the bursary. I gratefully acknowledge the staff at Ukulinga Research Farm, particularly Alet Botha, Sam Khumalo, Emmanuel Makhoba, Belly Ngcobo, Shadreck Dlamini, John Khumbula, Siphamandla Ntshangase, Sibusiso Dumakude and the late Misheck Mosi for taking care of the pigs. My gratitude also goes to Sithembie, Derbie and Marianne for their assistance in feed analysis. I owe thanks to my friends and fellow postgraduate colleagues, Titus Jairus Zindove, Conference Thando Mpendulo, Archibald Bakare, Munyaradzi Christopher Marufu, Nation Chikumba, Anderson Kuimba, Piniel Mhike, and Mandisa Mngonyama for their continuous support, input, encouragement and assistance in editing this document.

I also want to thank Amai Chimonyo and her family for their moral support and domestic care during my stay in South Africa.

I am deeply indebted to my wife, Mercy, for her infinite love, this document would not exist at all without her. I truthfully hope that, in future, I will stay home more.

Dedication

To the Makhado family and my late parents, Noleen and Posset, for their love, motivation, support and light but regretfully could not have a chance to enjoy their fruits.

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Chapter 1: General Introduction

1.1 Background

The global pork consumption is expected to increase by 75 % in 2020 in response to the increasing world human population which is likely to double in 2050 (Kearney, 2010). An increase in pork consumption is necessitated by growing consumer pork preferences for its healthy-eating quality and tenderness. Due to their remarkable farrowing index (2.4), prolificacy (11.4 piglets per sow per farrow), fast growth rates (over 900 g/per day) and high feed conversion efficiencies (0.80) relative to most livestock species, pig production can potentially alleviate animal protein demand (Adesehinwa, 2008).

Various pig production systems are practised. In South Africa, pig production systems can be categorised into small scale and large scale production systems. The large scale production systems are practiced by commercial farmers and are capital intensive; keeping entirely imported Large White, Landrace, Darland, Duroc and their crosses. The crosses, for example TOPIGS and PIC pigs, are favoured for heterosis and large frames (Visser, 2004). The smallholder production system is practiced mostly by communal farmers through scavenging, semi-intensive and intensive production systems. Indigenous breeds, such as Kolbroek, Mukota and Windsnyer, and to lesser extent exotic breeds and their crosses with minimum use of conventional feeds (Halimani *et al.*, 2010), are common.

In intensive production systems, increasing pig productivity is driving farmers to seek knowledge about how much feed a pig can consume to achieve potential growth and minimizing nutrient losses to the environment. Management of excreta, optimization of animal welfare, gut diseases, increases in feed costs and the increased demand for outdoor extensive pig production systems are other numerous challenges threatening the profitability, socio-economic and environmental sustainability of the pig industry (Aarnink and Verstegen, 2007). There is growing interest among pig feed compounders to address these challenges through incorporation of fibrous ingredients in diets of growing pigs (Manero *et al.*, 2006; Hansen *et al.*, 2007).

Fibrous ingredients are generally bulky and their inclusion reduces nutrient densities of the feeds, prompting the pig to increase voluntary feed intake (VFI). Inevitably, there comes a point beyond which the amount of feed consumed is no longer sustained to meet the pig's requirements to attain its potential growth. At that point, particularly in weaner pigs, the consumption of sufficient nutrients is limited by the pig's gut capacity and the bulky content of the feed (Whittemore *et al.*, 2003). The gut capacity is reached when feed intake of a pig that has not attained its desired nutrient intake becomes constant or decrease as bulkiness increase. Bulkiness is the physical tendency of a feed ingredient or indigestible material to occupy space (Whittemore *et al.*, 2003). It is not clear whether the effect of bulkiness is similar between weaner and finishing pigs. Finishing pigs are expected to have developed the capacity to ferment and utilise fibrous feeds (Kanengoni *et al.*, 2004). Little has been done to determine the maximum inclusion levels of different dietary fibre sources to allow consumption of sufficient nutrients for potential growth in pigs. Sound nutritional programmes should, therefore, allow a balance to be struck by allowing the pig to consume adequate nutrient for potential growth as well as alleviating these challenges.

The amount of feed that can be consumed by a pig is undoubtedly determined by physicochemical measures of the feed bulk and the gut capacity of the pig. Physicochemical measurements of bulkiness can be defined as chemical and physical properties of a feed that determine its tendency to occupy space. Examples of physicochemical properties that can be used to measure bulkiness of feedstuffs are water holding capacity (WHC), solubility, bulky density, viscosity, contents of crude fibre, crude fat, neutral detergent fibre, acid detergent fibre, particle size and mineral elements (Wenk, 2001; Bindelle *et al.*, 2008). Information on the influence of physical properties on intake is largely ignored in ration formulation, yet these could be the best measures of bulkiness that can be used to predict gut capacity.

Potential fibrous feed ingredients that can be incorporated in pig diets when predicting feed intake include common, readily available and cheap crop residues and agro-industrial by-products, such as maize cobs, maize stover, lucerne hay and sunflower husks. Agro-industrial by-products are usually thrown away and may cause pollution to the environment; therefore, feeding them to pigs could be a possible way to protect ecosystems. The nutritional quality and impact of fibre ingredients on VFI is poorly understood but may be influenced largely by their chemical composition and physical properties. In finishing pigs, fermentability of the fibre source is also likely to influence VFI.

To date, little efforts had been made to determine the influence of physicochemical measurements of bulkiness on gut capacity of fibrous feeds in weaner and finishing pigs. In pigs between 12 and 90 kg body weight, the main driving force for performance is feed intake. Prediction of the effects that physicochemical measurement of bulkiness might have on the amount of feed consumed is, therefore, crucial (Montagne *et al.*, 2003). The bulkiness of commonly used non-fibrous ingredients is not known. The effectiveness of predicting the gut capacities of growing pigs solely depends on understanding relationships among physicochemical properties of a wide range of feed ingredients and their additive effects in pig diets which is usually ignored when describing the nutritional composition of pig feeds. If the physicochemical properties of these bulky feeds are not quantified, their usefulness in feeds may be incorrectly judged and may impose undesirable effects on feed intake, digestibility and, subsequently, growth performance of pigs.

1.2 Justification

Each feed ingredient needs to be described in such a way that it is possible to predict its maximum inclusion level. To achieve a more comprehensive understanding of bulk characteristics of feeds, there is need to characterize physicochemical properties of all feed ingredients. Understanding physicochemical properties of fibrous ingredients assists nutritionists to know how much of a given fibre source can be included in a feed beyond the gut capacity. Investigating the impact of the physicochemical properties of fibrous diets on gut capacity assists pig producers to estimate optimum inclusion levels in feeds before VFI and subsequently growth rates are constrained. The need to accurately predict gut capacities of pigs assist feed compounders to design appropriate feed programmes which ensure that optimum nutrient intake could be achieved, without overfeeding and minimising loss of nutrients through excretion. Together with performance characteristics, knowledge of how much feed of a particular type has been consumed can be used to estimate the economic value of an individual pig at any given stage of growth.

1.3 Objectives

The broad objective of the current study was to determine physicochemical properties of a feed that best describe the bulkiness of the feed, such that the gut capacity of a pig can be predicted. The specific objectives were to:

1. Characterise physicochemical properties and fermentation parameters of various feed ingredients;
2. Determine the gut capacity of weaner pigs using physicochemical properties of a feed; and
3. Determine physicochemical properties that can be used to predict voluntary feed intake of bulky feeds in finishing pigs

1.4 Hypotheses

The hypotheses tested were that:

1. Feed ingredients have variable physicochemical properties and fermentation characteristics;
2. As feed bulk increase, feed intake in weaner pigs increases linearly up to a point when it becomes constant or starts to decrease; and
3. Physicochemical measurements of bulkiness of the feeds adequately predict VFI in finishing pigs.

1.5 References

Aarnink, A.J.A. and Verstegen, M.W.A. (2007). Nutrition, key factor to reduce environmental load from pig production. *Livestock Science*, 109: 194-203.

Adesehinwa, A.O.K. (2008). Energy and protein requirements of pigs and the utilization of fibrous feedstuffs in Nigeria: A review. *African Journal of Biotechnology*, 7: 4798-4806.

Bindelle, J., Lerterne, P. and Bulgen, A. (2008). Nutritional and environmental consequences of dietary fibre in pig nutrition: a review. *Biotechnology, Agronomy, Society and Environment*, 12: 69-80.

Halimani, T.E., Muchadeyi, F.C., Chimonyo, M. and Dzama, K. (2010). Pig genetic resource conservation: The Southern African perspective. *Ecological Economics*, 69: 944-951.

Hansen, M.J., Chwalibog, A. and Tauson, A. (2007). Influence of different fibre sources in diets for growing pigs on chemical composition of faeces and slurry and ammonia emission from slurry. *Animal Feed Science and Technology*, 134: 326-336.

Kanengoni, A.T., Dzama, K., Chimonyo, M., Kusina, J. and Maswaure, S.M. (2004). Growth performance and carcass traits of Large White, Mukota and their F_1 crosses fed on graded levels of maize cobs. *Animal Science,* 78: 61-66.

Kearney, J. (2010). Food consumption trends and drivers. *Philosophical transactions of the royal society B*, 365: 2793-2807.

Manero, A., Vilanova, X., Cerda-Cuellar, M. and Blanch, A.R. (2006). Vancomycin- and erythromycin-resistant enterococci in a pig farm and its environment. *Environmental Microbiology*, 8: 667-674.

Montagne, L., Pluske, J.R. and Hampson, D.J. (2003). A review of interactions between dietary fibre and the intestinal mucosa, and their consequences on digestive health in young non-ruminant animals. *Animal Feed Science and Technology*, 108: 95-117.

Visser, D.P. (2004). The components of the pork supply chain in South Africa. PhD Thesis. University of Pretoria. Pretoria, South Africa.

Wenk, C., (2001). The role of dietary fibre in the digestive physiology of the pig. *Animal Feed Science and Technology*, 90: 21-33.

Whittemore, E.C., Emmans, G.C. and Kyriazakis, I. (2003). The relationship between live weight and the intake of bulky foods in pigs. *Animal Science*, 76: 89-100.

Chapter 2: Literature review

2.1 Introduction

Prediction of the gut capacity of growing pigs enables feed compounders to formulate diets which meet animal requirements knowing the threshold nutrient availability for particular intake level. There is a need to understand the impact physicochemical measurements of bulk have on VFI and how they interact in influencing the gut capacity of growing pigs. The current chapter discusses factors affecting VFI and classes of fibrous ingredients. It also reviews opportunities for including fibrous feed ingredients and effects of physicochemical measurements of bulkiness of fibre-rich diets on VFI in growing pigs. The current state of knowledge on predicting the gut capacity of growing pigs subjected to fibre-rich diets will also be discussed.

2.2 Physicochemical measurements of bulkiness

Water holding capacity, bulk density, neutral detergent fibre, crude fibre, viscosity, solubility and swelling capacity are the major physicochemical parameters used to describe feed bulk.

2.2.1 Water holding capacity

Water holding capacity describes the ability of fibre to trap or immobilise water within its matrix, swell and form gels with high water contents (Kyriazakis and Emmans, 1995). As the WHC of the feed increase, more space will be required in the gut, thereby reducing feed intake (Tsaras *et al.*, 1998). The WHC of fibre sources differ according to the variation in the monomeric composition of these fibrous materials and structural arrangement of their molecules. For example, reported that WHC is greater in pectin, potato pulp, and sugar beet pulp than in seed residues, pea hulls, and intermediate in wheat and barley (Serena and Bach-Knudsen, 2007). The variation noticed in WHC of fibrous ingredients warrants prediction of gut capacity to be done using a wide variety of fibrous sources.

Water holding capacity interacts with other physical properties of fibres. For example, as the ability of the fibre source to immobilise water increases, the bulk density of the fibre matrix also increases (Kyriazakis and Emmans, 1995). The relationship between WHC and other chemical properties of fibres can be explained by the prevalence of hydrogen bonds within the fibre matrix and the extent with which these bonds are exposed as possible binding sites (hydroxyl groups) with water molecules (Oakenfull, 2001). As a result, processing of feed ingredients, such as grinding or chopping may influence exposure of hydroxyl groups, and subsequently, the WHC of the feed. The relationship between WHC and feed intake in weaner and finishing pigs is still unclear. Investigating dynamics change in conjunction with other physicochemical properties of these fibrous is critical so that relationships between bulkiness and gut capacity can be accurately predicted.

2.2.2 Bulk density

Bulk density is defined as the degree of consistency measured by the quantity of mass per unit volume occupied by the fibrous material (Kyriazakis and Emmans, 1995). Inclusion the levels of fibrous ingredients which are lighter and more fluffy than the conventional diet caused a decrease in the quantity of less bulk material per unit volume that could be consumed implying that more space per unit mass will be required to accommodate the feed in the gut. The bulk density of the ingesta is subject to change in different sections of gut depending on the inclusion level fibre in the diet and rate of water absorption during gut transit. As feed absorbs water in the gut, the volume of the ingesta is increased in such a way that the bulk density will be increased. Information on how the bulk density of feed constrains feed intake in pigs is undermined. There is need, therefore, to predict the gut capacity of pigs using bulk density of fibrous diets formulated from fibre sources with a widespread range of bulky densities.

2.2.3 Neutral detergent fibre

The NDF is another common measure of fibre content that can be used to predict gut capacity in growing pigs. It measures most of the structural components in plant cells, i.e. lignin, hemicellulose and cellulose (Van Soest *et al.*, 1991). An increase in inclusion level of the fibre in the diet is associated with an increase in NDF content, reduction in nutrient density and bulkiness. Therefore, when growing pigs are given a diet with high NDF levels, the levels of feed intake will increase to compensate for the reduced content of digestible material, especially in weaner pigs. However, in finishing pigs, due to their ability to digest fibre and elongation of their large intestines and caecum, the anticipated patterns are likely to vary.

2.2.4 Crude fibre

Crude fibre is the structural component of a feed that is mainly composed of indigestible cellulose, hemicellulose and lignin determined after sequential digestion through acid and basic hydrolysis. Although it is of low nutritive value, it facilitates the peristaltic movements of feed in the gut. However, finishing pigs have the ability to ferment the fibre content of the feed in hindgut (Bindelle *et al*., 2008). Fibre-rich diets with high inclusion levels of fibre stimulate gut distension in young pigs and may mask the availability of non-fibrous feed ingredients from digestion in the foregut prompting the pigs to increase the intake levels up to a point when the gut capacity is reached, then intake becomes constant or starts to decrease (Tsaras *et al*., 1998).

2.2.5 Viscosity

Viscosity refers to the relationship between the resistance to flow of fibre and the force that moves it (Dikeman and Fahey, 2006). Viscosity depends on the ability of the porous matrix structure formed by polysaccharide chains to hold water through hydrogen bonding, dietary concentration and solvent characteristics (Borchani *et al.*, 2011). The inclusion of polysaccharides imposes non-Newtonian flow of the digesta (Sanderson, 1981). Fibres which are water soluble have high viscosity (Abdul-Hamid and Luan, 2000). Viscosity of fibrous diets increases with an increase in fibre concentration in the diet (Elleuch *et al.*, 2011). The extents with viscosity of DF affects feed intake, digestibility and flow rate have not been documented but are likely to improve the description of effects physicochemical measurements of bulkiness have on VFI of pigs.

2.2.6 Solubility

Solubility of a feed also influences VFI (Wenk, 2001; Elleuch *et al.*, 2011). It can be defined as the portion of the polysaccharide which can homogenously mix in solvents namely cold water, hot water, dilute acid or dilute alkali (Urriola, 2010). Various fibre sources such as brans from different crops may have the same constituent monosaccharide but differ in their solubility. The differences in the solubility are largely dependent on the glycosidic links between the monosaccharides as they make up the polysaccharides as well as constituent functional groups (e.g., sulphates and carboxyl) (Elleuch *et al.*, 2011). Water-soluble fibres are associated with high viscosity. For example, rice bran has a low viscosity (1.25 cps) and contains about 90 g/kg soluble fibre, implying that intakes of fibrous diets based on these are likely to be higher than those of conventional diets (Abdul-Hamid and Luan, 2000). Soluble fibre sources, such as maize cob prolong satiety, while insoluble fibre has a lower impact (Wenk, 2001).

2.2.7 Swelling capacity

Swelling capacity is the volume occupied by a known weight of fibre as it absorbs water within its matrix (Borchani *et al.*, 2011). Feeds that have a high swelling capacity tend to occupy more in the gut thereby limiting feed intake. There is little knowledge on the effects of swelling capacity of the feed on feed intake. The swelling ability of the feed components during gut transit is likely to be pronounced more in finishing pigs than weaner pigs, thus, intake patterns during these phases may differ.

Although the physicochemical properties form part of the dietary factors of VFI, it is crucial that the animal and environmental factors affecting feed intake are understood.

2.3 Factors affecting voluntary feed intake in growing pigs

Various factors influence VFI. These can be categorised into animal, dietary and environmental factors (Nyachoti *et al.*, 2004). The extent to which these factors influence VFI and consequently gut fill in growing pigs fed on fibrous diets is unclear. Feed intake depends on frequency of visits to the feeder, time spent eating at each visit, meal size and feeding rates, feed bulk, physical capacity of the gut and gut transit time (Nyachoti *et al.*, 2004; Hopwood *et al.*, 2004). When predicting VFI, the complexity in the influence of these factors on VFI warrants a holistic approach which concurrently evaluates all key factors including physicochemical properties of feed ingredients.

2.3.1 Animal factors

Voluntary feed intake is affected by the desired nutrient intake, gut capacity, health status, stage of growth, body weight, physiological status and genetic composition of the pig (Nyachoti *et al.*, 2004; Bindelle *et al.*, 2008). As pigs grow, their VFI is driven by the need for nutrient requirements for body maintenance functions and accretion of different body components (Noblet *et al.*, 2001, Whittemore *et al.*, 2003). When a growing pig is faced with challenges that compromise its immune system, its ability to consume feed and utilize it is impaired. Voluntary feed intake for growing pigs is also influenced by the stage of growth and physiological needs for nutrients which varies with body composition, gut morphology and gut capacity.

The ability of growing pigs to meet their physiological needs is also a subject of its capacity to ingest, digest and metabolize nutrients during the growth phase. As the body weight of the pig increase, its physical capacity for feed bulk also increases. Between 12 and 40 kg body weight, adaptation to bulky feeds increase with body weight because change in body weight is related to increase in the gut size (Kyriazakis and Emmans, 1995; Whittemore *et al.*, 2003). The scaled capacity for bulk decreased with body weight and then became constant from 80 kg for commercial hybrid (Large White × Landrace) given bulky diets based different inclusion levels of sugar-beet pulp (Whittemore *et al*., 2003). Research on the use of physicochemical measures of bulkiness of feeds with varying inclusion levels of a wide range of fibre sources with different bulk contents in terms of their solubility, viscosity, bulk density, WHC and swelling properties on gut capacities in growing pigs with different body weights is limited. Such research is crucial if a comprehensive description of the relationships between capacity for bulk and physicochemical measurements for bulk are established to ensure that optimum nutrient intake could be achieved, or allow a proportional degree of restriction to be imposed where this might be desirable.

Animal factors are divergent within and between genetic lines. For example, pigs selected for faster growth have high VFI compared to slow growing pigs. No studies have focused on the prediction of gut capacity of the new pig lines that are being introduced in commercial pig industry in South Africa, such as the TOPIGS and PIC hybrids. Prediction of gut capacities will assist feed compounders to formulate feeds that allow pigs to consume sufficient nutrients which meet the desired nutrient intake for that particular pig breed. Apart from the physical capacity of the pig for bulk feeds, the ability to digest fibre that could be having a large bearing on VFI in finishing pigs, therefore, can be explained also by the genetic makeup of the pig and physicochemical properties of dietary ingredients. Considering difference in body weight and gut morphology between weaner and finishing pigs, influence of physicochemical measurements of bulkiness are likely to vary in pigs during the weaner, and finishing stage.

2.3.2 Dietary factors

Voluntary feed intake of pigs getting all or a fraction of their nutrient requirements from fibre-rich diets depend solely on the bulkiness of the diet (Kyriazakis and Emmans, 1995; Tsaras *et al.*, 1998; Whittemore *et al.*, 2001). Bindelle *et al.* (2008) and Borchani *et al.* (2011) argued that, besides WHC, solubility, swelling, oil holding capacity and viscosity also influence gut-fill. The effect of bulk content of the diet on VFI needs to be defined. Apart from the physical feed intake capacity, other dietary factors that influence VFI include, feed form and presentation, as well as availability of drinking water. The effect that the bulky properties of non-fibrous ingredients that escape digestion in the foregut have on feed intake is often ignored during feed formulation. Feed ingredients vary widely in terms of their chemical composition and bulk contents, hence, their effects on the amount of nutrients consumed and available to cater for growth performance are complex. The accuracy in the description of how these dietary factors influence VFI depends on their relationship with gut fill thus characterization of physicochemical measurements of bulkiness of all feed ingredients is crucial.

Gut fill is influenced by the amount of space that the feed occupies in transit through different sections of gut, its absorption rate and the time it takes before egestion. It is also crucial to determine the additive effects of all feed ingredients on bulky properties of complete diets before mixing the diets to allow prediction of the maximum amount of feed that can be consumed by the pig before the gut capacity is constrained. Knowledge of the additive effects of physicochemical properties of feed ingredients also enables feed compounders to adjust the nutrient proportions so that sufficient nutrients for growth can be met, if the need arise. Inclusion of fibrous feed ingredients may also decrease VFI as a consequence of gut filling compromising nutrient intake in growing pigs. The inclusion of 0, 100, 200 and 300 g/kg maize cob in pig diets with balanced energy concentrations had no effect on VFI in growing pigs (Kanengoni *et al.*, 2004). Physicochemical properties of fibrous diets, thus, could be having greater influence on intake than nutrient densities.

The role that locally available dietary fibre (DF) sources of distinct physicochemical properties and inclusion levels play is not well established. Inclusion of some of these fibrous feed ingredients reduces the energy and protein content of the diets which result in the pig consuming more feed to meet its nutrient requirement. However, as the body-weight of the pigs increase, its ability to utilize the fibrous ingredients also improves (Kyriazakis and Emmans, 1995; Tsaras *et al.*, 1998). Apart from the increase in body-weight, utilisation of fibrous ingredients is enhanced by the development of the hindgut especially in finisher pigs. In ruminants, degradation of fibrous ingredients had been reported to influence VFI (Tolera and Sundstol, 2001; Abdou *et al.*, 2011). It is, therefore, imperative, also to determine the fermentation properties of fibrous ingredients given to pigs as these may alter the physicochemical nature of digesta and influences intake of fibrous feeds following digestion in the foregut and fermentation of feed components in the hindgut.

2.3.3 Environmental factors

Environmental factors affecting VFI are physical and social conditions with which pigs are subjected to during the rearing period. Environmental factors affecting VFI include temperature, humidity, ventilation, space allocation, animal-animal interactions, feeding strategies, housing, grouping and the quality of handing by stockman.

The thermal-neutral zone (TNZ) for ranges between 18 and 21^{o}C for sow and, between 30 and 37^{o}C for piglets, temperatures outside this range influence the VFI and, subsequently, performance in growing pigs (Quiniou *et al.*, 2000). For every 1^{o}C above the TNZ, VFI reduces by 40-80 g per day (Nyachoti *et al.*, 2004). The effect of bulkiness of the feed in relation to changes in temperature on VFI is not well established. A reduction in temperature from 22 to 12^{o}C caused an increase in intake. However, WHC was identified as the property of feed limiting intake of bulk feeds (Whittemore *et al*., 2001). Too few diets were used during these investigations, thus there exist a need for further investigations including a variety of fibre sources with a wide range of physicochemical measurements of bulkiness to describe the effect of temperature on intake of bulk feeds in growing pigs. The high temperatures in the sub-tropics depress appetite and thereby reduce growth performance.

Feed intake also depends on the humidity and the ventilation rates. Low ventilation rates and high humidity decrease gaseous movements and increase microbial proliferation. Furthermore, example, gases of 10ppm and above reduce appetite (Nyachoti *et al.*, 2004). There is need to quantify the effects that gaseous concentration has on VFI especially when pigs are subjected to fibrous diets. Due to climate change, sub-tropical conditions of southern

Africa has been threatened implying feed intake, availability of feed and pig welfare will be compromised (Gregory, 2007). It is imperative to conserve pig genotypes that can utilize locally available resources with minimum adverse effects of the environment.

Housing and feeding strategies affect VFI. Various social factors including space allocation, group size, feeder space and re-grouping pigs influence VFI of growing pigs. Regrouping, reduction in space allocation as well as group size reduces feed intake for pigs given conventional diets (Table 2.1). With the introduction of bulky fibrous ingredients into pig diets, there is need to implement strategies on the development of appropriate stocking densities to ensure that sufficient nutrient intake is available to all pigs in the pen. There is need to investigate the effect of type and inclusion level of fibres on VFI at different stocking densities. Inclusion levels may have varying effects on bulkiness, passage rate and duration of satiety, thereby indirectly influencing number of visits to the feeder and consequently VFI. Because physicochemical properties of fibrous feed ingredients are complex, feeding strategies involving exchange of diets based on different fibre feedstuffs could be way of reducing the constraining effect of bulky feeds. The qualities of handling or presence of stockman also influence VFI, stressful or novel situation will prevent pigs from consuming enough nutrients to meet their requirements.

2.4 Attributes of dietary fibre in growing-finishing pigs

The role of dietary fibre (DF) in growing pigs is undoubted (Kanengoni *et al.*, 2004; Bindelle *et al.*, 2008; Jarret *et al.*, 2011). If appropriate inclusion levels of dietary fibres in pig diets are identified, incorporating them in pig diets has various benefits in growing pigs. Its use in

Table 2.1: Effect of environmental factors on feed intake in growing pigs

Factor	ADFI (kg/d)	% change in ADFI	Source
Space (m^2 pig^{-1})			
0.545	2.70	-11.1	Edmonds *et al.* (1998)
0.345	2.40		
0.740	2.87	-11.9	McGlone and Newby (1994)
0.560	2.53		
Group size			
7	2.28	-3.1	Gonyou and Stricklin (1998)
15	2.21		
10	2.66	+4.5	McGlone and Newby (1994)
40	2.78		
Regrouping			
-	2.18	-7.8	Hyun *et al.* (1998)
$+^{y}$	2.01		

- means pigs were not regrouped.

+ mean pigs were regrouped by mixing with unfamiliar pigs.

ADFI=Average daily feed intake.

Adopted from Nyachoti *et al.* (2004).

pig diets is supported by low price and also by some beneficial effects reported on pig welfare, gut health, reduction in gas emissions and nutrient losses from excreta (Bindelle *et al.*, 2008; Jarret *et al.*, 2011).

2.4.1 Promotion of animal welfare

Pork consumers are increasing their concerns about the pig pre-slaughter conditions including housing and feeding strategies, inclusion of DF opens way for improving the welfare status of pigs during the growing phase. Good practices of animal welfare are underpinned by the framework provided in the five familiar freedoms that describe a pig's fundamental needs, including freedom from hunger, discomfort, pain and expressing normal behaviour (Gregory, 2007). Incorporation of DF induces early satiety in pigs (Bindelle *et al.*, 2008). Early satiety is vital for the wellness of the pigs for it hinders pigs from expressing stereotypic behaviours. Stereotypic behaviours, such as cannibalism, chain-chewing and bar-biting may be observed in pigs which are subjected to conventional low fibre-based diets. If appropriate inclusion levels of DF are not established, fibrous ingredients may impose early satiety in growing pigs which may not be desirable for it limits sufficient nutrient intake for potential growth.

Changes in behavioural responses of sows subjected to fibrous diets are shown in Table 2.2. These studies did not explain how behavioural expressions change during the day in relation to the physicochemical nature of the feed which has great influence on VFI and consequently gut fill. In growing pigs, behavioural patterns are likely to deviate from those observed in sows because bulky ingredients induce early satiety thereby influencing the feeding

Table 2.2: Mean percentage of time spent per behavioural element per treatment in the morning and afternoon

	Morning		Afternoon	
	Reference	Satiated	Reference	Satiated
Inactive	41.0	83.4	29.6	77.3
Self-directed behaviour	26.1	10.4	3.5	2.2
Lying lateral	11.4	33.0	8.7	28.5
Standing	40.7	14.8	48.0	16.6
Moving	3.4	2.4	4.3	2.1

(adopted from Zonderland *et al.*, 2004).

behaviours. If appropriate inclusion levels of DF are not established, fibre-rich diets may induce early satiety in growing pigs, however, this reduces feed intake and hinder the pig from meeting its nutrient requirements for desired growth performance. Reducing stereotypic behaviours and restlessness is beneficial through reduction of the amount of energy spent in physical activity, hence lowering the maintenance energy cost. There is need to characterise how different fibre physicochemical properties influence satiety level and duration, and consequently pig welfare status at different inclusion levels also in growing pigs.

2.4.2 Enhancement of gut health and microbial populations

Fermentable fibre in pig diets has prebiotic properties (Bindelle *et al.*, 2008). Accumulation of short chain fatty acids (SCFA), by-products of hindgut fermentation of oligosaccharides impedes the growth of undesirable microbes, such as coliforms and *Salmonella* species in the diet (Charalampopoulos *et al.*, 2002; Verstegen and Williams, 2002). Conversely, inclusion of fermentable polymers, such as non-starch polysaccharides (NSP), stimulates further the growth of selected enteric micro fauna namely *Lactobacilli* and *Bifidobacteria* which reduce gut ulcerations and diarrhoea (Bindelle *et al.*, 2008). Other DF sources may have laxative effects on the walls of the gastrointestinal tract (GIT), thereby promoting wellness and gut motility. For example, SCFA in the hind gut stimulates absorption of sodium, which increases absorption of water from the colon, thereby reducing incidences of non-pathogenic diarrhoea.

Increase in bulkiness stimulates secretions of mucin that facilities protection of the gut epithelium from pathogenic microorganisms, chemical and physical injuries thus reducing ulcers (Montagne *et al.*, 2003). As a result, the presence of DF modifies the microbial equilibrium in the intestines with a beneficial impact on gut health and the physiological status of the pig (Bindelle *et al.*, 2008). Deviations may occur due to physicochemical properties each fibre exhibits. Information on how physical properties of DF affect gut health is lacking, but crucial to fully describe DF as a nutrient to promote gut health. It is, therefore, necessary to investigate the impact of physical properties of the DF and identify the appropriate inclusion levels which promote growth of microbes with beneficiary effects to the gut health without compromising nutrient intake in growing pigs.

2.4.3 Reduction of gaseous emissions and nutrient losses to the environment

Attention has been paid to DF for its potential to reduce volatile losses and leaching of nutrients to the environment. Incorporation of DF in pig feeds promotes microbial growth which facilitates fermentation in the hindgut (Nahm, 2003). Following hindgut fermentation and microbial growth, there is induction of an uptake of bodily urea in the large intestines which favours the synthesis of bacterial proteins which are eliminated in faeces (Bindelle *et al.*, 2008). Eventually, this physiological process reduces urea excretion in urine and, consequently, NH_3 emission from the manure and slurry which causes odours is reduced (Nahm, 2003). For example, for each increase of 100 g NSP in pig diets, the slurry pH decreases by 0.12 units and ammonia emission reduces by 5.4 % (Cahn *et al*., 1998). Figure 2.1 illustrates the relationship between NSP content of the diet and the urinary-N/faecal-N ratio (Jongbloed, 2001). In South Africa, responses of locally available feedstuffs in reducing nutrient losses to the environment are not known.

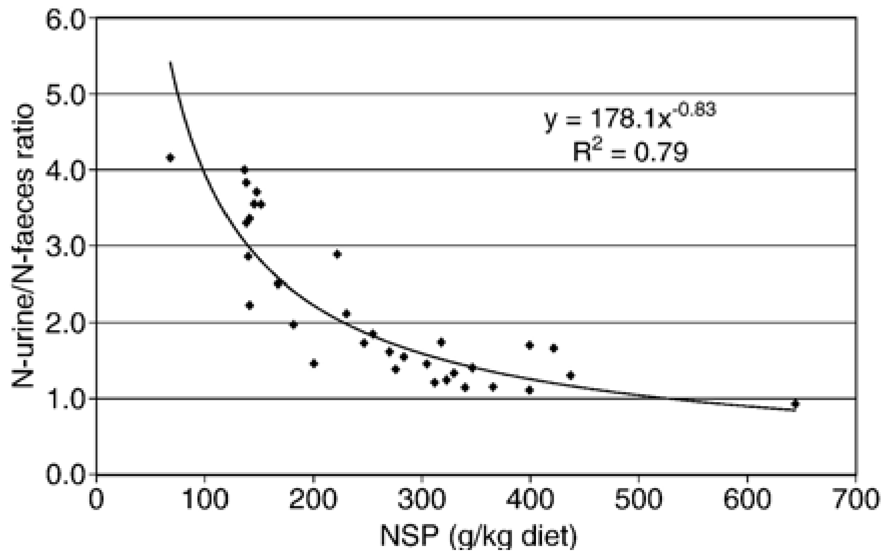

Figure 2.1: Relationship between NSP content of the diet and the urine-N/faecal-N ratio

(extracted from Jongbloed, 2001).

The physiological properties of NSP and its fermentability are predicted more accurately by their physical properties than chemical composition (Asp, 1996). Dietary fibre increases the laxative nature of the digesta thus reducing the transit time and consequently inhibiting microbial activity hind gut, as such conversion of urinary N to faecal N will be limited. For example, reduction in transit time reduces digestion of non-fibre dietary nutrients. There is, therefore, need to investigate the impact of physicochemical properties of DF on nutrient emission dynamics. A study in nutrient dynamics of the fibre-rich diets improves the understanding of the contribution of fibre residue in reducing nutrient losses and the costs of feeding.

2.4.4 Reducing the need for grain and feed costs

Feed resources are scarce and, if available, prices are increasingly becoming prohibitive, energy being the greatest part of the costs. The continued increase in feed costs can be partly attributed to the competition for raw materials between animal feed processors and the increasing world human population needs for food and biofuel (Bindelle *et al.*, 2008). Formulating diets that meet pig's requirement as well as reducing feeding costs is, therefore, crucial. The use of fibrous agro-industrial by-products and crop residues that are usually thrown away for human consumption increases the options and number of feed ingredients that can be used in pig production (Chimonyo, 2005). However, due to their bulkiness, fibrous ingredients impose early satiety yet gut fill is one of the constraints that prevent pigs from eating as much as they need in order to grow at their potential. If pig producers make use of bulky ingredients when they are available at reasonable costs, the amount that should be included in the feed should not be such that the physicochemical nature of the diet should not be such that the pig is prevented from consuming what it needs to grow at its potential.

Despite the reduction in feed energy content, fibre can be fermented in the hindgut and provide energy through production of SCFA (Buddington, 2001). Following hindgut fermentation, the proportion of energy that contributes to overall metabolic energy depends on the type and inclusion level of the fermentable carbohydrates of the DF. Besides the provision of energy, cereals, fruit and vegetable by-products that are cheap and readily available supply bioactive compounds, thereby reducing further the cost of feed ingredients. The energy that DF produces can cover up to 15 and 30 % of the ME in growing pigs and matured pigs, respectively (Dierick *et al.,* 1989; Varel *et al.,* 1997; Anguita *et al,,* 2006). Bindelle e*t al.* (2008) proposed that the utilization of SCFA is inefficient, however, its usefulness at varying DF inclusion levels in conjunction with the cost of feeding is not well known, thus warrants further investigation. Crop residues are usually thrown away from the agricultural industry, implying that they have insignificant effects on feeding cost.

In view of fibre sources being accessible, cheap and readily available and the ability of pigs to utilise them, they can act as value added replacements for nutrients in pig diets and reduce competition for feed ingredients with humans. For example, the inclusion of 380 g/kg cassava peels and 5 % palm oil doubled the crude fibre content, but the latter counterbalanced the decrease in DE content and the cost saving per kg of weight gain reached 240 g/kg (Balogun and Bawa, 1997). Unconventional fibrous feedstuffs may enhance performance and healthiness of growing pigs through provision of valuable nutrients such as minerals (calcium, manganese and iron), vitamins and oils (Nguyen *et al.*, 2004; Leterme *et al.*, 2005; 2006). Furthermore, other crop residues and forages, such as maize cobs and soybean hulls may also increase the crude protein (CP) content of the diets and stimulate performance in growing pigs (Kanengoni *et al.*, 2004; Bindelle *et al.,* 2008). The extent with which fibre inclusion reduce the cost of feeding with the local fibrous sources is unknown. Therefore, incorporation of fibrous feedstuffs may not always be efficient in terms of animal performance but the economical asset of the operation is most at the advantage of a substantial substitution. To fully define the usefulness of fibre as possible nutrient for growing pigs, the impact of physicochemical properties on intake need to be understood.

2.4.5 Enhancement of crop-livestock production systems

An integrated crop-livestock farming system represents a key solution for enhancing pig production, crop production and reducing pressure on land. Use of alternative fibrous agro-industrial by-products such as maize cobs, sunflower husk, which are usually thrown way, increases the interdependence of farm enterprises, as products from crop production are channelled towards pig production whilst manure will be used to fertilise crops (Chimonyo, 2005). Integrated systems help reduce poverty and malnutrition. Therefore, integrated farming systems consist of a range of resource-saving practices that aim to achieve profits, and high and sustainable production levels, while alleviating the negative effects of intensive farming and preserving the environment.

2.4.6 Promoting sustainability of pig production and utilisation of resources

The growing demand for livestock products makes it more important to ensure the effective use of feed resources that are usually thrown away, including crop residues. Utilization of local and readily available crop residues and agro-industrial by-products can promote sustainability of pig production and increase the efficiency of resource utilization. Agro-industrial by-products and cereal by-products are sometimes burnt, left to rot in farms, therefore, using them during animal feed formulation can be another way to enhance their usefulness, intensify land use as well as reducing pollution to the environment.

Feeding crop residues to pigs instead of burning them can be a solution of safeguarding environmental sustainability through prudent and efficient resource use. Furthermore, excreta plays a crucial role in the overall sustainability of farming systems because, besides improving nutrient cycling, it can provide energy thereby replacing charcoal and wood. Sometimes crop residues are thrown away or burnt thereby increasing pollution to the environment. Using them to feed pigs can be a prudent way to reduce emissions of global warming gases and nuisance disposal of crop residues which can disturb biodiversity.

2.4.7 Promotion of outdoor pig production systems

Outdoor pig production systems are increasingly gaining popularity for they enhance welfare of pigs as they permit occurrences of natural behaviours and increased environmental diversity. With the increase for demands for outdoor production systems (OPS), use of forages reduces the competition for grains (Rivera-Ferre *et al.*, 2001). The use of fibrous feedstuffs in feeding pigs is an imitation of OPS and also opens way for evaluating their usefulness or viability of organic pig enterprises.

2.5 Common fibrous feed ingredients in southern Africa

Inadequacy of animal feed resources is among major constraints limiting the development of pig production. Fibrous feedstuffs are potential ingredients to incorporate when formulating pig diets. Physicochemical properties, which can express themselves differently depending on the monomeric arrangement of constituent polysaccharides and their level of inclusion in the diet (Bindelle *et al.*, 2008), are largely unknown. The utilization of fibrous feedstuffs varies with geographical location, origin and method of extraction. The common fibrous feedstuffs used can be classified into cereal by-products, leguminous residues, agro-industrial by-products and forages.

2.5.1 Cereal by-products

Cereal crops are plants of the grass family (*Gramineae*) which produces edible seeds and sugar. Commonly cereal crops in southern Africa are maize, sorghum, millet, rice, wheat, sugar cane and oats. They are harvested and processed leaving by-products such as straw, stover, brans, leaves, haulms, hulls, stalks, pulps and husks. These by-products could be used as feed ingredients in pig diets. Their usefulness as sources of nutrients and effects on intake is, however, not well established.

Cereal by-products are principal sources of cellulose, lignin and hemicellulose and their usefulness have been extensively investigated, particularly in ruminants (Tolera and Sundstol, 2001; Abdou *et al.*, 2011). Examples of cereal by-products with potential nutritive value include oat bran, wheat bran, rice bran, maize cob, maize stover, wheat straw, barley, sorghum stover, millet stover and sugar cane bagasse (Kanengoni *et al.*, 2004; Bindelle *et al.*, 2008). Brans derived from wheat, rice and oats are commonly used in formulating pig diets. Conversely, Kanengoni *et al.* (2004) reported no changes in the feed intake as the level of maize cob was increased in successive diets. The paradox in the results by the latter and the former experiments can be explained by the changes which WHC and bulk density of digesta during transit in the gut.

Serena and Bach-Knudsen (2007) reported that WHC is greater in pectin, potato pulp, and sugar beet pulp than in seed residues, pea hulls, and intermediate in wheat and barley. The differences can be attributed to the variation in the monomeric composition of these fibrous materials and structural arrangement of their molecules. The effect of WHC capacity of bulky diets based on varying levels of fibrous cereal residues such as maize cobs and maize stover are scarce but have potential of use as feed ingredients in Southern Africa.

An increase in dietary fibre (DF) levels constrains VFI (Tsaras *et al.,* 1998; Nyachoti *et al.* 2004). Contrasting results were reported by Kanengoni *et al.* (2004) that 0, 100, 200 and 300 g/kg inclusion level of maize cobs did not affect VFI. However, physical properties of the individual diets were not determined. It can be hypothesized that the level of DF inclusion which constrains intake lies between 150 and 250 g/kg inclusion level for pigs with body weight of 25 kg, but is subject to change with age. The use of locally available fibrous feedstuffs is crucial to promote sustainability of the integration between the livestock industry and crop farming through efficient utilization of agricultural resources.

2.5.2 Leguminous residues

Leguminous residues remain after legume crops have been harvested to extract oilseeds for human consumption. Leguminous residues that are common in southern Africa include soybean straw, soybean hulls and groundnut hulls that are obtained after extraction of beans, oil and nuts. Due to their high N content, these leguminous residues are likely to be valuable replacements in pig feeds. Tsaras *et al.* (1998) reported that there were no differences in ADG and intakes of pigs given 320 g/kg soya hulls based diets and those given a normal conventional diet. The similarities are likely to reflect the fact that leguminous residues contribute to the protein content of the diet which is usually ignored during feed formulation. Research on effects of physicochemical properties of leguminous residues on VFI is scanty.

2.5.3 Agro-industrial by-products

Agro-industrial by-products are waste products, roughages and crop residues that become available as livestock feed after crops and fruits have been processed in the food industry. Examples of agro-industrial by-products include cereal residues, husks, brewer's grains, leguminous by-products and fruit residues. The effectiveness of these fibre ingredients in pig nutrition is likely to be highly influenced by their physicochemical properties and treatment both during and after harvesting.

Due to their differences in the way they are harvested, processed and botanical composition; dry matter from different fibrous feed ingredients certainly has filling effects in the gut. The undigested dry matter, or organic, matter which escapes the foregut may also have different bulk equivalents thereby influencing digesta transit and gut emptying in growing pigs (Kyriazakis and Emmans, 1995). For example, Brouns *et al.* (1991) reported that VFI in sows was depressed far more by feeds based on sugar-beet pulp than by those based on more indigestible material such as straw and rice bran. Due to their low water holding capacities, when cereal brans derived from wheat and millet are diluted in pigs feed they do not constrain feed intakes as much as other fibrous sources, such as grass hay and sugar beet pulp (Whittemore *et al.*, 2001). In South Africa, for example, agro-industrial by-products such as sunflower husks are usual thrown away and always available throughout the year from the cooking oil extraction industry. Their effects on VFI in growing pigs, however, need to be investigated.

Fibrous feed ingredients of fruit and legume origin can be wastes derived from citrus fruits, soybean, and groundnut residues after extraction of juice and cooking oil respectively (Borchani *et al.*, 2011). Examples of fruit derivatives include citrus pulp, grape residues and those from legumes are soybean cake, soybean hulls and groundnut haulms. Fruit and legume residues are primary sources of pectin, gums, mucilage and bioactive compounds, such as flavonoids, carotenoids and proteins (Borchani *et al.*, 2011). These feedstuffs are likely to share the same solubility and viscosity characteristics as cereal brans. However, they have better nutritional qualities than those originating from cereals. Due to their bioactive content, incorporating fibrous feed ingredients of fruit origin may improve immune system activation, but more research is needed to elucidate the mechanisms responsible and their effects VFI and performance in growing pigs.

Brewer's grains and biofuel production residues can also be used in pig feed rationing and have potential to boost pig immune systems. The nutritional abilities of these fibrous feedstuffs need to be evaluated at varying inclusion levels in grower-finisher pigs. The extent with which they influence VFI and digestibility of other feed ingredients also warrants investigation. Insoluble fibres such as sunflower husks are characterized by their low porosity, low density and they reduce viscosity as well as the transit time and are likely to increase intake (Roehrig, 1988). Soluble fibres such as maize cobs are digestible and are likely to reduce transit time.

Kyriazakis and Emmans (1995) diluted a basal diet with 250, 500 and 750 g/kg of wheat bran, 500 g/kg dried grass and 500 g/kg dried citrus pulp whilst Tsaras *et al.* (1998) included 320 and 800 g/kg of basal diet in either sugar-beet pulp, dry grass or soya hulls. Kanengoni *et al.* (2004) used maize cobs at inclusion levels of 0, 100, 200 and 300 g/kg. The diversity of these inclusion levels in these reports indicates that appropriate inclusion levels of DF are poorly understood. The scope of these studies could not, however, explain DF constrains the gut capacity in growing pigs. Therefore, there is need to investigate effects of varying inclusion levels of both soluble and insoluble fibre on VFI in growing pigs.

2.5.4 Forage plants

In tropical countries, alternative feeding programmes involving incorporation of fibrous feedstuffs have been investigated. Examples of forages used in feeding pigs include *Acacia karroo, Acacia nilotica, Amarunthus hybridus, Colophospermum* mopane, *Desmodium intortum*, *Ipomea batatas*, lucerne, *Manihot esculenta*, *Morulus alba* and *Richardia scabra* (Halimani *et al.*, 2005; Leterme *et al*., 2005; Bindelle *et al.*, 2008). Information on the effect that these fibres have on feed intake in pigs is scanty.

Most of the above mentioned forages have high CP content, implying that including it in pig diets might increase the nutritional value of pig diets. In Vietnam, the incorporation of 150 g/kg spinach or *I. batatas* leaves in a diet for Mon Cai × Large White growing pigs increased the CF content of the diets, but also CP (0.172 to 0.182 g CP.kg^{-1}DM and the α-linoleic acid (0.14g ALA.MJ^{-1}ME) contents (Bindelle *et al.*, 2008). Although the effects that these formulations had on intake were not accounted for, low inclusion level of protein-rich fibres stimulates growth performance (Nguyen *et al.*, 2004). Leterme *et al.* (2005; 2006) reported that, for sows, inclusion of green forages increased VFI due to a poor palatability and a tilling effect of the fibrous ingredient. However, 300 g/kg of tropical tree leaves did not affect the digestive process. Using forage plants in feeding pigs provides opportunities to reduce feed costs, particularly, if their VFI is established.

2.7 Estimation of gut capacity in growing pigs

Estimating the gut capacity of pigs gives nutritionists an opportunity to adjust the feeding rations so that adequate nutrient intakes which meet the pig's requirements can be achieved. The gut capacity of a pig is reached when maximum feed intake by a pig that has not met its desired nutrient intake is reached or starts to decrease with increase in bulkiness. Previous experiments had been using a narrow range of fibrous sources to dilute conventional feeds, such that their physicochemical measures of bulkiness were used to predict the maximum feed intake (Kyriazakis and Emmans, 1995; Tsaras *et al.*, 1998; Whittemore *et al.*, 2003). The range of physicochemical properties could, however, not provide a break point that could be used to identify the threshold level for each parameter so that when nutritionist are formulating feeds, the bulky content at that point should not be exceeded if sufficient nutrient intake is to be achieved.

To allow the threshold levels of inclusion to be identified for each physicochemical measurements of bulkiness, there is, need to use a wide variety of fibre sources and possibly include them in feeds at varying inclusion levels. Table 2.3 illustrates that fibrous ingredients are made up of various types of polymers which are build up from different constituent monomers, implying that physicochemical measures of bulky may vary depending on the arrangement and monomeric composition of individual fibre sources. In this regard, a wider range of each physicochemical property can then be fitted to identify the threshold values of measures of bulkiness that could be used to identify the point where equilibrium intake is achieved or starts to increase as the bulky content of the feed continues to increase. Although quadratic equations can be used to predict changes in VFI as each physical property increases, broken stick models are likely to provide more accurate levels of estimating the gut capacity in pigs.

2.8 Summary

The pig, diet and environment all affect VFI. Common fibre sources with potential of being used in growing pig diets were identified and their usefulness in relation to VFI was reviewed. The objective of the present study was to identify the most accurate physicochemical properties that best describe bulkiness of a feed, such that the gut capacity of pigs can be accurately predicted using that parameter. It is, therefore, imperative to characterise physicochemical properties of feed ingredients so that pig producers can have a comprehensive understanding of their effects on bulkiness, and consequently their effects on the maximum amount of feed that can be consumed.

Table 2.3: Chemical classification of potential fibre feedstuffs that can be used in pig diets

Possible sources of fibre in pig diets	Type of polymer(s)	Constituent monomers	Source
Oat hulls, Soybean hulls	Hemicellulose, cellulose	Glucose, xylose, mannose, galactose, rhamnose, arabinose, fucose	Bindelle *et al.* (2008)
Barley, Oat bran, Rye	B-glucans	glucose	Johansson *et al.* (2000)
Maize cob	Xylans, cellulose hemicellulose	Glucose, xylose, arabinose	Jeevan *et al.* (2011)
Maize Stover	Lignin	glucose	Tolera and Sundstol (2001)
Sugar beet pulp	Pectins, xylose	Uronic acids, glucose	Le Goff *et al.* (2001)
Pea hulls	Pectins, xylose	Uronic acids, glucose	Bindelle *et al.* (2008)
Fruit by-products			,Borchani *et al.* (2011)
Lucerne hay	Pectin	Arabinose, galactose, rhamnose, galacturonic acid	Hatfield (1991)

2.9 References

Abdou, N., Nsahlai, I.V. and Chimonyo, M. (2011). Effect of groundnut haulms supplementation on millet stover intake, digestibility and growth performance. *Animal Feed Science and Technology*, 169: 176-184.

Abdul-Hamid, A. and Luan, Y.S. (2000). Functional properties of dietary fibre prepared from defatted rice bran. *Food Chemistry*, 68: 15-19.

Anguita, M., Canibe, N., Perez, J.F. and Jensen, B.B. (2006). Influence of the amount of dietary fibre on the available energy from hindgut fermentation in growing pigs: use of cannulated pigs and *in vitro* fermentation. *Journal of Animal Science*, 84: 2766-2778.

Asp, N.G. (1996). Dietary carbohydrates: classification by chemistry and physiology. *Food Chemistry*, 57: 9-14.

Balogun, T.F. and Bawa, G.S. (1997). Cassava peels in the diet of young pigs in Nigeria. *Tropical Animal Health Production*, 4: 209-215.

Bindelle, J., Leterme, P. and Buldgen, A. (2008). Nutritional and environmental consequences of dietary fibre in pig nutrition: a review. *Biotechnology Agronomy Social and Environment*, 12: 69-80.

Borchani, C., Besbes, S., Masmoudi, M., Blecker, C., Paquot, M. and Attia, H. (2011). Effect of drying methods on physicochemical and antioxidant properties of date fibre concentrates. *Food Chemistry*, 125: 1194-1201.

Brouns, F., Edwards, S.A. and English, P.R. (1991). Fibrous raw material in sow diets. *Animal Production*, 52: 598-605.

Buddington, R.K. (2001). The use of non-digestible oligosaccharides to manage the gastrointestinal ecosystem. *Microbial Ecology in Health and Disease*, 13: 9-15.

Canh, T.T., Verstegen, M.W.A., Aarnink, A.J.A. and Schrama, J.W. (1998). Dietary carbohydrates alter the faecal composition and pH and the ammonia emission from slurry of growing pigs. *Journal of Animal Science*, 76: 1887-1895.

Charalampopoulos, D., Wang, R., Pandiella, S.S. and Webb, C. (2002). Application of cereals and cereal components in functional foods: a review. *International Journal of Food Microbiology*, 79: 131-141.

Chimonyo, M. (2005). Evaluation of production and genetic potential of indigenous Mukota and their crosses with Large White pigs in Zimbabwe. PhD Thesis. University of Zimbabwe, Harare, Zimbabwe.

Dierick, N.A., Vervaeke, I.J., Demeyer, D.I. and Decuypere, J.A. (1989). Approach to the energetic importance of fibre digestion in pigs. I. Importance of fermentation in the overall energy supply. *Animal Feed Science and Technology*, 23: 141-167.

Dikeman, C. L., and Fahey Jr., G. C. (2006). Viscosity as related to dietary fibre: A review. *Critical Reviews in Food Science and Nutrition*, 45: 649-663.

Edmonds, M.S., Arentson, B.E. and Mente, G.A. (1998). Effect of protein level and space allocation on performance of growing-finishing pigs. *Journal of Animal Science*, 76: 814-821.

Elleuch, M., Bedigian, D., Roiseux, O., Besbes, S., Blecker, C. and Attia, H. (2011). Dietary fibre and fibre-rich by-products of food processing: Characterisation, technological functionality and commercial applications: A review. *Food Chemistry*, 124: 411-421.

Gonyou, H.W. and Stricklin, W.R. (1998). Effects of floor allowance and group size on the productivity of growing/finishing pigs. *Journal of Animal Science*, 76: 1326-1330.

Gregory, N.G. (2007). Animal Welfare and Meat Production, 2nd Edition, CAB International, Wallingford, UK: 10-25.

Halimani, T. E., Ndlovu, L. R., Dzama, K., Chimonyo, M. and Miller, B. G. (2005). Metabolic response of pigs supplemented with incremental levels of leguminous *Acacia karroo*, *Acacia nilotica* and *Colophospermum* mopane leaf meals. *Animal Science*, 81: 39-45.

Hatfield, R.D. (1993). Cell wall polysaccharide interactions and degradability. In: Jung, H.J., Buxton, D.R., Hatfield, R.D. and Ralph, J., Editors, Forage Cell Wall Structure and Digestibility, ASA-CSSA-SSSA, Madison, WI, USA: 285-313.

Hopwood, D.E., Pethick, D.W., Pluske, J.R. and Hampson, D.J. (2004). Addition of pearl barley to a rice-based diet for newly weaned piglets increases the viscosity of the intestinal contents, reduces starch digestibility and exacerbates post-weaning *colibacillosis*. *British Journal of Nutrition*, 92: 419-427.

Hyun, Y., Ellis, M., Riskowski, G. and Johnson, R.W. (1998). Growth performance of pigs subjected to multiple concurrent environmental stressors. *Journal of Animal Science*, 76: 721-727.

Jarret, G., Cozannet, P., Martinez, J. and Dourmad, J.Y. (2011). Effect of different quality wheat dried distiller's grain solubles (DDGS) in pig diets on composition of excreta and methane production from faeces and slurry. *Livestock Science*, 140: 275-282.

Jeevan, P., Nelson, R. and Rena, E.A. (2011). Optimization studies on acid hydrolysis of corn cob hemicellulosic hydrolysate for microbial production of xylitol. *Journal of Microbiology and Biotechnology Research*, 1: 114-123.

Johansson, L., Virkki, L., Maunu, S., Lehto, M., Ekholm, P., and Varo, P. (2000). Structural characterisation of water soluble b-glucan of oat bran. *Carbohydrate Research*, 42: 143-148.

Jongbloed, A.W. (2001). Do feeding measures for lowering ammonia emission have a negative effect on the digestibility and utilization of nutrients? In: Jongbloed, A.W., Blok, M.C., Editors, Veevoeding en Ammoniakemissie uit Varkensstallen. Samenvattingen van de themamiddag, Productschap Diervoeder, The Hague, The Netherlands (2001): 11-23.

Kanengoni, A.T., Dzama, K., Chimonyo, M., Kusina, J. and Maswaure, S.M. (2004). Growth performance and carcass traits of Large White, Mukota and their F_1 crosses fed on graded levels of maize cobs. *Animal Science,* 78: 61-66.

Kyriazakis, I and Emmans, G.C. (1995). The voluntary feed intake of pigs given feeds based on wheat bran, dried citrus pulp and grass meal, in relations to measurements of bulk. *British Journal of Nutrition*, 73: 191-207.

Le Goff, A., Renard, C.M.G.C., Bonnin, E. and Thibault, J.F. (2001). Extraction, purification and chemical characterisation of xylogalacturonans from pea hulls. *Carbohydrate Polymers*, 45: 325-334.

Leterme, P., Londono, A.M., Estrada, F., Souffrant, W.B. and Buldgen, A. (2005). Chemical composition, nutritive value and voluntary intake of tropical tree foliage and cocoyam in pigs. *Journal Science Food Agriculture*, 85: 1725-1732.

Leterme, P., Botero, M., Londono, A. M., Bindelle J. and Buldgen A. (2006). Nutritive value of tropical tree leaf meals in adult sows. *Animal Science*, 82: 175-182.

McGlone, J.J. and Newby, B.E. (1994). Space requirements for finishing pigs in confinement: behaviour and performance while group size and space vary. *Applied Animal Behaviour Science*, 39: 331-338.

Montagne, L., Pluske, J. R. and Hampson, D. J. (2003). A review of interactions between DF and the intestinal mucosa, and their consequences on digestive health in young non-ruminant animals. *Animal Feed Science and Technology*, 108: 95-117.

Nahm, K.H. (2003). Influence of fermentable carbohydrates on shifting nitrogen excretion and reducing ammonia emission of pigs. *Critical Reviews in Environmental Science and Technology*, 30, 165-186.

Nguyen, L.Q., Everts, H., Hue, H.T. and Beynen, A.C. (2004). Feeding of spinach or sweet potato leaves and growth performance of growing pigs kept on smallholder farms in Central Vietnam. *Tropical Animal Health and Production*, 36: 815-822.

Noblet, J. (2001). Digestive and metabolic utilization of dietary energy in pig feeds: comparison of energy systems. In: Garnsworthy P.C. and Wiseman J., Editors, Recent Developments in Pig Nutrition, Nottingham University Press, Nottingham University Press, UK (2001): 161-184.

Nyachoti, C.M., Zijlstra, R.T., de Lange, C.F.M. and Patience, J.F. (2004). Voluntary feed intake in growing-finishing pigs: A review of the main determining factors and potential approaches for accurate predictions. *Canadian Journal of Animal Science*, 84: 549–566.

Oakenfull, D. (2001). Physical chemistry of dietary fibre. In: Spiller G. A., Editor, Dietary fibre in human nutrition, 3rd Edition, CRC Press, Boca Raton, Florida, USA (2001): 33-47.

Quiniou, N., Dubois, S. and Noblet, J. (2000). Voluntary feed intake and feeding behaviour of group-housed growing pigs are affected by ambient temperature and body weight. *Livestock Production Science*, 63: 245-253.

Rivera-Ferre, M.G., Edwards, S.A., Mayes, R.W., Riddoch, I. and Hovell, F.D.D. (2001). The effect of season and level of concentrate on the voluntary intake and digestibility of herbage by outdoor sows. *Animal Science*, 72: 501-510.

Roehrig, K.L. (1988). The physiological effects of dietary fibre. *Food Hydrocolloids*, 2: 1-18.

Sanderson, G. R. (1981). Polysaccharides in foods. *Food Technology*, 35: 50-57.

Serena, A., and Bach-Knudsen, K.E. (2007). Chemical and physiochemical characterisation of co-products from the vegetable food and agro industries. *Animal Feed Science and Technology*, 139: 109-124.

Tolera, A. and Sundstol, F. (2001). Prediction of feed intake, digestibility and growth rate of sheep fed basal diets of maize stover supplemented with *Desmodium intortum* from dry matter degradability of the diets. *Livestock Production Science*, 68: 13-23.

Tsaras, L.N., Kyriazakis, I. and Emmans, G.C. (1998). The prediction of the voluntary food intake of pigs on poor quality foods. *Animal Science*, 66: 713-723.

Urriola, P.E. (2010). Digestibility of dietary fibre by growing pigs. PhD Dissertation. University of Illinois, Urbana-Champaign. USA.

Van Soest, P. J., Robertson, J. B. and Lewis, B. A. (1991). Methods for dietary fibre, neutral detergent fiber, and non-starch polysaccharides in relation to animal nutrition. *Journal of Dairy Science*, 74: 3583-3597.

Varel, V.H. and Yen, J.T. (1997). Microbial perspective on fibre utilization by swine. *Journal of Animal Science*, 75: 2715-2722.

Verstegen, M. and Williams, B. (2002). Alternatives to the use of antibiotics as growth promoters for monogastric animals. *Animal Biotechnology*, 13: 113-127.

Wenk, C. (2001). The role of dietary fibre in the digestive physiology of the pig. *Animal Feed Science and Technology*, 90: 21-33.

Whittemore, E.C., Kyriazakis, I., Emmans, G.C. and Tolkamp, B.J. (2001). Tests of two theories of food intake using growing pigs. 1. The effect of ambient temperature on the intake of foods of differing bulk content. *Animal Science,* 72: 351-360.

Whittemore, E.C., Emmans, G.C. and Kyriazakis, I. (2003). The relationship between live weight and the intake of bulky foods in pigs. *Animal Science*, 76: 89-100.

Zonderland, J.J., De Leeuw, J.A., Nolten, C. and Spoolder, H.A.M. (2004). Assessing long-term behavioural effects of feeding motivation in group-housed pregnant sows; what, when and how to observe. *Applied Animal Behaviour Science,* 87: 15-30.

Chapter 3: Physical properties, chemical composition and fermentation characteristics of feed ingredients

Abstract

Understanding the effects of physicochemical properties of feeds on feed intake, digestibility and growth performance in pigs is essential. The objective of the current study was to characterise physicochemical properties and fermentation parameters of various feed ingredients. Chemical composition and physical properties were determined in nine feed ingredients and eight fibrous feedstuffs. Maize stover had the highest water holding capacity (WHC) ($P < 0.05$). Lucerne hay and saw dust had significantly the highest bulky densities. Among fibrous feed ingredients, NDF had a high negative correlation ($P < 0.001$) with CP and ether extract (EE), whilst WHC was significantly correlated to EE and ash. Density was correlated with EE, neutral detergent fibre (NDF) and acid detergent fibre (ADF) ($P < 0.01$). Rice bran and maize cob had the highest ($P < 0.05$) acetate concentrations. Rice bran, maize cob, groundnut haulms were the most fermentable of all fibrous feed ingredients. Prediction of the gut capacity of growing pigs using physicochemical properties and fermentation parameters of fibrous feed ingredients is recommended.

Keywords: bulkiness, bulk density, feed intake, *in vitro* fermentation, water holding capacity.

3.1 Introduction

Pig feed compounders are continuously searching for alternative feed formulation strategies that improve the nutrition and welfare status of pigs. Conventional diets predispose pigs to gut health problems, impair animal well-being and escape the GIT, thereby causing nutrient losses to the environment (Aarnink and Verstegen; 2007; Bindelle *et al.*, 2008; Jorgensen *et al.*, 2010). Gut fill is one of the constraints that prevent pigs from consuming as much fibrous feeds as they need to grow at their potential. Variability in bulkiness of feed ingredients, that are usually ignored, additively alters the physicochemical nature of feeds both during formulation and transit in the GIT, thereby affecting the amount of feed that pigs can consume.

The bulk content of a feed should not be such that the pig is prevented from consuming sufficient nutrients that are required for it to attain its potential growth. Accurate prediction of when gut fill is likely to be a constraint warrants the knowledge of characteristics of the feed that mostly describe its bulkiness. The bulkiness of the commonly used feedstuffs is not known. Some of these feed ingredients are assumed not to contribute towards bulkiness. To achieve a more comprehensive understanding of the bulk characteristics of feeds, there is need, therefore, to characterise physicochemical properties of feed ingredients. Physicochemical measurements of bulk, such as solubility, viscosity, water holding capacity (WHC), bulk density, fibre content, hindgut degradation rate, speed at which long particles are reduced to smaller particles, partitioning factors, quantity of short chain fatty acids (SCFA) produced during fermentation and outflow rates are important factors affecting the intake of bulky feeds (Orskov, 1994; Tsaras *et al.*, 1998; Borchani *et al.*, 2011).

The available literature on physicochemical properties of bulky diets has been based on limited materials (Tsaras *et al.*, 1998; Anguita *et al.*, 2007; Behgar *et al.*, 2009). Little work has, however, been done to establish relationships among these physicochemical properties and fermentation profiles of different feed ingredients, but such information is crucial if the best descriptors of bulkiness are to be identified. Understanding the effects physicochemical properties of feed ingredients on feed bulk assist nutritionists to design appropriate feeding programmes that ensure that optimum nutrient intake required for potential growth is achieved. The objective of the current study was, therefore, to characterise physicochemical properties and fermentation profiles of common fibrous feed ingredients. It was hypothesized that the physicochemical properties and fermentation characteristics of different feed ingredients are highly variable.

3.2. Materials and Methods

3.2.1 Feed ingredients

The feedstuffs analysed comprised of fibre sources namely lucerne hay, groundnut haulms, maize cobs, maize stover, grass hay, rice bran, sunflower husks and saw dust. Lucerne hay and starch were purchased from Agricultural Products Supply, Mkondeni, Pietermaritzburg. Rice bran, sunflower husks, soybean oil cake and fishmeal were obtained from food processing industry in Willowton, Pietermaritzburg. Groundnut haulms, maize cobs and maize stover as well as grass hay, soybean and maize were harvested and sundried at Ukulinga Research Farm, University of KwaZulu-Natal. Saw dust was obtained from the wood processing industry in Pietermaritzburg.

Conventional feed ingredients analysed included, yellow maize, soybean, soybean oil cake, cotton seed cake, sunflower oil cake, fishmeal, whole wheat; molasses syrup and starch. Yellow maize, soybean and whole wheat were harvested and sun-dried at Ukulinga Research farm, University of KwaZulu-Natal. Soybean oil cake, cotton seed cake and sunflower oil cake were obtained from oil making industry at Willowton, Pietermaritzburg. Fishmeal, molasses syrup, and starch were purchased from Agricultural Products Supply, Mkondeni, Pietermaritzburg.

3.2.2 Chemical composition

All feed ingredients were analysed, in duplicate, in the Animal and Poultry Science Laboratory at the University of KwaZulu-Natal, Pietermaritzburg. Dry matter (DM) content was determined by oven-drying the samples at 65^{o}C for 48 hours. Crude protein content was calculated as N x 6.25, where N content of the DM were determined using the Dumas Combustion method in a Leco Truspec Nitrogen Analyser, St Joseph MI, USA, according to 990.03 of AOAC (1990). The ash content was determined after incineration of the sample at 550°C for 4 h according to method 990.05 (AOAC, 1990). The dried samples were subjected to bomb calorimetry to determine gross energy (GE). Ether extract (EE) was determined using Soxhlet apparatus according to method 920.39 of AOAC (1990). Crude fibre (CF), neutral detergent fibre (NDF) and acid detergent fibre (ADF) contents were determined using ANKOM Fibre Analyser (Ankom, Macedon, NY, USA), according to Van Soest (1991). The NDF content was determined without a heat stable amylase.

3.2.3 Determination of water holding capacity

Water holding capacities of feed ingredients and the commercial feed were determined according to Whittemore *et al*. (2003). Briefly, 0.5 g of each feed ingredient was placed into a 50 ml centrifuge tube and 25 ml distilled water was also added. The tubes were securely sealed and shaken intermittently for 24 hours. The tubes were then centrifuged at 6000 ×g for 15 min at 20^{o}C. The supernatant was discarded and fresh weight of the sample was determined. After freeze-drying, the weights of the fluid retained were calculated from the difference between fresh sample and dried sample. The weight of the fluid retained was divided by the weight of the dried sample to determine WHC, which was expressed in g water/ g of dry material.

3.2.4 Determination of bulk density

The densities of the feedstuffs, defined as the degree of consistency measured by the quantity of mass per unit volume were measured according to the modifications of the water displacement method, as described by Kyriazakis and Emmans (1995). The method is based on the *Archimedes Principle* of determining the volume of a known mass of feed ingredient. Briefly, 50g of feed were weighed and placed into a 250 ml volumetric flask. First 100 ml distilled water was gently added into the flask and the contents were allowed to equilibrate for 15 min. The flask was gently tapped for 10 to 12 times to pack it and additional 50 ml distilled water was added. After allowing 15 min to equilibrate, a measured amount of water was added using a burette to bring to volume. The flask was shaken frequently to minimise the displacement of water by air. The total amount of water contained in the flask was subtracted from 250 ml. To calculate the density, unit mass of the feed ingredient was expressed per unit volume of water displaced (g/ml).

3.2.5 In vitro organic matter disappearance and gas production

Five growing pigs, selected from Ukulinga Research Farm, University of KwaZulu-Natal, Pietermaritzburg, were used as the faecal donors. The pigs were clinically healthy and were not fed on antibiotics for at least three months prior to sampling. Faecal collection and inoculum preparations were performed according to modifications of the method proposed by Wang *et al.* (2004). All procedures were done under anaerobic conditions through a constant flow of carbon dioxide (CO_2). Immediately after defaecation, faecal samples were collected. The pigs were fed on a conventional grower feed with 50g CF/kg DM, approximately 13.7 MJ digestible energy and 160 g CP/kg DM obtained from Meadow Feeds Ltd, Pietermaritzburg, South Africa.

The faecal samples were immediately sealed and placed into pre-warmed (39^{o}C) plastic bags that were filled with CO_2 and a sterile anaerobic salt medium to give final slurry of 100 g of faeces/L. The plastic bags containing faecal slurries were immersed under water at 37^{o}C and transported to the laboratory. After mixing in a blender for 60 s, the faecal slurries were filtered through a double layer of sterile cheesecloth to extract faecal inoculum into a pre-warmed (39^{o}C) vacuum flask flushed with CO_2. Inoculum preparation commenced within 1 hour of faecal collection.

To each Duran bottle containing 1 g DM of each of the fibrous feed ingredients, 100 ml of the resulting inoculum mixture were added. The Duran bottled were flushed with CO_2, and immediately closed. Three Duran bottles containing 100 ml of the faecal inoculum were used as blanks (controls). The bottles were placed into pre-warmed (39^{o}C) incubators. Pressure sensors were fitted and settlement time of approximately 30 min was allowed to pass before starting pressure logging at 20 min interval for a 24 h incubation period at a constant temperature of 39^{o}C. The 24 h incubation period was adopted in the current study because most of the fermentation occurs during this period; thereafter they become constant due to end product inhibition that results in a declining microbial population and the death of bacteria (Wisker *et al.*, 1998; Coles *et al.*, 2005; Awati *et al.*, 2006). Magnetic stirring were done at 30 min intervals for all samples. The experimental scheme was as follows: 8 fibrous ingredients × 3 replicates + 3 blanks (containing the inoculums only) repeated over 4 runs (batches).

After incubation, the bottles were vented and quenched in ice water. Terminal pH was taken and samples were centrifuged at 18 000g, 4^{o}C for 10 min. The supernatant was carefully extracted in order to take out the fluid and leave organic matter. The remaining organic matter residues were dried in a fanned oven at 60^{o}C for 48 h until a constant weight of undigested dry matter was attained. The *in vitro* organic matter degradability (IVOMD) for each fibre source was calculated from the modification of the equation by Boisen and Fernandez (1997) and Jha *et al.* (2011) after the undigested residue was corrected for dry matter in the blank and moisture content, as follows:

$$IVOMD = \frac{\text{weight of sample before incubation} - \text{weight of residue}}{\text{weight of the sample before incubation}}$$

The gas pressures (kPa) recorded using a computerised pressure analyser in each Duran bottle were converted into gas volume (ml) using the ideal gas law, assuming an atmospheric pressure of 101.325 kPa and a temperature of 312.15 K . The total gas produced (G_f) were determined by the difference between volume readings at 0 and 24 h, respectively and expressed in mlg^{-1} OM.

Coles *et al*. (2005) proposed that *in vitro* gas production at various end points, such as 6, 12 and 24 h of incubation can be used to estimate DM disappearance during fermentation. Three stages were identified from the gas production kinetics namely; stage 1 (0 to 8 h period), stage 2 (8 to 16 h period) and stage 3 (16 to 24 h period). The total volume of gas produced during each phase was divided by 8 h and expressed as mlh^{-1}g^{-1} OM incubated to give rate of gas production per incubation period. The rates of gas production during stages 1, 2 and 3 were defined as G_8, G_{16} and G_{24}, respectively. To determine the overall rate of gas production (G_{ov}), G_f was divided by 24 h and expressed in mlh^{-1}g^{-1} OM. The partitioning factor (PF), a measure of efficiency of the fermentation process, was calculated as the total gas production (G_f) per g OM degraded and expressed in mlg^{-1} OM.

3.2.6 Statistical analyses

Chemical composition and fermentation data were analysed using the general linear model (GLM) procedure of SAS (2008) to determine differences in the chemical composition, physical properties and fermentation parameters of feed ingredients, respectively. Separation of least square means was done using the probability of difference (PDIFF) procedure (SAS, 2008). Pearson's correlation coefficients among physicochemical properties and fermentation parameters of feedstuffs were estimated using the PROC CORR (SAS, 2008). Pearson's correlation coefficients were also used to determine relationships between calculated and analysed bulk density and WHC of the commercial feed.

3.3 Results

3.3.1 Chemical composition and bulk characteristics of non-fibrous feedstuffs

The chemical components bulk characteristics of non-fibrous feed ingredients that are commonly used in formulating pig diets are shown in Table 3.1. The bulky density of soybean oil cake was the highest (P < 0.05). All the non-fibrous feed ingredients differed significantly in their WHC. However, soybean had the greatest (P < 0.001) WHC.

3.3.2 Physicochemical properties and fermentation parameters of fibrous feedstuffs

The chemical compositions and bulk characteristics of the fibrous feedstuffs are shown in Table 3.2. Groundnut haulms had the greatest GE values (P < 0.001). Rice bran and lucerne hay had the highest (P < 0.001) CP content. However, CP contents for maize stover and maize cob, as well as for sunflower husks and veld grass were similar (P > 0.05). Saw dust had the greatest NDF and ADF, whilst rice bran has the lowest values (P < 0.05). Lucerne and saw dust had the highest (P < 0.001) bulk densities. The WHC of maize stover was the highest (P < 0.05). No differences were observed in the WHC of groundnut haulms and sunflower husks (P > 0.05). Table 3.3 shows the least square means for gas production parameters and IVOMD of fibrous feedstuffs after 24 h of incubation using faecal inoculum.

Table 3.1: Physicochemical properties of feedstuffs used in formulating pig feeds

	MAZ[1]	SBY	SBC	CSC	SOC	FML	WWT	MOL	STC	S.E.	*Sig.*
Components											
DM (g/kg)	881^{a}	885^{b}	904^{c}	886^{b}	880^{a}	915^{d}	860^{e}	762^{h}	862^{e}	0.57	***
GE (MJ/kg DM)	17.6^{a}	23.1^{b}	19.0^{c}	20.1^{d}	15.2^{g}	21.6^{e}	16.9^{f}	17.5^{f}	16.5^{f}	0.03	***
CP(g/kg DM)	79.2^{a}	379^{b}	466^{c}	358^{d}	360^{d}	634^{e}	176^{f}	50.8^{f}	15.8^{f}	2.56	*
EE(g/kg DM)	30.1^{a}	205^{b}	21.2^{c}	88.7^{d}	33.3^{a}	135^{d}	115^{d}	1.1^{ef}	1.1^{ef}	0.21	***
Ash (g/kg DM)	10.8^{a}	49.0^{b}	71.6^{c}	76.6^{d}	73.2^{c}	147^{e}	42.7^{b}	2.7^{f}	2.7^{f}	0.38	**
Bulk characteristics											
CF (g/kg DM)	35.8^{a}	24.0^{b}	56.4^{c}	124^{d}	104^{d}	1.3*	32.8^{a}	0.0^{e}	2.8^{e}	0.59	*
NDF (g/kg DM)	69.9^{a}	216^{b}	139^{c}	368^{d}	402^{d}	3.1^{e}	400^{d}	0.0^{f}	0.0^{f}	0.73	*
ADF (g/kg DM)	27.4^{a}	159^{b}	96.8^{c}	210^{d}	286^{h}	4.4^{e}	120^{b}	0.0*	0.0*	1.48	*
Density (g DM/ml)	0.9^{ag}	0.7^{a}	5.5^{b}	1.3^{c}	5.9^{b}	1.4^{cf}	4.6^{g}	1.4^{d}	1.6^{d}	0.04	***
WHC (g water/g DM)	2.2^{a}	9.4^{b}	5.5^{c}	5.9^{d}	6.5^{h}	3.0^{e}	2.6^{a}	-	1.6^{f}	0.11	***

^{abcdefg} Values with different superscripts within a row are significantly different (P > 0.05). S.E. = ± standard error; *Sig.*= significance level; * = P < 0.05; ** = P < 0.01; *** = P < 0.001.

[1]MAZ = Yellow maize; SYB = soybean; SBC = soybean oil cake; CSC = cotton seed cake; SOC = sunflower oil cake; FML = fishmeal; WWT = Whole Wheat; MOL = Molasses syrup; STC = starch.

DM = dry matter; GE = gross energy; CP = crude protein; EE = ether extract; CF = crude fibre; NDF = neutral detergent fibre; ADF = acid detergent fibre; WHC = water holding capacity.

Table 3.2: Chemical composition (g/kg DM feed) and bulk characteristics of the fibrous feedstuffs

	GH[1]	LC	MC	MS	RB	SD	SH	VG	S.E.	*Sig.*
Components										
Dry matter (DM) (g/kg)	882^{a}	811^{b}	948^{c}	947^{c}	810^{b}	956^{d}	941^{e}	940^{e}	1.22	*
Gross energy (MJ/kg DM)	22.9^{a}	17.7^{b}	17.8^{c}	16.8^{d}	19.9^{e}	19.1^{f}	19.7^{g}	17.4^{h}	0.02	***
Crude protein (g/kg DM)	117^{a}	189^{b}	52.2^{c}	53.4^{c}	190^{d}	44.1^{e}	59.5^{f}	60.2^{f}	1.22	***
Ether extract (g/kg DM)	21.3^{a}	12.2^{b}	7.5^{c}	5.1^{d}	19.9^{e}	16.9^{f}	63.9^{g}	15.9^{h}	0.20	***
Ash (g/kg DM)	27.9^{a}	86.6^{b}	40.8^{c}	61.5^{d}	72.5^{e}	6.2^{f}	33.1^{g}	70.8^{h}	0.36	***
Bulk characteristics										
Crude fibre (g/kg DM)	236^{a}	287^{b}	168^{c}	320.0^{d}	156.1^{e}	679^{f}	408^{g}	213^{h}	0.57	***
NDF (g/kg DM)	775^{a}	398^{b}	873^{c}	724^{d}	378^{e}	897^{f}	558^{g}	749^{h}	2.95	**
ADF (g/kg DM)	654^{a}	386^{b}	501^{c}	482^{d}	184^{e}	700^{f}	279^{g}	348^{h}	1.67	***
Bulk density (g DM/ml)	0.9^{a}	1.4^{b}	1.2^{c}	1.0^{a}	1.3^{d}	1.4^{b}	0.7^{e}	1.3^{d}	0.2	***
WHC (g water/g DM)	6.8^{a}	12.1^{b}	7.8^{c}	18.3^{d}	5.9^{a}	6.6^{a}	6.8^{a}	14.0^{e}	0.28	***

^{abcdefg}Values with different superscripts within a row are different ($P > 0.05$); S.E. = ± standard error; *Sig.* = Significance level.*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

[1]GH = groundnut haulms; LC = lucerne hay; MC = maize cob; MS = maize stover; RB = rice bran; SD = saw dust; SH = sunflower husks; VG = veld grass.

NDF = neutral detergent fibre; ADF = acid detergent fibre; WHC = water holding capacity.

Table 3.3: ***In vitro*** **fermentation parameters of different fibrous feed ingredients following 24 hours of incubation using faecal inoculum**

Fermentation parameter	[1]GH	LC	MC	MS	RB	SD	SH	VG	S.E.	*Sig.*
G_8 (ml hr-1 g-1 OM)	72.9[a]	54.4[b]	168[c]	50.4[b]	43.6[b]	88.0[ef]	97.6[e]	78.3[af]	3.96	***
G_{16} (ml hr-1 g-1 OM)	144[ae]	128[a]	63.8[b]	193.8[c]	401[d]	57.9[b]	179[ce]	126[a]	5.96	***
G_{24} (ml hr-1 g-1 OM)	216[a]	302[b]	228[a]	184[c]	170[c]	64.3[d]	106[e]	62.2[d]	7.88	***
$G_{Ov.}$ (ml hr-1 g-1 OM)	18.0[a]	20.2[b]	19.2[b]	17.8[a]	25.6[c]	8.76[d]	15.9[e]	11.1[f]	0.51	***
G_f (ml g^{-1} OM)	432[a]	485[b]	461[b]	428[a]	614[c]	210[d]	382[e]	266[f]	12.2	***
IVOMD	0.36[a]	0.29[b]	0.39[c]	0.17[d]	0.50[e]	0.07[f]	0.23[g]	0.21[h]	0.003	***
PF (mg ml^{-1})	0.83[a]	0.59[b]	0.84[a]	0.40[c]	0.81[a]	0.35[c]	0.60[b]	0.78[a]	0.024	***

[abcdefg]Means with one or more similar superscripts within a row are significantly different ($P > 0.05$); S.E. = ± standard error; Sig. = significance level; * = $P < 0.05$; ** = $P < 0.01$; *** = $P < 0.001$.

GH = groundnut haulms; LC = lucerne hay; MC = maize cob; MS = maize stover; RB = rice bran; SD = saw dust; SH = sunflower husks; VG = veld grass.

G_8 = Rate of gas production from 0 to 8 h; G_{16} = Rate of gas production from 8 to 16 h; G_{24} = Rate of gas production from 16 to 24 h; $G_{Ov.}$ = Overall rate of gas production during the 24 h incubation period; G_f = Total gas produced during the 24 h fermentation process; IVOMD = *In vitro* organic matter disappearance; PF = Partitioning factor.

For the first 8 hours of incubation, maize cob had the greatest ($P < 0.001$) rate of gas production. The fastest rate of gas production ($P < 0.001$) during the 16 to 24 hour period occurred for lucerne and maize cob. The overall rate of gas production was fasted ($P < 0.05$) in rice bran and lucerne hay. Rice bran had the greatest ($P < 0.001$) volume of gas produced while saw dust had the lowest values. The IVOMD after 24 h of incubation were highest ($P < 0.001$) for rice bran and maize cob. Table 3.4 shows correlation coefficients among physicochemical properties of fibrous feedstuffs. The EE was negatively correlated to WHC (P < 0.05) and density (P < 0.01) of the fibrous feedstuffs. The bulk density was negatively correlated (P < 0.05) to ADF and NDF. The ash content was negatively correlated with CF, NDF and NDF (P < 0.01), GE (P < 0.05), but positively correlated (P < 0.05) with WHC.

Table 3.5 shows the SCFA concentrations after incubation of fibrous ingredients for 24 h using in vitro fermentation system. Acetate production was greatest for rice bran and maize cob. The n-butyrate production was observed in groundnut haulms and rice bran (P < 0.001). Total SCFA from rice bran and maize cob were the greatest.

The IVOMD positively correlated ($P < 0.05$) with G_{16} (r = 0.59) and G_{24} (r = 0.52). The PF was positively correlated (r = 0.45; $P < 0.05$) with G_f. Table 3.6 gives correlation coefficients between *in vitro* fermentation end product profiles and physicochemical properties of fibrous ingredients following 24 h incubation using pig faecal inoculum. Rate of gas production during the first 8 hours was positively correlated ($P < 0.05$) with DM and WHC, but negatively correlated ($P < 0.05$) to CP. There were negative correlations between CF content and G_{24} ($P < 0.05$), G_f ($P < 0.01$), IVOMD ($P < 0.001$) and PF ($P < 0.001$) of the fibrous feedstuffs.

Table 3.4: Correlation coefficients among physicochemical properties of fibrous sources

	CP[1]	EE	Ash	CF	NDF	ADF	GE	WHC	Density
DM	-0.96***	0.10^{NS}	-0.60*	-0.13^{NS}	0.82***	0.23^{NS}	-0.27^{NS}	0.19^{NS}	-0.35^{NS}
CP	-	-0.12^{NS}	0.58*	-0.38^{NS}	-0.82***	0.31^{NS}	0.24^{NS}	-0.10^{NS}	0.32^{NS}
EE		-	-0.30^{NS}	0.23^{NS}	0.27^{NS}	0.35^{NS}	0.41^{NS}	-0.45*	-0.66**
Ash			-	-0.65**	-0.69**	-0.68**	-0.46*	0.53*	0.32^{NS}
CF				-	0.33*	0.49*	0.02^{NS}	-0.14^{NS}	0.03^{NS}
NDF					-	0.78***	-0.04^{NS}	0.03^{NS}	-0.46*
ADF						-	0.22^{NS}	0.05^{NS}	-0.28*
GE							-	-0.68^{NS}	-0.35^{NS}
WHC								-	0.06^{NS}

Significance level: NS = $P>0.05$; * = $P<0.05$; ** = $P<0.01$; ***= $P<0.001$.

[1]DM = dry matter (g/kg); CP=crude protein (g/kg DM); EE=ether extract (g/kg DM); Ash (g/kg DM); CF=crude fibre (g/kg DM); NDF = neutral detergent fibre (g/kg DM); ADF=acid detergent fibre (g/kg DM); GE= Gross energy (MJ/kg DM); water holding capacity= WHC (g water/g DM); Density = Bulk density (g DM/ml).

Table 3.5: Mean molar concentrations of short-chain fatty acids after incubation of fibrous ingredients for 24 h using *in vitro* fermentation system

Fibre source	Concentration of short chain fatty acids (µmol/ml)				
	Acetate	Iso-butyrate	n-butyrate	Iso-valerate	Total SCFA
GH	13.5^{a}	0.0^{a}	0.7^{a}	0.0^{a}	14.2^{a}
LC	11.9^{c}	0.9^{a}	0.0^{a}	0.0^{a}	12.8^{a}
MC	23.9^{d}	1.3^{e}	0.0^{a}	5.7^{b}	30.9^{b}
MS	11.4^{c}	0.3^{b}	0.0^{a}	0.8^{a}	12.5^{a}
RB	38.7^{e}	0.0^{a}	0.7^{b}	0.0^{a}	39.4^{c}
SD	0.0^{a}	0.0^{a}	0.0^{a}	0.5^{a}	0.5^{d}
SH	0.9^{a}	0.5^{c}	0.0^{a}	0.0^{a}	1.4^{d}
VG	5.5^{b}	0.0^{a}	0.0^{a}	0.0^{a}	5.5^{e}
S.E.	0.96	0.03	0.02	0.18	0.23

^{abcdefg} Values within columns with different superscripts significantly differ ($P > 0.05$); S.E.=standard error; GH=groundnut haulms; LC=lucerne hay; MC=maize cob; MS=maize stover; RB=rice bran; SD=saw dust; SH=Sunflower husks; VG=veld grass.

Table 3.6: Correlation coefficients among fermentation end product profiles of fibrous feed ingredients and physicochemical properties following 24 hours of incubation

	G_8	G_{16}	G_{24}	G_f	IVOMD	PF
DM	0.55*	-0.59**	-0.59*	-0.73***	-0.65**	0.13^{NS}
CP	-0.52*	0.19^{NS}	0.69**	0.63**	0.54*	-0.23^{NS}
EE	0.05^{NS}	0.16^{NS}	-0.36^{NS}	-0.09^{NS}	-0.05^{NS}	-0.01^{NS}
Ash	-0.15^{NS}	0.05^{NS}	0.13^{NS}	0.53*	0.37^{NS}	-0.26^{NS}
GE	-0.14^{NS}	0.22^{NS}	0.22^{NS}	0.14^{NS}	0.34^{NS}	-0.28^{NS}
CF	-0.03^{NS}	-0.04^{NS}	-0.46*	-0.68**	-0.80***	-0.84**
NDF	-0.58*	-0.71***	-0.37^{NS}	-0.67**	-0.47*	0.29*
ADF	0.26^{NS}	-0.70**	-0.01^{NS}	-0.52*	-0.46^{NS}	0.45^{NS}
WHC	0.32*	-0.10^{NS}	0.10^{NS}	0.12^{NS}	0.29*	0.28^{NS}
Density	-0.16^{NS}	-0.06^{NS}	0.07^{NS}	-0.05^{NS}	0.01^{NS}	0.03^{NS}

Significance level: NS = $P > 0.05$; * = $P < 0.05$; ** = $P < 0.01$; ***= $P < 0.001$.

DM = dry matter (g/kg); CP=crude protein (g/kg DM); EE=ether extract (g/kg DM); Ash (g/ kg DM); GE= gross energy (MJ/kg DM); CF=crude fibre (g/kg DM); NDF = neutral detergent fibre (g/kg DM); ADF=acid detergent fibre (g/kg DM); water holding capacity= WHC (g water/g DM); bulk density (g DM/ml). G_8 = rate of gas production from 0 to 8 h; G_{16} = rate of gas production from 8 to 16 h; G_{24} = rate of gas production from 16 to 24 h; G_f = total gas produced during the 24 h fermentation process; IVOMD = *in vitro* organic matter disappearance; PF = partitioning factor.

3.4 Discussion

Characterisation of physicochemical properties, such as the fibre content, bulk density and WHC of feed ingredients is vital in designing intervention formulation strategies to ensure that feed bulk does not constrain intake of sufficient nutrient required for growth. The high WHC values observed for soybean, soybean oil cake and cotton seed cake could be explained by the vast pool of charged groups within their matrices which increases their hydrophilic nature thereby increasing their ability to bind water. This hypothesis is supported by the considerably higher ash content of these feed ingredients compared to other feedstuffs with low water holding capacities. The observed high WHC capacities of soybean could further attest the decrease in feed intake in growing pigs. High protein diets increase the need for water intake to cater for excretion of surplus dietary mineral intake and catabolised nitrogenous compounds from protein, however, some water molecules will be held within the soybean fibre matrices thus limiting space (Pfeiffer *et al.*, 1995). The observed negative correlation coefficient between EE and WHC for non-fibrous ingredients agrees with Tsaras *et al.* (1998), who found that ingredients with low EE content are associated with high WHC. As EE content increase, molecules cover the matrix of the hydrophilic groups, thus reducing the ability of the fibre to hold water.

Low CP content of grass hay observed in in the current study suggests that the comprised of low protein species or they were harvested in their late stage. Inclusion of bulky ingredients with higher protein levels, such as lucerne hay and rice bran than grass hay may suppress the need for the pig to consume more for these ingredients may also contribute to the protein content of the diet. As expected, both sunflower husk and groundnut haulms had the highest fat contents. The CF, NDF and ADF contents were lower than those reported by Ginenne and Lebas (2002) for sunflower husk. These differences can be ascribed to the effects of different seasons, stage of harvesting or the processing mechanism used in oil extraction.

Both saw dust and lucerne had high density values, suggesting that the amount of DM deposited within their matrices were congruent chiefly because of their structural function in the physiology of the plant. Additionally, congruency in density may also be ascribed to the packing nature of their particles which was consistent. If they are included in pig diets, they are likely to improve the voluntary feed intake because particle consistency and density are principal factors which physically regulate consumption of fibre-based feeds in young pigs (Kyriazakis and Emmans, 1995; Anguita *et al*., 2007).

On the other hand, WHC was highest for maize stover and lowest in saw dust. The difference in WHC of the fibrous sources can be attributed to the fact that exposure of hydrophilic binding sites within the fibre matrix differ with fibre types principally because of the difference in the polysaccharide building block forming the structure of those feedstuffs (Elleuch *et al.*, 2011). Similarities in WHC noticed among fibrous sources such as groundnut haulms, sunflower husks and rice bran can be explained by the grinding which uniformly exposes those hydrophilic sites, thereby consolidating the water binding capacity of the fibres. The similarities can also be due to the congruency of the non-starch polysaccharide types of the fibrous ingredients, especially those of groundnut haulms and sunflower husks. Thus, studies to characterize the nature of the polysaccharide composition should be considered if a valid explanation of the effects these fibrous feedstuffs have on the bulkiness of feeds and consequently feed intake in growing pigs is to be achieved.

Extent of fermentation of locally available fibrous feed ingredients in pigs is poorly understood. Differences in rate of gas production, volume of gas production, IVOMD and SCFA concentration following *in vitro* fermentation of fibrous ingredients were due to differences in protein content, CF, NDF, WHC in combination with type of processing employed (Blummel *et al.*, 2003; Darshan *et al*., 2007; Serena and Bach-Knudsen, 2007). During the first 8 hours of incubation, the fastest rate of gas production observed in maize cob might be caused by presence of readily soluble materials that are quickly degraded (Kuan and Liong, 2008). Furthermore, moderate WHC of maize cob found in the current study agree with (Kuan and Liong, 2008). After 8 hours of incubation, rice bran had a rapid rate of gas production which could be due to high levels of soluble carbohydrates which are readily fermentable as well as low crude fibre, protein and fat content (Bindelle et al., 2008). Due to its high content of soluble fibre, rice bran may fail to exhibit its viscous characteristics during *in vitro* digestion. Incorporating rice bran in the diet could be beneficial in increasing faecal bulk and laxation (Orgue-Bon *et al*., 2011).

Overall rates of gas production and amount of total gas produced were greatest for those fibres with high protein content such as lucerne, rice bran, maize cob and sunflower husk. The probable reason for the high rates might be that proteins promote growth of the microbial population and its enzyme systems for they are sources of nutrients for micro-organisms (Carrol *et al.*, 1991). It is logical that rates of gas production have a relative high precision to predict feed intake. Similar values for total gas produced and rate of gas production among maize derivatives could be ascribed to the fact that these sources had the same proportions of soluble material such as polysaccharides and their availability is congruent. The similarities in PF values among some of the fibrous ingredients suggest a clear limitation in the use of PF as a formulation criterion during prediction of VFI in pigs (Jackson *et al.*, 2010).

The negative correlation between density and NDF agrees with Giger-Reverdin (2000) and Chaji (2008). Giger-Reverdin (2000) postulated that feedstuffs with low densities and high level of NDF enhance gut fill and results in a decrease in dry matter intake. The negative correlation between WHC and EE content could be attributed to the presence of the non-bound fats within the matrix of fibres which form sheaths which covers the water-binding sites. The negative relationship between ash and fibre components suggests that the mechanism involved in the accumulation of fibre within the polysaccharide matrix is supported by the depletion of the mineral pool as they are used during biochemical processes. The positive correlation between WHC and ash agrees with Behgah *et al*. (2009).

The observation that G_8 correlated positively with WHC strengthen the hypothesis that during the first 8 h of incubation, soluble carbohydrates are rapidly hydrated and readily available for microbial degradation as they have a great ability to hold water. Thus, intakes of fibrous diets based on fibres with high WHC are likely to be lower than those with little tendencies to hold water. High water retention leads to more intense fermentation of fibre (Auffret *et al.,* 1993; Anguita *et al.,* 2007). Fibre sources with the highest WHC such as maize stover and grass hay were not the most fermentable. It could, therefore, be assumed that there could be other properties of the fibre which enhances fermentation. Interestingly, negative strong correlations between rates of gas production, G_f and IVOMD with the fibre-related properties such as NDF and ADF, support the fact that cellulose and lignin are less fermentable by the intestinal microbiota thus, increase the bulkiness of the diets thereby limiting intake of adequate nutrients to meet requirements for growth (Jha *et al*., 2011).

3.4 Conclusions

The chemical composition, physical properties and fermentation parameters of feed ingredients varied widely. Lucerne and rice bran had the highest CP content. Rice bran and saw dust had the lowest WHC of 5.9 and 6.6 g water/g DM, respectively, whilst maize stover and grass hay had the highest WHC of 18.3 and 14.0 g water/g DM, respectively. Sunflower husk had the lowest bulk densities of 0.7 g DM/ ml, whilst both lucerne hay and saw dust had the greatest bulk densities of 1.4 g DM/ ml. Based on the physicochemical properties obtained, there is need to select widely varying fibre sources that can be used to assess their effects on feed intake.

3.5 References

Aarnink, A.J.A. and Verstegen, M.W.A. (2007). Nutrition, key factor to reduce environmental load from pig production. *Livestock Science*, 109: 194-203.

Anguita, M., Gasa, J., Nofrarias, M., Martín-Orúe, S.M. and Perez, J.F. (2007). Effect of coarse ground corn, sugar beet pulp and wheat bran on the voluntary intake and physicochemical characteristics of digesta of growing pigs. *Livestock Science*, 107: 182-191.

AOAC, (1990). Official methods of analysis. 16th Edition. Association of Analytical Chemists, Washington DC, USA.

Auffret, A., Barry, J.L. and Thibault, J.F. (1993). Effect of chemical treatments of sugar-beet fibre on their physicochemical properties and on their in vitro fermentation. *Journal of the Science of Food and Agriculture*, 61, 195-203.

Awati, A., Williams, B.A., Bosch, M.W., Gerrits, W.J.J. and Verstegen, M.W.A. (2006). Effect of inclusion of fermentable carbohydrates in the diet on fermentation end-product profile in faeces of weanling piglets. *Journal of Animal Science*. 84, 2133-2140.

Behgah, M., Valizadeh, R., Mirzaee, M., Naserian, A.A. and Nasiri, M.R. (2008). Correlation between the physical and chemical properties of some forages and non-forage fibre sources. *Journal of Animal and Veterinary Advances*, 8: 2280-2285.

Bindelle, J., Leterme, P. and Buldgen, A. (2008). Nutritional and environmental consequences of dietary fibre in pig nutrition: a review. *Biotechnology Agronomy Society and Environment*, 12: 69-80.

Blummel, M., Karsli, A. and Russell, J.R. (2003). Influence of diet on growth yields of rumen micro-organisms in vitro and in vivo: influence on growth yield of variable carbon fluxes to fermentation products. *British Journal of Nutrition*, 90: 1–11.

Boisen, S. and Fernandez, J.A. (1997). Prediction of the total digestibility of energy in feedstuffs and pig diets by in vitro analyses. *Animal Feed Science and Technology*, 68: 277-286.

Borchani, C., Besbes S., Masmoudi, M., Blecker, C., Paquot, M. and Attia, H. (2011). Effect of drying methods on physicochemical and antioxidant properties of diet fibre concentrates. *Food Chemistry*, 125: 1194-1201.

Carrol, M.D., Lopez, S., Gonzales, J.S. and Ovejero, F.J. (1991). The use of the rumen degradation characteristics of hay as predictors of its voluntary intake by sheep. *Journal of Animal Production*, 52: 133-139.

Chaji, M. (2008). Determination of nutrition value of steam treated sugarcane pith by chemical, fermentative and productive characteristics for sheep and goat. PhD Thesis, Ferdowsi University of Mashhad, Mashhad, Iran.

Coles, L.T., Moughan, P.J. and Darragh, A.J. (2005). In vitro digestion and fermentation methods, including gas production techniques, as applied to nutritive evaluation of foods in the hindgut of humans and other simple-stomached animals. *Animal Feed Science and Technology*, 123: 421-444.

Darshan, K.A., Krishnamoorthy, U., Kiran, D., Bhaskaran, R. and Manjunath, V. (2007). Effect of supplementing finger millet straw with two concentrates differing in their partitioning factor on dry matter intake, organic matter digestibility and nitrogen metabolism in Karan Friesian crossbred heifers. *Animal Feed Science and Technology*, 137: 35-45.

Elleuch, M., Bedigian, D., Roiseux, O., Besbes, S., Blecker, C. and Attia, H. (2011). Dietary fibre and fibre-rich by-products of food processing: Characterisation, technological functionality and commercial applications: A review. *Food Chemistry* 124: 411-421.

Giger-Reverdin, S., (2000). Characterization of feedstuff for ruminant using some physical parameter. *Animal Feed Science and Technology*, 86: 53-69.

Ginenne, T. and Lebas, F. (2002). Role of dietary fibre in rabbit nutrition and digestive troubles prevention. *Proceedings of 2nd Rabbit Congress of the Americas*, Habana City, Cuba: 19-22.

Jackson, W., Krishnamoorthy, U., Robinson, P.H. and Fadel, J.G., (2010). Effects of changing partitioning factor (PF) and in vitro gas production (k) of diets on intake and digestibility, microbial N production, as well as milk production and composition, of lactating crossbred dairy cows. *Animal Feed Science and Technology*, 160: 128-136.

Jha, R., Bindelle, J., Rossnagel, B., Van Kessel, A. and Leterne, P. (2011). In vitro evaluation of the fermentation fractions of hulless barley and other cereals in the gastrointestinal tract of pigs. *Animal Feed Science and Technology*, 163: 185-193.

Jorgensen, H., Theil, P.K. and Knodsen, K.E.B. (2010). Satiating properties of diets rich in dietary fibre fed to sows as evaluated by physicochemical properties, gastric emptying rate and physical activity. *Livestock Science*, 134: 37-40.

Kuan, Y. H. and Liong, M. T. (2008). Chemical and physicochemical characterization of agrowaste fibrous materials and residues. *Journal of Agricultural and Food Chemistry*, 56, 9252-9257.

Kyriazakis, I. and Emmans, G.C. (1995). The voluntary feed intake of pigs given feeds based on wheat bran, dried citrus pulp and grass meal, in relations to measurements of bulk. *British Journal of Nutrition*, 73: 191-207.

Ogue-Bon, E., Khoo, C., Hoyles, L., McCartney, A.L., Gibson, G.R. and Rastall, R.A. (2011). In vitro fermentation of rice bran combined with *Lactobacillus acidophilus* 14 150B or *Bifidobacterium longum* 05 by the canine faecal microbiota. *Microbiology Ecology,* 75: 365-376.

Orskov, E.R. (1994). Plant factors limiting roughage intake ruminants. In: Thacker, P.A., Editor, Livestock production in 21st Century: Priorities and Research needs. University of Saskatchewan, Saskatoon, Saskatchewan.

Pfeiffer, A., Henkel, H., Verstegen, M.W.A. and Philipczyk, I. (1995). The influence of protein intake on water balance, flow rate and apparent digestibility of nutrients at the distal ileum in growing pigs. *Livestock Production Science*, 44: 179-187.

SAS, (2008). SAS User's Guide: Statistics, Version 9.1. SAS Institute, Cary, NC, USA.

Serena, A., and Bach-Knudsen, K.E., (2007). Chemical and physicochemical characterisation of co-products from the vegetable food and agro-industries. *Animal Feed Science and Technology*, 139: 109-124.

Tsaras, L.N., Kyriazakis, I. and Emmans, G.C. (1998). The prediction of the voluntary food intake of pigs on poor quality foods. *Animal Science*, 66: 713-723.

Van Soest, P.J., Robertson, J.B. and Lewis, B.A. (1991). Methods of dietary fibre, neutral detergent fibre, and non-starch polysaccharides in relation to animal nutrition. *Journal of Dairy Science,* 74: 3583–3597.

Wang, J.F., Zhu, Y.H.Z., Wang, D., Li, F. and Jensen, B.B (2004). In vitro fermentation of various fibre and starch sources by pig fecal inocula. *Journal of Animal Science*, 82: 2615-2622.

Whittemore, E.C., Emmans, G.C. and Kyriazakis, I. (2003). The relationship between live weight and the intake of bulky foods in pigs. *Animal Science*, 76: 89-100.

Wisker, E., Daniel, M., Rave, G. and Feldheim, W. (1998). Fermentation of non-starch polysaccharides in mixed diets and single fibre sources: comparative studies in human subjects and in vitro. *British Journal of Nutrition*, 80: 253-261.

Chapter 4: Prediction of gut capacity in weaner pigs with the use of the physicochemical properties of fibrous feeds

Abstract

Prediction of voluntary feed intake of growing pigs facilitates the accurate formulation of feeds. The objective of the current study was to predict the gut capacity in weaner pigs using physicochemical properties of feeds. A basal feed with 13.7 MJ digestible energy and 180 g crude protein per kg dry matter was diluted to six inclusion levels (0, 80, 160, 240, 320 and 400 g/kg) with the use of lucerne hay, maize cob, maize stover, saw dust, sunflower husks or grass hay. Each of the resultant 31 diets was offered *ad libitum* to four pigs, in individual cages, for four weeks. A total of 124 pigs weighing 18.1 (s.d. 1.37) kg body weight were used. Properties of bulkiness measured were water holding capacity (WHC; g water/ g DM), bulk density (g DM/ml), crude fibre (CF), neutral detergent fibre (NDF) and acid detergent fibre (ADF). WHC, bulk density, NDF and ADF influenced (R^2 = 0.65; P < 0.01) scaled average daily feed intake (SFI). The quadratic relationship between SFI and WHC was SFI = 19.1 (± 3.49) + 10.0 (± 1.61) WHC – 1.1 (± 0.17) WHC^2 (P < 0.01). SFI was also related (P < 0.01) to NDF and ADF by quadratic functions SFI = 24.3 (± 3.55) + 0.1 (± 0.23) NDF - 0.0001 (± 0.000036) NDF^2 and SFI = 30.2 (± 1.95) + 0.1 (±0.02) ADF – 0.0003 (±0.000061) ADF^2, respectively. By use of the broken stick model, the gut capacity was attained when WHC = 4.5 ± 1.25 g water/g DM, NDF = 367 ± 29 g/kg DM and ADF = 138 ± 77 g/kg DM, respectively. In conclusion, WHC, NDF and ADF contents are responsible for constraining intake of bulky feeds in weaner pigs.

Key words: dietary fibre, intake, gut capacity, weaner pigs, water holding capacity

4.1 Introduction

An understanding of feed intake in growing pigs is crucial for the prediction of productivity, sustainability and profitability of pig enterprises (Whittemore *et al.*, 2003a; Bindelle *et al.*, 2008). Prediction of the gut capacities of growing pigs facilitates the nutritionally and economically accurate formulation of feeds. Bulky feeds are expected to reduce the nutrient density of the feed, prompting the pig to consume more feed to meet its nutrient requirement for potential growth (Kyriazakis and Emmans, 1995; Tsaras *et al.*, 1998). At some point, intake will reach a maximum, become constant or may begin to decrease because of physiological limitation of the gut capacity as one or more of the physicochemical measurements of feed bulk increase. Knowledge of the gut capacity enables feed compounders to ensure that ingestion of sufficient nutrients by growing pigs is achieved without excessive or restricting nutrients to optimize performance. Together with performance characteristics, measurements of gut capacity can also be used to estimate the economic value of an individual pig at any given stage of growth.

Several reports have suggested that WHC is the most accurate physicochemical measurement of feed bulk that predicts VFI (Tsaras *et al.*, 1998; Whittemore *et al.*, 2001; Whittemore *et al.*, 2003a). These reports were, however, based on a few fibrous sources with a narrow range of water holding capacities. The relationships generated are likely to be inaccurate, given the wide variation in physical properties of fibrous feedstuffs. For example, the WHC for sunflower husks and maize stover are 6.8 and 18.3 g water/g dry matter, respectively (Chapter 3). In addition, the impact of other variables such as density, ADF, NDF and CF, on VFI of 'bulky' feeds is poorly understood. It is, therefore, crucial to determine the relationship between physicochemical properties and VFI in young growing pigs. In Chapter 3, physicochemical properties and fermentation characteristics of potential fibrous feed ingredients were evaluated. To ensure that the range of physicochemical properties was widely spread, fibre sources which were hugely different in CP, NDF, ADF and CF contents, WHC and bulk density, were selected. Lucerne hay, maize cobs, maize stover, grass hay, sunflower husks and saw dust were, therefore, used in the current study.

The physicochemical properties that influence VFI as well as their impact on intake in weaner pigs are poorly understood, and warrant further investigation. Weaner pigs have a limited capacity to digest, ferment and utilize fibrous diets. Since the inclusion of bulky feeds is likely to constrain intake of nutrients, the gut capacity can be estimated using the physicochemical properties of the feed. The objective of the study was to determine physicochemical properties of a feed that best describe the bulkiness of the feed, such that the gut capacity of a weaner pig can be predicted using this measurement. It was hypothesized that as feed bulk increase, feed intake in weaner pigs increases linearly up to a point when it becomes constant or starts to decrease.

4.2 Materials and Methods

4.2.1 Description of study site

The study was conducted at Ukulinga Research Farm, University of KwaZulu-Natal, Pietermaritzburg, situated in a subtropical hinterland, located at 30° 24`S, 29° 24` E and is approximately 700 m above sea level. The climate is characterized by an annual rainfall of 735 mm, which falls mostly in summer between October and April. Mean annual maximum and minimum temperatures are 25.7°C and 8.9°C, respectively. Light to moderate frost occurs in winter.

4.2.2 Pigs and housing

Care and use of the pigs were performed according to the ethical needs by Certification of Authorization to Experiment on Living Animals provided by UKZN Animal Ethics Committee, Reference number 096/11/Animal. The pig house consisted of 62 individual cages mounted in a room that had a single heating, lighting and ventilation system. The individual cages were arranged in two rows such that they were 31 cages on each side. Each cage measured 1.5 × 1 m and contained a plastic self-feeder trough (Big Dutchman Lean Machine®) and a low-pressure nipple drinker providing water *ad libitum*. The weaner pigs were purchased from Kanhym farm, Dalton, KwaZulu-Natal Province, South Africa. The pigs were transported on a tarred road for 60 km in a truck moving at an average speed of 60 km/h and were loaded at a loading density of 0.12 m^2/pig.

A total of 124 male F1 hybrid pigs (Large White × Landrace, PIC group, South Africa) were moved at six weeks of age at 18.1 (s.d. 1.37) kg body weight, into individual pens in two batches. The pigs were ear tagged for identification purposes. Pigs were not given any antibiotics or growth promoters in their diets either before or during the trial. The ambient temperature and relative humidity were recorded automatically every 15 min throughout the trial using a HOBO TEMPERATURE, RH©, 1996 ONSET logger. The average temperature and humidity was 21.15 (s.d. 2.74)^{o}C and 42.64 (s.d. 1.56) %.

4.2.3 Feeds

A high quality commercial feed (Express Weaner, Meadow feeds Ltd, Pietermaritzburg, South Africa) with a low level of DF (50 g/kg DM of total dietary fibre, TDF) was used as the basal feed. Table 4.1 shows the composition of the basal feed used as the control. The basal feed contained 13.7 MJ DE and 180 g crude protein (CP)/kg DM. To have a wide range of physicochemical properties, six fibre sources, namely maize cob, maize stover, sunflower husks, grass hay, lucerne and sawdust were selected to dilute the basal diet. The aim was to select fibre sources with as wide a range of the physicochemical properties as possible.

From the six fibre sources selected, 30 complete 'bulky' diets were formulated by diluting the summit diet with five different inclusion levels for each fibre source. The contents of the fibre sources in the complete diets were 80, 160, 240, 320 and 400 g/kg, respectively. It was assumed that the pigs would increase their intake proportionately to the degree of dilution of the basal feed with the fibre source up to the point where gut capacity is reached. To ensure that feed intake increased, the feeds in the dilution series were not supplemented in any way.

Analysis of chemical composition and bulky characteristics of each of the 31 complete diets, shown in Tables 4.2 and 4.3 were conducted according to the methods described in Section 3.2. The analyses of diets were performed in the Discipline of Animal and Poultry Science Laboratory at the University of KwaZulu-Natal, Pietermaritzburg.

4.2.4 Experimental design and management of pigs

Each of the 31 diets was fed to four randomly selected pigs over two batches, i.e. two pigs per

Table 4.1: Major ingredient composition of the basal feed

Ingredient	(kg/ 100 kg DM)
Yellow maize	42.56
Soybean	17.56
Soybean oil cake	8.38
Whole wheat	10.00
Wheat bran	10.00
Sunflower oil cake	7.50
Cape fish	2.00
Additives	2.00

Table 4.2: Chemical composition of the basal diet (B), and diets based on lucerne hay (LC), maize cob (MC), maize stover (MS), saw dust (SD), sunflower husk (SH) and veld grass (VG) at varying inclusion levels

Fibre source	Level (g/kg)	Dry matter (DM)(g/kg)	Gross energy (MJ/kg DM)	Crude protein (g/kg DM)	Ether extract (g/kg DM)	Ash (g/kg DM)
B	0	989	18.1	196	52.9	61.1
LC	80	989	18.1	197	49.2	63.1
	160	990	18.1	188	45.2	65.1
	240	990	18.0	174	41.5	67.2
	320	989	17.9	169	39.2	69.2
	400	989	17.9	166	33.3	71.3
MC	80	989	18.0	186	51.2	59.0
	160	990	17.9	168	45.9	54.9
	240	990	17.9	153	45.2	53.2
	320	990	17.9	139	41.3	52.1
	400	991	17.8	116	39.9	46.7
MS	80	990	18.0	179	50.1	62.3
	160	990	17.9	170	44.9	64.2
	240	989	17.8	148	39.3	65.3
	320	989	17.7	143	37.1	66.4
	400	989	17.6	141	31.9	66.5
SD	80	989	17.4	117	51.5	53.7
	160	989	17.2	165	47.7	48.3
	240	989	17.1	146	45.6	44.1
	320	989	17.1	131	42.4	41.6
	400	989	17.0	118	36.7	39.2
SH	80	989	18.2	167	54.1	56.6
	160	989	18.3	146	55.4	53.8
	240	989	18.5	135	55.7	51.6
	320	989	18.7	132	56.6	48.5
	400	989	19.2	124	57.3	44.9
VG	80	989	18.0	186	51.7	60.4
	160	990	18.2	145	49.3	61.9
	240	990	17.9	136	40.7	63.9
	320	990	17.9	121	36.6	64.9
	400	990	17.8	113	32.4	65.9
Standard error		0.94	0.02	1.22	0.34	0.70

Table 4.3: Bulk characteristics (g/kg DM) of the basal diet (B), and diets based on lucerne hay (LC), maize cob (MC), maize stover (MS), saw dust (SD), sunflower husk (SH) and veld grass (VG) at varying inclusion levels

Fibre source	Level (g/kg)	Crude fibre (g/kg DM)	NDF (g/kg DM)	ADF (g/kg DM)	Density (g DM/ml)	WHC (g water/g DM)
B	0	26.1	192.3	88.4	1.45	3.76
L	80	46.1	218	101	1.54	3.65
	160	67.6	261	126	1.46	4.26
	240	87.9	302	151	1.39	5.04
	320	109	344	176	1.32	5.56
	400	130	386	200	1.27	6.52
MC	80	36.4	231	112	1.52	3.17
	160	47.9	294	147	1.47	3.57
	240	59.3	355	181	1.42	4.08
	320	70.8	401	218	1.25	4.41
	400	82.2	457	251	1.22	4.75
MS	80	48.6	192	111	1.49	4.15
	160	72.2	228	143	1.31	5.24
	240	95.8	280	175	1.30	6.48
	320	119	332	208	1.12	7.49
	400	143	383	240	1.10	8.31
SD	80	77.4	257	128	1.54	3.41
	160	130	318	178	1.49	3.95
	240	182	379	227	1.43	4.27
	320	234	440	277	1.40	4.79
	400	287	501	327	1.31	5.21
SH	80	55.6	223	94.5	1.49	3.16
	160	86.3	270	111	1.44	3.48
	240	117	317	126	1.33	3.76
	320	148	363	142	1.31	4.06
	400	178	410	158	1.21	4.38
VG	80	40.1	230	122	1.51	3.76
	160	55.1	284	167	1.50	4.28
	240	70.2	338	214	1.47	5.14
	320	85.2	391	259	1.31	6.45
	400	100	444	304	1.20	7.13
Standard error		0.17	2.11	0.89	0.03	0.09

NDF= neutral detergent fibre; ADF=acid detergent fibre; WHC=water holding capacity.

batch. Each treatment was blocked by randomising these on either side of a central passageway. Feed was provided *ad libitum*. An adaptation period of 10 days was allowed for each batch, then pigs were subjected to the treatment diets from 18.1 (s.d. 1.37) to 55.4 (s.d. 5.93) kg body weight for four weeks. Pigs were weighed every week throughout the trial and the difference between weight at the end and beginning of the week were divided by 7 to determine the ADG. Feed intake was determined by weighing the feed trough at the beginning and end of each week. A plastic tray was placed under each trough to collect feed spillages. The feed spilled was dried, weighed and discarded daily. Weights of feed refusals and spillages were subtracted from the total weight of the feed allocated to determine feed intake for that particular week.

The weight of the feed consumed each week was divided by 7 to determine the average daily feed intake (ADFI). To account for differences in mean pig weight between treatments, ADFI was scaled to live-weight. A scaled average daily feed intake (SFI) was calculated as g feed per kg body weight per day. The average weight gain (ADG) was also scaled to give a scaled average daily gain (SADG). Feed conversion efficiency (FCE) was determined by dividing the ADG by ADFI. After the pigs were moved out of the pig house, the research facility was washed, disinfected and rested for two weeks, and a second batch of 62 pigs was introduced.

4.2.5 Statistical analyses

The effects of age of the pigs (week), fibre source, fibre inclusion level, batch and their interactions on SFI were determined using the GLM procedure (SAS, 2008). Two-way interactions of the variables as well as the effect of the batch on SFI were not significant and were therefore eliminated from the statistical model. The model used was as follows:

$Y_{ijklm} = \mu + \alpha_i + \nu_j + \delta_k + \lambda_l + (\alpha \times \nu \times \delta)_{ijk} + \varepsilon_{ijklm}$,

where;

Y_{ijklm} is the scaled feed intake;

μ is the overall mean response common to all observations;

α_i is the effect of fibre source;

ν_j is the effect of the fibre inclusion level;

δ_k is the effect of the week of feeding;

λ_l is the effect of the batch;

$\alpha \times \nu \times \delta_{ijk}$ is the interaction of fibre source, fibre inclusion level and week of feeding; and

ε_{ijklm} is the residual error.

Stepwise regression in SAS (2008) was used to identify physicochemical properties which influenced ADFI, SFI, ADG, SADG, and FCE, respectively. The quadratic response surface model (PROC RSREG) procedure of SAS (2008) was used to determine the relationship between ADFI, SFI, ADG, SADG, and FCE and each of the physicochemical properties selected using stepwise regression. To estimate the threshold at which physicochemical property of a feed causes SFI to be constant or decrease with feed bulk, the simplest piecewise regression (broken stick) analysis was conducted using NLIN procedure (SAS, 2008). In this model, breakpoints were used to estimate the thresholds of physicochemical properties of the feed at which the amount of feed consumed will be constrained by the gut capacity of the pig. The model was established as follows:

$SFI_i = \gamma_o + \gamma_1 (x_i) + \gamma_2 (x_i > x_c) (x_i - x_c) + \varepsilon_i$, when $(x_i > x_c) = 1$

Using parameters (γ_o, γ_1, γ_2) and the x_c, the two segmented simple regression functions were;

$SFI_j = \gamma_o + \gamma_1 (x_i)$, for $x_i \leq x_c$; and

$SFI_k = SFI_o + (\gamma_1+\gamma_2) x_i$, for $x_i \geq x_c$

Where;

SFI_i is the scaled feed intake when VFI is maximum;

SFI_o is the scale feed intake when $x_i = 0$;

γ_o is the intercept or minimum SFI when $x_c < 0$;

γ_1 is the rate of change of SFI when $x_i < x_c$;

γ_2 is the rate of increase in SFI when $x_i > x_c$;

x_i is the value of the physicochemical property of the feed; and

x_c is the optimum physicochemical property value when gut capacity is attained.

4.3 Results

4.3.2 Effects of fibre source, and inclusion level and week on scaled feed intake

The SFI varied with fibre source ($P < 0.05$) and inclusion levels. Scaled feed intake was not significantly different between the two batches. The changes in SFI's of pigs given incremental levels of each of the bulky feeds during the 4 week period are illustrated in Figure 4.1. At 80 g/kg inclusion level, the SFI was similar across all fibre sources except for sawdust-based diet. The SFI decreased ($P < 0.001$) during successive week of feeding when pigs were given the

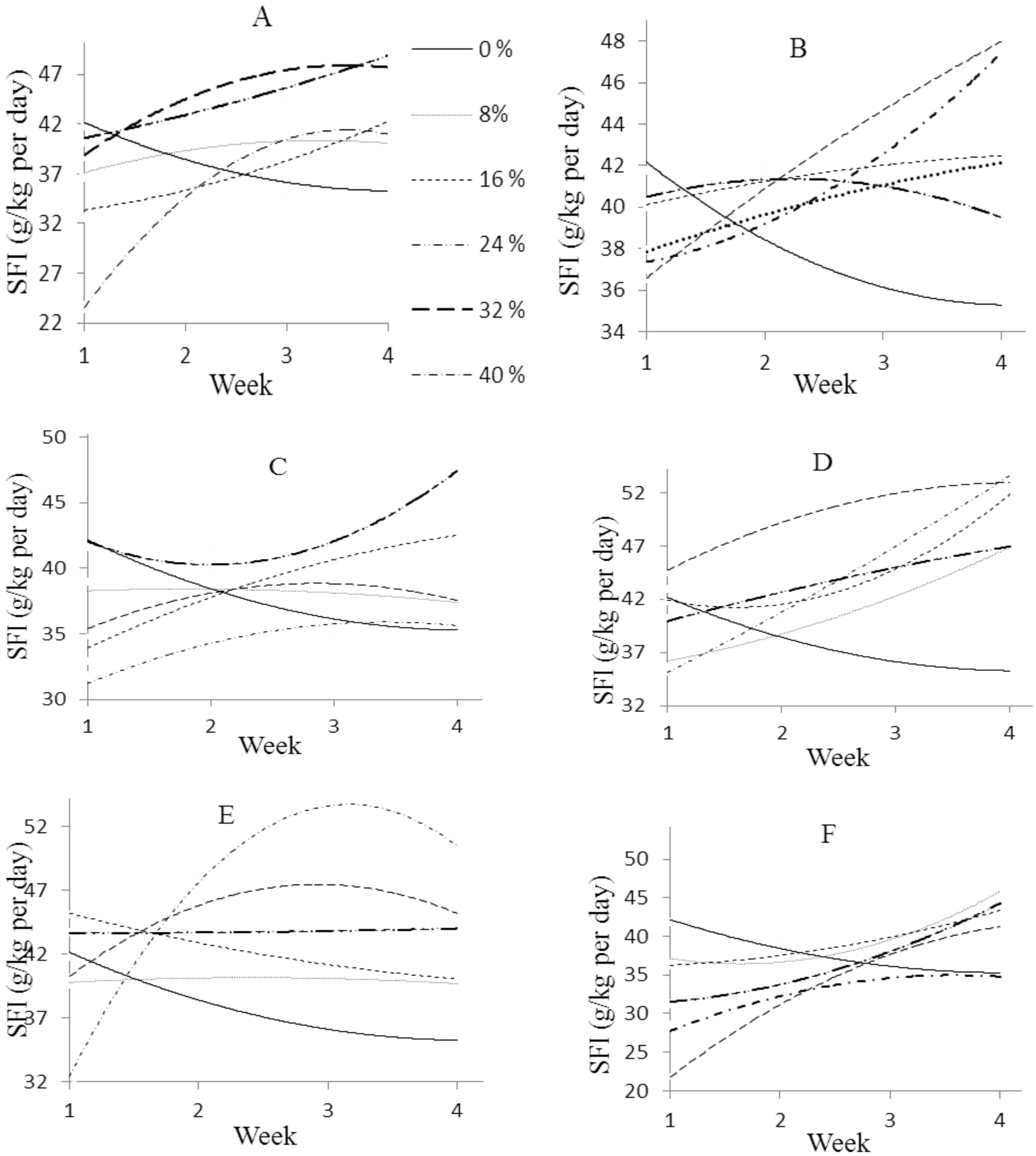

Figure 4.1: Weekly changes in scaled feed intake of pigs given bulk feeds based on lucerne hay (A), maize cob (B), maize stover (C), saw dust (D), sunflower husk (E) and veld grass (F)

basal diet and had lowest ($P < 0.001$) intake values of almost all 'bulky' diets except for a diet with 400 g/kg grass hay. As the level of fibre inclusion increased, the SFI increased ($P < 0.05$) during each week, but at 80 and 160 g/kg inclusion level, intake started decreasing ($P < 0.01$) such that by the end of the period, SFI was close to constant across all feeds. There was, however, a continuous increase ($P < 0.001$) in SFI for sawdust, veld grass, and 240 g/kg maize cob-based diet as well as for 320 and 400 g/kg maize stover inclusion levels.

4.3.3 Physicochemical properties of fibrous feeds affecting intake, weight gain and feed conversion efficiency

Using stepwise regression, the effects of physicochemical properties on ADFI, SFI, ADG and SADG were tested. The ADF ($R^2 = 0.35$; P < 0.05) content, NDF ($R^2 = 0.77$; $P < 0.001$) content, bulk density ($R^2 = 0.44$; $P < 0.05$) and WHC ($R^2 = 0.50$; $P < 0.05$) of the bulky diets were selected variables to predict ADFI. Variables that were significant in predicting SFI were ADF ($R^2 = 0.62$), NDF ($R^2 = 0.61$), bulk density ($R^2 = 0.64$) and WHC ($R^2 = 0.64$). Bulk density of the feed was the best single predictor, its selection increased precision to accounting for 64.2 % of the variation, in SFI ($P < 0.01$).

The best predictors for ADG are WHC ($R^2 = 0.57$, $P < 0.001$) and ADF ($R^2 = 0.50$, $P < 0.01$). The SADG was accurately predicted ($P < 0.001$) by the ADF ($R^2 = 0.13$), and EE ($R^2 = 0.16$). Crude protein ($R^2 = 0.15$), ADF ($R^2 = 0.15$) content and WHC ($R^2 = 0.13$) were significantly the most accurate predictors of FCE.

4.3.4 Prediction of feed intake and estimation of gut capacity

Equations relating ADFI and physicochemical properties of the bulky feeds are shown in Table 4.4. Figure 4.2 illustrates the relationships between SFI of weaner pigs using WHC, NDF, bulk density and ADF of fibrous feeds, respectively. There was a significant quadratic decrease ($P < 0.001$) in SFI as the WHC, ADF and NDF of the diets increased. An increase in bulk density of the feed was associated with a linear decrease in SFI ($P < 0.001$).

The broken stick model was used to determine the thresholds of physicochemical properties of bulky feeds indicating the break point when maximum SFI was attained. The dataset for SFI and bulk density could not fit into a broken stick model of regression. Using WHC, ADF and NDF at the descriptors, the maximum SFI was reached at 4.5 ± 1.25g water/ g DM, 367 ± 29 g/kg DM and 138 ± 77 g/kg DM, respectively (Table 4.5). This occurred when VFI became constant or started to decrease due to limitations of the gut of the pig.

4.3.4 Prediction of weight gain and feed conversion efficiency

Equations for prediction of ADG, SADG and FCE using physicochemical properties of the feeds are shown in Table 4.6. There was a linear decrease in ADG as the WHC and ADF increased ($P < 0.001$). The SADG reduced linearly with an increase in ADF ($P < 0.001$). The FCE decreased by quadratic functions as the CF and WHC of the bulky feed increased ($P < 0.001$). There was a linear increase ($P < 0.001$) in FCE as the crude protein content of the diets increased.

Table 4.4: Prediction of average daily feed intake (ADFI) from physicochemical properties

Equations	R^2	RMSE	*Sig.*
ADFI = 1.6(0.16) – 0.0075 (0.00075)WHC	0.19	0.49	***
ADFI = 11.4(3.11) – 9.6(4.58)Density + 4.0(0.67) Bulk density^2	0.10	0.51	*
ADFI = 1.4(0.17) + 0.001(0.000012)NDF – 0.000004(0.0000002)NDF^2	0.12	0.38	*
ADFI = 1.6(0.092) – 0.004(0.000011)ADF	0.17	0.37	***

Values in parentheses are standard errors. RMSE = root mean square error; *Sig.* = significance level; * = $P < 0.05$; ** = $P < 0.01$; *** = $P < 0.001$. WHC = water holding capacity (g water/ g DM); Density (g DM/ml); NDF = neutral detergent fibre (g/kg DM); ADF = acid detergent fibre (g/kg DM).

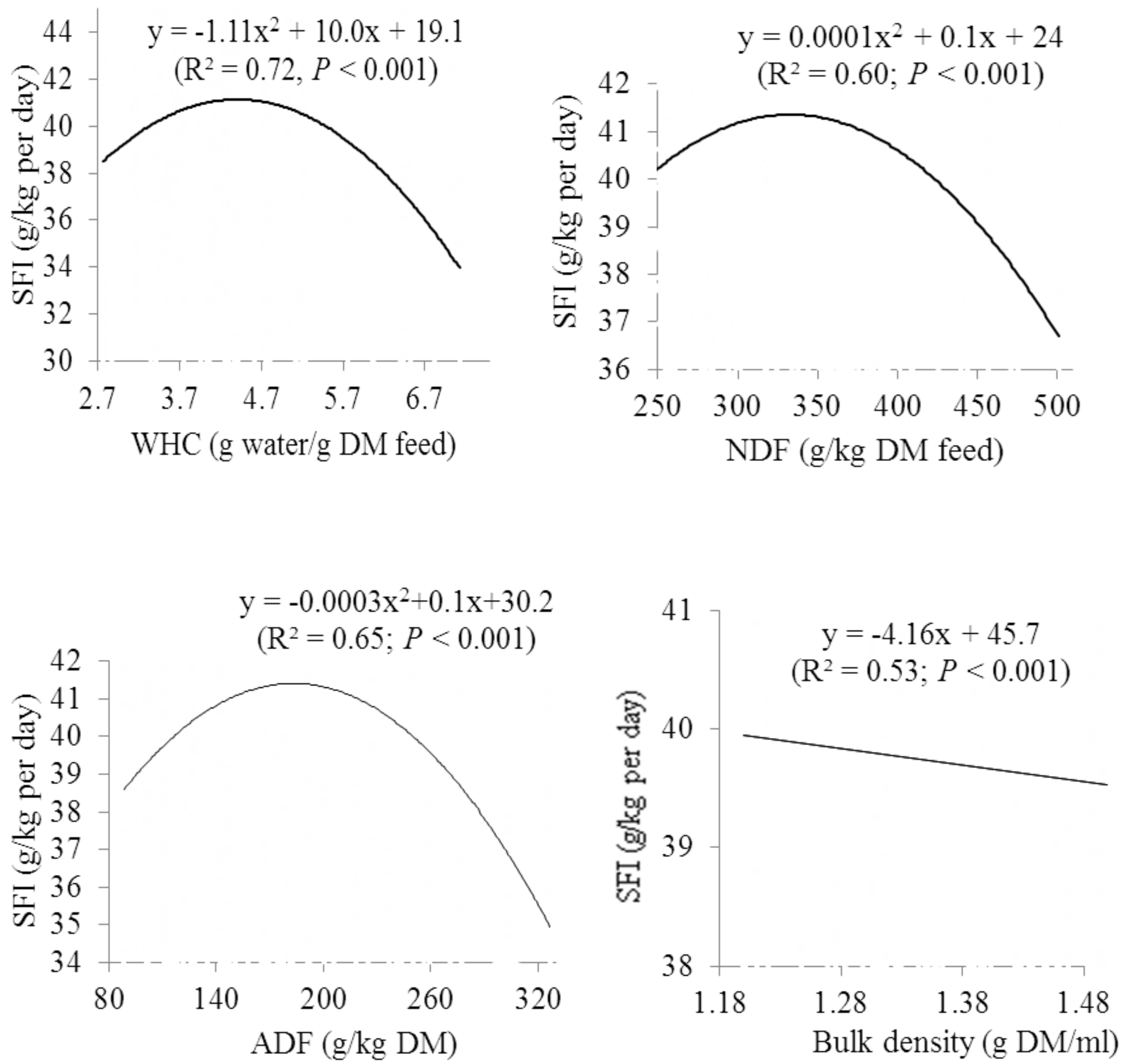

Figure 4.2: Prediction of scaled feed intake (SFI) using water holding capacity (WHC), neutral detergent fibre (NDF), bulk density and acid detergent fibre (ADF) of fibrous feeds

Table 4.5: Threshold values of physicochemical properties when gut capacity is attained

Physicochemical property	γ_o	γ_1	γ_2	x_c	*Sig.*
WHC	31.3	2.57	-5.60	4.5±1.25	***
NDF	35.6	0.02	-0.05	367±29	***
ADF	38.2	0.01	-0.12	138±77	**

Sig. = significance level; $SFI_i = \gamma_o + \gamma_1 (x_i) + \gamma_2 (x_i > x_c) (x_i - x_c) + \varepsilon_i$, when $(x_i > x_c) = 1$.

WHC=water holding capacity (g water/ g DM); NDF= neutral detergent fibre (g/kg DM); ADF=acid detergent fibre (g/kg DM).

γ_o is the intercept or minimum SFI when $x_c < 0$;

γ_1 is a linear coefficient describing the rate of change of SFI when $x_i < x_c$;

γ_2 is a linear coefficient describing the rate of increase in SFI when $x_i > x_c$;

x_i is the value of the physicochemical property of the feed; and

x_c is the optimum physicochemical property value when gut capacity is attained.

Table 4.6: Prediction of average daily gain (ADG), scaled average daily gain (SADG) and feed conversion efficiency (FCE) using physicochemical properties of fibrous feeds

Equations	R^2	RMSE	*Sig.*
ADG = 1440 (13.7) – 247 (52.3) WHC	0.29	255	***
ADG = 1090 (63.2) – 3.33 (0.81) ADF	0.29	25.7	***
SADG = 23.1 (1.72) – 0.01 (0.02) ADF	0.13	6.98	***
FCE = 625 (19.6) – 2.3 (0.39) CF + 0.01 (0.001) CF^2	0.11	199	***
FCE = -153 (290) + 5.33 (3.75) CP	0.63	195	***
FCE = 927 (87.4) – 152 (40.2) WHC + 10.2 (4.36) WHC^2	0.67	196	***

RMSE = root mean square error; *Sig.* = significance level; *P < 0.05; **P < 0.01; ***P < 0.001.

Values in parentheses are standard errors.

WHC=water holding capacity (g water/ g DM), NDF= neutral detergent fibre (g/kg DM); ADF=acid detergent fibre (g/kg DM); Density (g DM/ml); Ash (g/ kg DM).

4.4 Discussion

Pigs eat at a level to allow potential performance or maximum biological efficiency to be achieved, unless constrained in some way (Whittemore *et al.*, 2001). The gut capacity occurs when the pig given a constraining feed reaches an equilibrium level of feed intake which is below the desired level required for the genetic potential to be achieved (Kyriazakis and Emmans, 1999). Predictive relationships between feed bulk and VFI had been developed using a limited number of diets (Kyriazakis and Emmans, 1995; Tsaras *et al.*, 1998; Whittemore *et al.*, 2003a). Due to a narrow range of physicochemical measurements of bulkiness and a limited number of diets used in these previous experiments, the relationship established may not be comprehensive to provide accurate measurements of gut capacities.

The current study was designed to determine the physicochemical properties of a feed that best describe the bulkiness of the feed, such that the gut capacity of a weaner pig can be predicted. The fibre content in the diet is defined solely as the non-starch polysaccharide (NSP) (Bindelle *et al.*, 2008). A wide variety of fibrous ingredients were used in the current study because different NSPs do not behave in a similar way in the GIT. For example, insoluble NSPs, such as cellulose and xylans, can hold water (as they behave like sponges in the GIT), resulting in considerable bulking properties. Soluble NSPs, on the other hand, form gels and contribute to the viscosity of the contents of the GIT (Tsaras *et al.*, 1998).

The increase in intake of bulky feeds as the inclusion level of the fibre increased during the beginning of the trial suggests that pigs increased consumption to compensate for the increase indigestible material content so that they could acquire sufficient to allow their growth potential

(Whittemore *et al.*, 2001). The observation that the SFI of pigs given the control diet decreased was due to the low WHC of the feed which allowed pigs to consume adequate nutrients to meet their requirements for maintenance and growth. As expected, inclusion of fibre limited the nutrient supply which was required for maintenance and growth. When 80 or 160 g/kg of all fibre sources, except grass hay and saw dust were included in the diets, feed intake increased and then became constant towards the end of the trial, suggesting that the pigs gradually increased their ability to cope with the bulky feeds. Continuous increase in feed intake of saw dust-based diets could be attributed to their low abilities to bind water within their matrices (Kyriazakis and Emmans, 1995; Tsaras *et al.*, 1998). Since saw dust is indigestible, its inclusion decreased the nutrient density, thereby stimulating consumption of more feed to meet the desired nutrient requirements of the pigs.

The observation that SFI at 80, 160 and 240 g/kg maize cob inclusion levels were similar agree with Kanengoni *et al.* (2004) who reported no differences in ADFI diets containing maize cob at levels between 100 and 300 g/kg inclusion levels. The similarities in intakes across these levels are largely due to the uniformity of the WHC and bulk densities of the feeds. Maize cob meal has low WHC. The uniformity in WHC of the maize cob-based diets could be due to its low WHC, implying that it has little additive effects on the overall bulk content of the feed even when included at high inclusion levels in the diet. Furthermore, maize cob is highly soluble, suggesting that it is readily available for microbial fermentation and may increase the transit time in the GIT, thereby limiting feed consumption. It is, therefore, imperative to estimate changes in the WHC of the maize cob-based digesta along the gut.

The findings that NDF, ADF and bulk density were significant in predicting ADFI contradict with earlier reports (Kyriazakis and Emmans, 1995; Tsaras *et al.*, 1998). The ADF and NDF values of feeds in the current study were higher than in previous studies. These discrepancies could also be ascribed to the differences in the types and characteristics of fibre sources used in the current study. In addition, increase in NDF content in the diet causes gut distension, leading to a reduction in the availability of other non-fibrous feed ingredients for digestibility. Feed intake is, consequently, reduced. Furthermore, the prediction of ADFI using bulky feed properties on as-fed basis does not provide a comprehensive description of the effects those physicochemical properties per unit body weight.

The observed quadratic relationship between SFI and WHC indicates the existence of an equilibrium intake level where maximum SFI is reached and intake starts to decrease. That point defines the gut capacity of the pig. Water holding capacity measures the ability of the feed to hold water, thus, a diet with a high WHC can hold more water and occupies more room in the gut. Using the broken stick model, the optimum value of WHC of the feed at which the gut capacity constrained intake was 4.53 g water/g DM. Furthermore, increase in WHC of the feeds beyond this level caused a decrease in SFI because the capacity of the gut for feed was filled up with the water molecules being held within the fibre matrix thus initiating swelling. The quadratic relationship between SFI and WHC in the current study could be plotted owing to the wide variety of fibre sources (and wide range of the WHC) used. Dietary fibres have complex chemical properties, physical composition with variable metabolic effects. The optimum inclusion level for each fibre source should, therefore, depend on the WHC of the feeding material used.

Apart from WHC, NDF, ADF content and bulk density were significant in the prediction of SFI. The NDF, ADF and density could be used to predict the gut capacity of pigs. The broken stick model indicated that maximum NDF content of the feed that constrained SFI when the gut capacity was attained at a break point of 367 ± 29 g/kg DM, corresponding to about less than 320 g/kg inclusion level of all the fibre sources used. In addition, when the ADF content of the feed increased, it followed the same trend as that observed with NDF constraining the gut capacity at 138 g/kg DM, however, the maximum ADF value corresponded to 160 g/kg inclusion level of all the fibre sources except sunflower husks that has a corresponding inclusion level of 320 g/kg veld grass at this break point. The break points of ADF and NDF values suggest that, if the decisions of including fibrous ingredients in weaner diets are being considered when these are available at reasonable costs, the levels of inclusion as a measured by these parameters should not exceed these inclusion levels to facilitate sufficient intake of nutrients required for growth.

The rate of change of SFI after the breakpoint is reached show that, for all the physicochemical properties used to estimate gut capacity, continued increase in bulkiness decreased feed intake. The reduction in feed intake indicates that the GIT is not adapted to fibrous feeds (Whittemore *et al.*, 2003b). The negative linear relationship between bulk density and VFI can also be ascribed to the effect of increasing fibre which is lighter and fluffy than the conventional diet. The degree of consistency of the feed components caused a decrease in the quantity of less bulk material per unit volume that could be consumed implying that more space per unit mass was required to accommodate the feed in the gut thereby limiting the SFI. The bulk density could, however not permit the model to provide a break point indicating the threshold that can be used to predict SFI when the gut capacity is attained.

Apart from estimating the gut capacity using SFI, it is also necessary to determine the influence of physicochemical properties on ADG and FCE. A linear relationship was significant between both ADG and SADG and each of the following; WHC, bulk density and NDF, respectively. As the bulkiness of the feed decreased, there was an increase in ADG. The ability of growing pigs to utilize fibrous diets is limited because fibrous ingredients reduce mean retention time in the GIT, thereby reducing time of exposure of diet to the host's digestive enzymes (Low, 1982; Wilfart *et al.,* 2007; Bindelle *et al.,* 2008). The decrease in SADG as bulk content of the diet increased suggests that the high WHC limited the consumption of nutrients. Another plausible explanation for the reduction in SADG as the bulkiness of the diets increase is that the low energy content of fibrous feeds promotes early satiety, thereby limiting growth performance (Wenk, 2001).

The observation that bulkiness of the diets was related to a decrease in FCE agrees earlier reports (Tsaras *et al.*, 1998; Whittemore *et al.*, 2001). The mechanisms with which digestibility of fibre diets is constrained are complex. For example, reduction in FCE could be ascribed to the potential masking effect fibrous matrices have on availability of non-fibre feed ingredients for digestion and absorption in the foregut. Digestibility is also a function of the level and the type of the fibre. The rate of diffusion, towards the mucosal surface, of the solubilized components is slowed down by the viscosity and WHC of the intestinal content (Wenk, 2001).

4.5 Conclusions

As the bulk content of the feed increased, SFI was constrained by the gut capacity. Although WHC, NDF and ADF all can predict gut capacity of weaner pigs, the threshold values were different. When the bulk content of the feed increases beyond the threshold values marking the break point, the amount of feed consumed decreased. Since the ability to ferment DF increases as the pig grows, the influence of physicochemical properties of feed on gut capacity in finishing pigs need to be determined.

4.6 References

Bindelle, J., Leterme, P. and Buldgen, A. (2008). Nutritional and environmental consequences of dietary fibre in pig nutrition: a review. *Biotechnology, Agronomy, Society and Environment*, 12: 69-80.

Kanengoni A.T., Dzama K., Chimonyo M., Kusina J. and Maswaure S.M. (2004). Growth performance and carcass traits of Large White, Mukota and their F_1 crosses fed on graded levels of maize cobs, *Animal Science* 78: 61-66.

Kyriazakis, I and Emmans, G.C. (1995). The voluntary feed intake of pigs given feeds based on wheat bran, dried citrus pulp and grass meal, in relations to measurements of bulk. *British Journal of Nutrition*, 73: 191-207.

Kyriazakis, I. and Emmans, G.C. (1999). The voluntary food intake and diet selection of pigs. In: Kyriazakis, I., Editor, A quantitative biology of the pig. CAB International, Wallingford, UK (1999): 229-248.

Low, A.G. (1982). Digestibility and availability of amino acids from feedstuffs for pigs: a review. *Livestock Production Science*, 9: 511-520.

SAS (2008). SAS User's Guide: Statistics, Version 9.1. SAS Institute, Cary, NC, USA.

Tsaras L.N., Kyriazakis I. and Emmans G.C. (1998). The prediction of the voluntary food intake of pigs on poor quality foods. *Animal Science*, 66: 713-723.

Wenk, C. (2001). The role of dietary fibre in the digestive physiology of the pig. *Animal Feed Science and Technology*, 90: 21-33.

Whittemore, E.C., Kyriazakis, I., Emmans, G.C. and Tolkamp, B.J. (2001). Tests of two theories of food intake using growing pigs. 1. The effect of ambient temperature on the intake of foods of differing bulk content. *Animal Science*, 72: 351-360.

Whittemore, E.C., Emmans, G.C. and Kyriazakis, I. (2003a). The relationship between live weight and the intake of 'bulky' foods in pigs. *Animal Science*, 76: 89-100.

Whittemore, E.C., Emmans, G.C. and Kyriazakis, I. (2003b). The problem of predicting food intake during the period of adaptation to a new food: a model. *British Journal of Nutrition*, 89: 383-398.

Wilfart, A., Montagne, L., Simmins, H., Noblet, J., and van Milgen, J. (2007). Effect of fibre content in the diet on the mean retention time in different segments of the digestive tract in growing pigs. *Livestock Science*, 109, 27-29.

Chapter 5: Influence of physicochemical properties of bulky feeds on voluntary feed intake in finishing pigs

Abstract

The objective of the study was to determine the physicochemical properties that can be used to describe effects of bulkiness on VFI in finishing pigs. A total of 84 pigs weighing 65 (s.d. 1.37) kg body weight were given, *ad libitum*, each of the 21 diets containing a basal feed diluted with 0, 80, 160, 240, 320 and 400 g/kg of lucerne hay, maize cob, maize stover, saw dust, sunflower husks or grass hay. Each of the 21 diets was given to each of the four pigs, in individual pens, for 21 days. Physicochemical properties of the feeds measured were DM, crude protein, ether extract, ash, water holding capacity (WHC), bulk density, crude fibre (CF), neutral detergent fibre (NDF) and acid detergent fibre (ADF). The most powerful predictors of SFI were NDF ($R^2 = 0.76$; ($P < 0.05$), CF ($R^2 = 0.76$; $P < 0.05$), CP ($R^2 = 0.75$; $P < 0.001$) and WHC ($R^2 = 0.73$; $P < 0.001$). There was a quadratic relationship between SFI and NDF given by the function SFI = 82.0 (± 5.30) - 0.18 (± 0.03) NDF + 0.0002 (± 0.00004) NDF^2 ($P < 0.01$). The SFI was related to CF and CP by quadratic functions; SFI = 63.4 (± 2.22) - 0.16 (± 0.03) CF + 0.0003 (± 0.00007) CF^2 ($P < 0.001$) and SFI = 61.8 (± 9.68) - 0.39 (± 0.16) CP + 0.002 (± 0.0006) CP^2 ($P < 0.01$), respectively. The SFI was related to WHC by linear function; SFI = 77.3 (± 4.37) - 7.43 (± 1.77) WHC ($P < 0.001$). Physicochemical properties of feed that can be used to describe the relationship between bulkiness and feed intake in finishing pigs are WHC, NDF and CF content. Unlike in weaner pigs, VFI decreased as the physical property of the feed increased.

Keywords: bulkiness, feed intake, finishing pigs, neutral detergent fibre, water holding capacity

5.1 Introduction

Sufficient evidence exist that as pigs grow, their ability to utilize fibrous feeds is enhanced (Bindelle *et al.*, 2008). There is lack of information on of how much fibre should be included in the feed without compromising potential growth of pigs. In Chapter 4, WHC, ADF, NDF and bulk density were the most reliable physicochemical properties that can be used to estimate gut capacity in weaner pigs. Due to the development of their large intestines and caeca, finishing pigs have the ability to ferment fibrous ingredients that escape digestion in the foregut (Bindelle *et al.*, 2008; Renteria-Flores *et al.*, 2008). Therefore, the influence of WHC, ADF, NDF and bulk density in predicting gut capacity between weaner and finishing pigs is likely to be different. Dry matter degradability as well as the development of the gut may influence gut transit, and consequently, VFI (Whittemore *et al.*, 2003a). Very few, if any, reports, exist on the relationship between physicochemical properties and VFI in finishing pigs.

Feed spillages from pigs fed on maize stover- and grass hay-based diets were high, making it difficult to estimate their intake in finishing pigs. Maize cob, sunflower husk, lucerne hay and saw dust were, therefore, used as fibre sources in the current study. The objective of the study was to determine if the physicochemical measurements of bulkiness can be used to predict feed intake in finishing pigs. It was hypothesized that physicochemical measures of bulkiness of a feed adequately describes the gut capacity of finishing pigs.

5.2 Materials and Methods

5.2.1 Description of study site

The study was conducted at Ukulinga Research Farm of the University of KwaZulu-Natal.

Details on the site description are given in Section 4.2.

5.2.2 Pigs and housing

Eighty-four male F1 hybrid weaner (about 12 kg body weight) pigs (Large White × Landrace, PIC group, South Africa) were purchased, in two batches, from Kanhym farm, Bainesfield, South Africa. They were transported on a tarred road for 60 km in a truck moving at an average speed of 60 km/h and were loaded at a density of 0.12 m^2/pig. The pigs were randomly grouped into 12 pigs per pen until they attained 65 (s.d. 1.37) kg body weights. At an age of 13 weeks, pigs were then randomly allocated to individual pens, which were arranged in three rows such that they were 14 cages in each row. Each individual pen, measuring 2.0 × 1.1 m in floor area, was equipped with a plastic self-feeder trough (Big Dutchman Lean Machine®) designed to minimise spillages and a low-pressure nipple drinker providing water *ad libitum*. The pens were constructed using wire-mesh with concrete floors in a room that had a single heating, lighting and ventilation system.

The ambient temperature and relative humidity were recorded automatically every 15 min throughout the trial by a HOBO TEMPERATURE, RH©, 1996 ONSET logger. The average temperature and humidity was 22.2 (s.d. 3.14)^{o}C and 45.6 (s.d. 10.22) %. The care and use of the animals were performed according to the ethical needs by Certification of Authorization to Experiment on Living Animals provided by UKZN Animal Ethics Committee, Reference number 096/11/Animal.

5.2.3 Feeds

A high quality commercial feed (Supreme Grower, Meadow feeds Ltd, Pietermaritzburg, South Africa) with 80 g DF/kg DM, was used as the basal feed. The basal feed contained approximately 12.9 MJ/kg digestible energy and 160 g CP/kg DM. The ingredient composition of the basal diet is given in Table 5.1. A total of 21 complete diets were formulated by diluting the basal diet with maize cob, sunflower husks, lucerne and saw dust at six inclusion levels (0, 80, 160, 240, 320 and 400 g/kg, respectively. To give the diets a wide range of bulkiness, the fibre sources were selected according to differences in WHC, bulk density, CP, CF, NDF and ADF.

The DM, gross energy, CP, EE, ash, CF, NDF, ADF, bulk density and WHC were analysed for all diets, as described in Chapter 3. To ensure that feed intake was increased, the feeds in the dilution series were not supplemented in any way. Pigs were not given any antibiotics or growth promoters in their diets both before and during the trial. The analyses of diets were performed in the Discipline of Animal and Poultry Science Laboratory at the University of KwaZulu-Natal, Pietermaritzburg. The chemical composition and bulk properties of the fibrous diets are shown in Table 5.2 and Table 5.3, respectively.

5.2.4 Experimental design and management of pigs

Two pigs were randomly allocated to each diet shown in Tables 5.1 and 5.2 with each treatment allocated to each pig in either side of the rows. The feed was provided *ad libitum*. The pigs were adapted to the treatment diets for 10 days. The trial ran for 21 days and the pigs were weighing 92.6 (s.d. 5.93) kg body weight. Feed intake was determined by weighing the feed trough at the

Table 5.1: Ingredient composition of the basal feed

Ingredient	(kg/ 100 kg DM)
Yellow maize	50.0
Soybean	15.8
Soybean oil cake	2.02
Wheat bran	16.3
Sunflower oil cake	8.50
Molasses syrup	2.50
Additives	4.88

Table 5.2: Chemical composition (g/kg DM) of the basal diet (B), and diets based on lucerne hay (LC), maize cob (MC), saw dust (SD) and sunflower husk (SH) and veld grass (VG) given to finishing pigs

Fibre source	Inclusion level (g/kg)	Dry matter (DM)(g/kg)	Gross energy (MJ/kg DM)	Crude protein (g/kg DM)	Ether extract (g/kg DM)	Ash (g/kg DM)
B		889	18.0	161	25.4	60.6
LC	80	889	17.9	151	24.3	62.6
	160	990	17.9	133	23.4	64.7
	240	990	17.9	118	21.7	66.7
	320	890	17.8	105	21.6	68.7
	400	990	17.7	81.8	20.4	70.7
MC	80	889	17.8	151	28.2	58.1
	160	890	17.9	134	31.4	54.5
	240	891	17.9	118	33.3	52.8
	320	893	17.8	105	37.5	51.7
	400	895	17.8	99.8	39.8	46.4
SD	80	894	18.0	139	24.7	53.3
	160	895	18.2	130	24.2	47.9
	240	896	18.2	112	22.6	43.7
	320	898	18.3	96.7	23.0	41.2
	400	901	18.4	82.9	22.2	38.9
SH	80	889	18.0	132	28.4	56.2
	160	898	18.3	111	31.4	53.4
	240	898	18.4	100	34.6	51.2
	320	899	18.7	97.6	39.0	48.1
	400	990	19.2	88.9	42.4	44.6
Standard error		0.36	0.12	1.33	0.34	0.68

Table 5.3: Bulk characteristics (g/kg DM) of the basal diet (B), and diets based on lucerne hay (LC), maize cob (MC), saw dust (SD) and sunflower husk (SH) given to finishing pigs

Fibre source	Inclusion level (g/kg)	Crude fibre (g/kg DM)	NDF (g/kg DM)	ADF (g/kg DM)	Bulk density (g DM/ml)	WHC (g water/g DM)
B	0	80.5	217	91.9	1.61	3.43
L	80	98.0	234	101	1.53	4.12
	160	116	258	126	1.47	4.74
	240	133	283	151	1.43	5.70
	320	151	307	176	1.25	6.55
	400	167	336	200	1.22	7.29
MC	80	96.9	266	129	1.53	3.95
	160	112	324	163	1.43	4.27
	240	127	384	196	1.42	4.61
	320	142	435	230	1.25	4.97
	400	157	496	25	1.22	5.38
SD	80	128	266	144	1.59	3.92
	160	177	322	195	1.57	4.42
	240	223	379	242	1.56	5.00
	320	273	439	294	1.54	5.44
	400	323	496	339	1.52	5.92
SH	80	109	241	111	1.54	3.64
	160	136	272	131	1.47	3.95
	240	162	300	146	1.39	4.31
	320	192	333	166	1.32	4.56
	400	225	363	199	1.25	4.95
Standard error		1.26	3.73	4.50	0.13	0.24

NDF= neutral detergent fibre; ADF=acid detergent fibre; WHC=water holding capacity.

beginning and end of the week. Feed spillages were collected from the floor using a hand broom and a duster. The feed spilled were oven dried at 80°C for 24 h, weighed and discarded daily. Weights of feed refusals and spillages were subtracted from the total weight of the feed that was put into the feeder to determine feed intake for that particular week. The weight of the feed consumed for that particular week was divided by 7 to estimate ADFI.

The pig house was cleaned daily. Pigs were weighed every week at the same time from the beginning of the trial up to the end of the feeding period. To take account of any differences in body weight between treatments, ADFI was expressed as SFI, calculated as g feed per kg body weight per day. The scaled WHC intake (SFI_{whc}; units per kg per day) was determined by dividing the WHC by SFI. The average body weight gain (ADG) was also scaled to give a scaled average daily gain (SADG). Feed conversion efficiency (FCE) was determined by dividing the ADG by ADFI. After the pigs were moved out of the pig house, the facility was washed, disinfected and rested for two weeks, and then a second batch was introduced. Care and use of the pigs were performed according to the ethical needs by Certification of Authorization to Experiment on Living Animals provided by UKZN Animal Ethics Committee, Reference number 096/11/Animal.

5.2.5 Statistical analyses

Effects of fibre source, fibre inclusion level, fermentation parameters of fibre sources, week of feeding, batch and their interactions on SFI were determined using the GLM procedures (SAS, 2008). The model used was:

$Y_{ijklm} = \mu + \alpha_i + \nu_j + \delta_k + \lambda_l + (\alpha \times \nu \times \delta)_{ijk} + \varepsilon_{ijklm}$, where;

Y_{ijklm} is the scaled feed intake

μ is the overall mean response common to all observations

α_i is the effect of fibre source

ν_j is the effect of the fibre inclusion level

δ_k is the effect of the week of feeding

λ_l is the effect of the batch

$\alpha \times \nu \times \delta_{ijk}$ is the interaction of fibre source, fibre inclusion level and week of feeding; and

ε_{ijklm} is the residual error.

Stepwise regression in SAS (2008) was used to identify physicochemical properties and fermentation parameters of fibrous feedstuffs which influenced ADFI, SFI, ADG, SADG and FCE. The quadratic response surface model (PROC RSREG) of SAS (2008) was used to determine the relationship between ADFI, SFI, ADG, SADG, and FCE and each of the physicochemical properties selected. The response surface regression model was also used to determine relationship between SFI_{whc} and body weight. To estimate the threshold at which physicochemical property of a feed causes FCE to be constant or decrease as feed bulk increased, the broken stick analysis model was conducted using NLIN procedure (SAS, 2008). In this model, break points were used to estimate the thresholds of physicochemical properties of the feed at which bulkiness constrained FCE. The model was established as follows:

$Y_i = \beta_o + \beta_1 (x_i) + \beta_2 (x_i > x_c) (x_i - x_c) + E_i$, when $(x_i > x_c) = 1$

Using parameters (β_o, β_1, β_2) and the x_c, the two segmented simple regression functions were;

$Y_j = \beta_o + \beta_1 (x_i)$, for $x_i \leq x_c$; and

$Y_k = Y_o + (\beta_1+\beta_2) x_i$, for $x_i \geq x_c$

Where;

Y_i is the FCE when ratio of weight gain to feed intake reaches a maximum value or starts decreasing with continuous increase in bulk content,

Y_o is the FCE when $x_i = 0$,

β_o is the intercept or minimum FCE when $x_c < 0$,

β_1 is the rate of change of FCE with bulkiness when $x_i < x_c$,

β_2 is the rate of change of FCE with bulkiness when $x_i > x_c$,

x_i is the value of the physicochemical property of the feed; and

x_c is the optimum physicochemical property value when maximum FCE is attained.

5.3 Results

5.3.1 Effects of fibre source, inclusion level and week on scaled feed intake

Batch had no significant effect on SFI. The SFI of finishing pigs given diets based on lucerne hay, maize cob, sunflower husks and saw dust during the 3-week period are illustrated in Figure 5.1. The SFI differed ($P < 0.05$) with fibre source across all inclusion levels except for 80 g/kg level of inclusion. The control diet was the most consumed ($P < 0.05$) feed. However, its SFI was similar ($P > 0.05$) to 160g/kg inclusion level for sunflower husk. For all fibre sources, the SFI increased ($P < 0.001$) with increase in inclusion level during the trial.

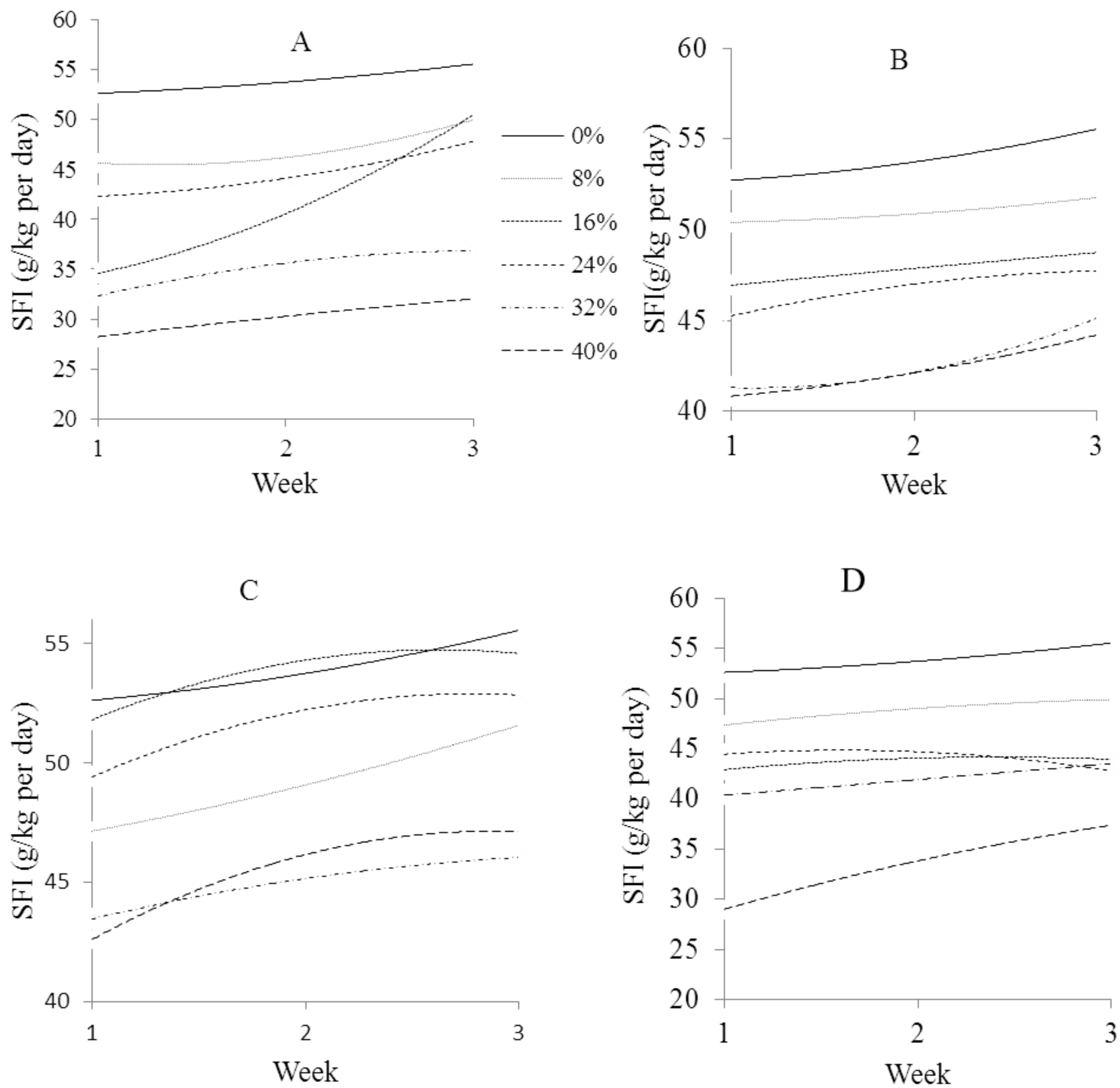

Figure 5.1: Weekly changes in scaled feed intake of pigs given bulk feeds based on lucerne hay (A), maize cob (B), sunflower husk (C) and saw dust (D)

5.3.3 Physicochemical properties of fibrous feeds affecting intake, weight gain and feed conversion efficiency

Using stepwise regression, the effects of physicochemical properties on ADFI, SFI, ADG and SADG in the finishing pigs were tested. The most powerful predictor of SFI was NDF (with a partial R^2 of 76 %) ($P < 0.05$). The other variables which were selected were CF ($R^2 = 0.77$; $P < 0.05$), CP ($R^2 = 0.76$; $P < 0.001$) and WHC ($R^2 = 0.74$; $P < 0.001$). Variables, such as bulk density, DM, GE, CP, EE and ash content were not significantly related to SFI ($P > 0.05$). The best predictor for ADG was bulky density ($R^2 = 0.15$; $P < 0.05$). Bulky density significantly predicted SADG ($R^2= 0.22$; $P < 0.05$). The CF ($R^2 = 0.26$; $P < 0.01$) and bulky density ($R^2 = 0.47$; $P < 0.05$) were the most accurate predictors of feed conversion efficiency.

5.3.4 Prediction of intake, daily gain and feed conversion efficiency of pigs given 'bulky' feeds

Figure 5.2 illustrates the relationships between SFI of finishing pigs using WHC, CP, CF and NDF of fibrous feeds, respectively. An increase in the WHC of the diet caused a significant linear decrease in SFI. As CF and NDF levels increased, there was a significant quadratic decrease in the SFI until it reached equilibrium. An increase in CP content in the feeds increased the SFI ($P < 0.01$). The SFI could not fit into a broken stick analysis model. Figure 5.3 shows that the intake of WHC per kg body weight reduced when body weight increased ($P < 0.01$).

An increase in bulk density of the fibrous diets caused a linear increase ($P < 0.05$) in ADG. The change in SADG and FCE as feed bulk increased is illustrated in Figure 5.4.

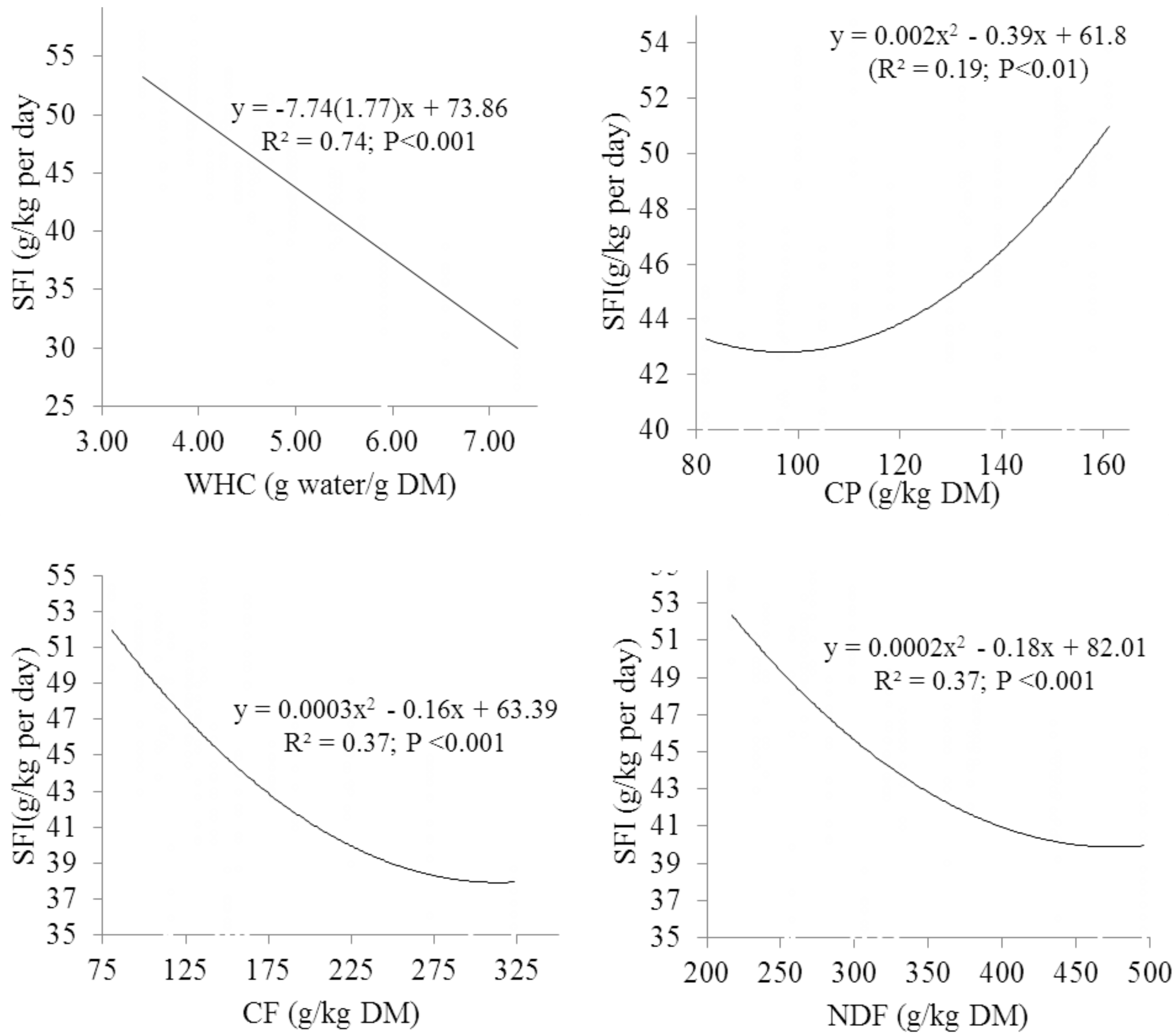

Figure 5.2: Prediction of scaled average daily feed intake (SFI) of weaner pigs using water holding capacity (WHC) , crude protein (CP) , crude fibre (CF) and neutral detergent fibre (NDF) of fibrous feeds

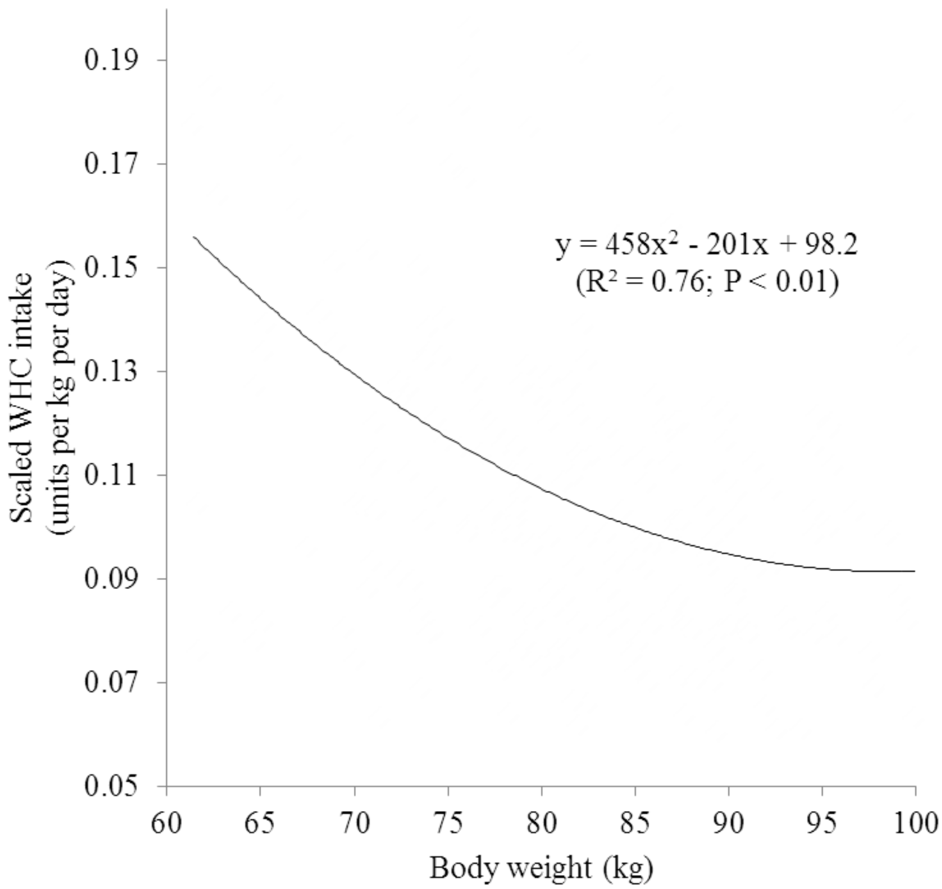

Figure 5.3: Relationship between body weight and scaled capacity for bulk (scaled WHC intake units per kg per day)

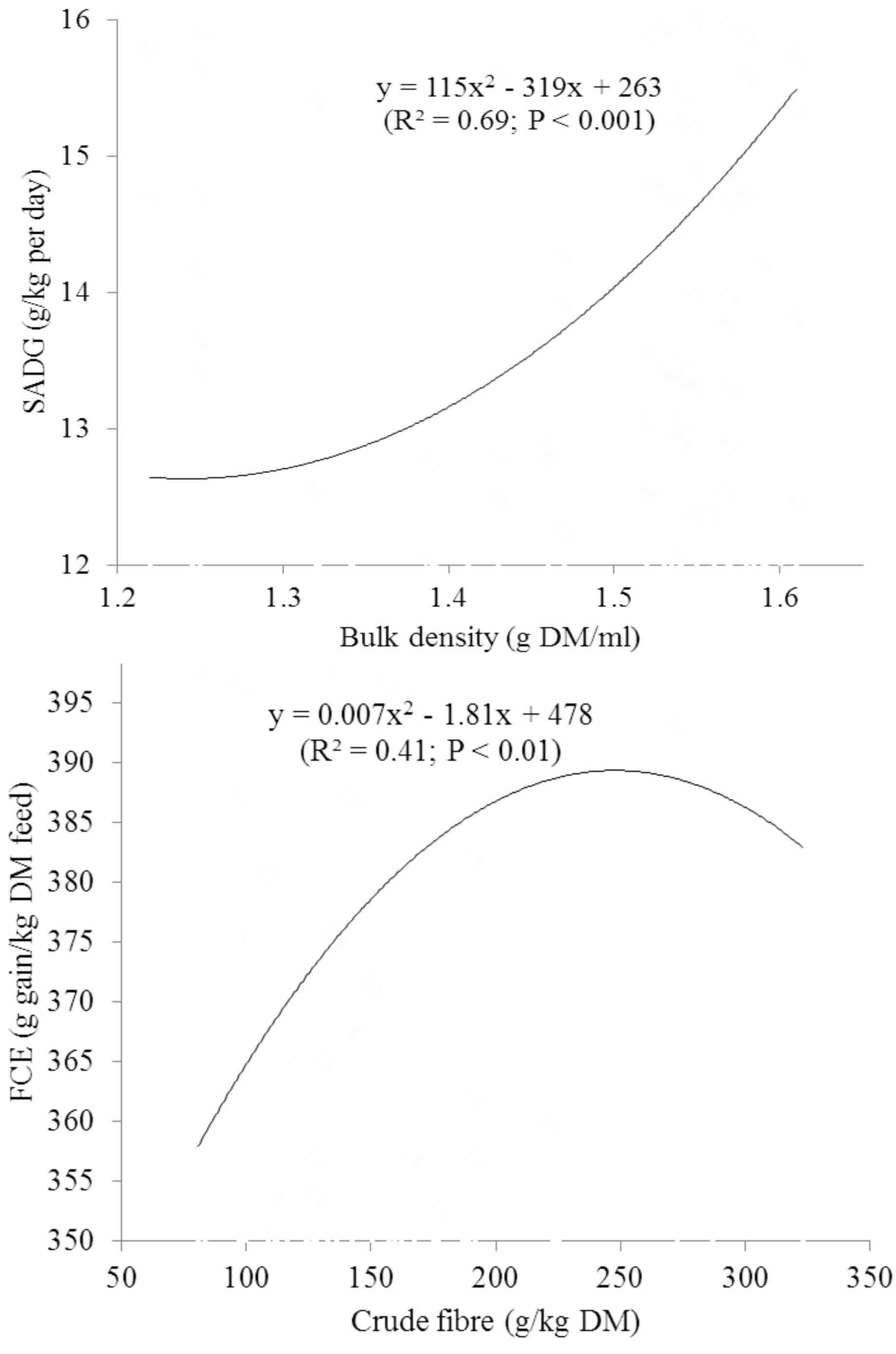

Figure 5.4: Variation in scaled average daily gain (SADG) and feed conversion efficiency (FCE) with bulk content of the feed

As the bulk density of the feed increased, there was a quadratic increase in SADG given by quadratic function:

SADG = 263 (± 66.1) – 319 (± 93.4) Bulk density + 115 (± 32.7) Bulk density^2 (R^2 = 69, P < 0.001).

Crude fibre content of the diets was related to FCE by the function:

FCE = 478 (± 104) – 1.81 (± 1.24) CF + 0.0068 (± 0.0032) CF^2 (R^2 = 41, P < 0.01).

Using the broken stick regression model, the threshold values of the physicochemical properties indicating the break point of FCE when the ratio of weight gain to feed intake reaches its maximum or starts to decrease occurred when CF was 116 ± 25 g/kg DM.

5.4 Discussion

The current study was designed mainly to determine how physicochemical properties of bulky feedstuffs relate to gut capacity in finishing pigs. Research on the use of physicochemical properties of locally available fibrous feedstuffs, such as maize cob, sunflower husks and lucerne, to estimate gut capacities of finishing pigs between 60 and 90 kg body weight has not been conducted. Understanding the relationships between physicochemical measurements of bulkiness of feeds and intake is crucial during feed formulation to allow sufficient nutrient intake and reduce overfeeding and nutrient losses to the environment.

High protein feeds (for growing pigs) were used because fibre inclusion was expected to reduce the CP content of the feeds. The reduction in SFI as the inclusion level of fibre increase indicates that replacing non-fibrous ingredients with bulky feedstuffs limits intake (Nyachoti *et al.*, 2004). The observed increase in SFI during the trial could be attributed to an increase in both the volume and length of the large intestines and caeca, which increases the capacity to utilise fibrous ingredients in finishing pigs (Whittemore *et al.*, 2003a). The finding that CF was one of the physicochemical properties that influenced SFI is inconsistent with the patterns observed in weaner pigs (Chapter 4). The effect of CF predicting feed bulk highlights the complexity of estimating feed intake and gut capacity as pigs approach maturity (Tsaras *et al.*, 1998; Bindelle *et al.*, 2008).

The linear reduction in SFI as the WHC increased reflects the physical 'bulk' of the feed exceeding the capacity of the gut (Cole *et al.*, 1972; Kyriazakis and Emmans, 1995; Whittemore *et al.*, 2003a). The bulkiness of the feeds is a result of an increase in fibre inclusion level, which enhances the ability of the feed, especially non-starch polysaccharides, to trap water within its matrices, swell and form gels with high water contents (Robertson and Eastwood, 1981). The levels of the NSPs in the diets used in the current study were, however, not determined. During transit of digesta in the GIT, feed particles tend to absorb water within their matrices and swell, thereby filling the gut quickly and reducing space for more feed to be consumed (Whittemore *et al.*, 2003b; Anguita *et al.*, 2006). As WHC of the digesta increase, changes in hydration properties in different sections of the gut, other physicochemical properties, such as density and viscosity also change, thus reducing the gut transit time (Anguita *et al.*, 2007). The reduction in SFI as WHC increased could suggest that the gut of finishing pigs developed mechanisms to cope with fibre-rich diets, thereby altering the WHC of the feed.

The observed increase in SFI at low CP levels was unexpected. Feed intake is expected to be higher for low protein diets (Ferguson and Gous, 1997; Wellock *et al.*, 2003). Considering that

CP was low in the diets with high fibre levels, the effects of CP were likely to have been confounded with NDF and CF contents of the feeds. Evidence exists that an average of 31 % of protein in commonly used fibre sources is bound to the NDF and is not available for the pig (Bindelle *et al.*, 2005). Besides, DF inclusion in the feed reduces protein concentration and may disturb the balance between amino acid concentrations. For example, the relatively high CP level in lucerne hay is likely to change the amino acid balance as compared to low protein fibre sources. As such, incorporation of fibrous ingredients in the current study could have physiologically contributed in depressing intake by disturbing the balance in nutrients. Henry *et al.* (1992) observed that low dietary ratio of tryptophan to large neutral amino acids reduce feed intake.

As the DF increased, SFI was initially reduced and then reached an equilibrium point where intake became constant. At this point, the coefficient describing the rate of change of SFI with the increase in bulkiness was closer to zero for CF than for NDF, suggesting that this physicochemical measurement of bulk could have been assisted by another dietary property such as water intake in constraining gut capacity. Water consumption was, however, not captured in the current study. Allen (2000) also reported negative relationships between dietary NDF concentration and intake. Undoubtedly, the NDF content is a major factor determining gut fill and can be used to predict the effect the bulkiness of a feed has on the gut capacity. Increase in NDF and CF concentrations in feeds impose some masking effects on the availability of feed ingredients for enzymatic degradation and increase the transit time in the small and large intestines (Le Goff *et al.*, 2003). The increase in transit time limits space in the gut, thereby, prolonging satiation. Alternatively, the reduction in SFI as the NDF or CF content of the diets increased could be attributed to the bulkiness of the fibrous feeds. A diet with low CF or NDF concentration occupies lesser space than a diet with high CF or NDF. Hence, gut capacity is easily attained for high CF and NDF thereby reducing feed intake.

The finding that SFI was not constrained by an increase in bulkiness agrees with Whittemore *et al*. (2003a). A decline in scaled capacity for bulk with an increase in body weight increase clearly indicates that capacity of bulk is not constant across the range of weights in finishing pigs (Whittemore *et al.,* 2003b). The observation that capacity for bulk for pigs decreased as body weight increased was unexpected (Tsaras *et al.*, 1998; Whittemore *et al.*, 2001a; b). Pigs were expected to increase intake per body weight as their body weight increased. These findings further confirm that mature pigs develop mechanisms to adopt to fibrous diets either through development of the morphology of the gut or nutritionally by increasing the enzymatic activity (Bindelle *et al.*, 2008). Therefore, a plausible explanation for the reduction in SFI as bulky content increase or reduction in scaled capacity for bulk in our study can be ascribed to reduction in space for more feed due to gut fill and availability of large amount of feed in the gut organs promoted by enlargement of large intestine and caeca. Whittemore *et al.* (2003a) also observed that the gut fill of pigs at 108 kg body weight given high fibre diets was higher than those of pig on a low fibre diet but the former had lower intakes levels than the later. Feed intake could have been depressed by increase in retention time in the stomach which causes gut distension due to elongation of stomach walls due to bulkiness of feed thereby elevating satiety levels and reducing desire to feed (Wenk, 2001). To establish the gut capacity in finishing pigs, it is, therefore important to determine gut fill in the different gut segments. Furthermore, the SFI could have decreased with increase in body weight due to contribution to the host maintenance energy supply by fermentation products that have been reported to compensate at least 15 % of metabolic energy demands in for growing-finishing pigs (Dierick *et al*., 1989; Jorgensen *et al*., 2007). This is a consequent of greater capacity for fermentation due to reduced rates of passage as the body weight of pigs increase (Le Goff *et al.*, 2003).

Reduction in SADG in pigs offered feeds with low bulky densities was expected. Increasing fibre inclusion level led to a reduction bulk density of the feed. The feed, consequently, occupies more space, but with limited digestible nutrients. Decrease in bulky density of the diet increased gut fill, possibly causing early satiety and restricting optimum nutrient intake required for potential growth. The reduction in SADG with as bulk density decreased could also be ascribed to decreasing proportion of feed components that could be digested (McDonald *et al.*, 2001). The pigs, might not have adjusted to utilising the fibrous feeds during the trial period.

An increase in FCE as CF increased up to a maximum point could be due to reduced feed intake in bulky feeds. Though highly likely, it is, however, difficult to confirm that the ability of the pigs to utilise fibre-based diets had been enhanced, as reported earlier (Jorgensen *et al.*, 2007; Bindelle *et al.*, 2008). By use of the broken stick model, the equilibrium FCE is reached when the CF value of the diets is 133 g/kg DM. The reduction in the FCE as CF content exceeded the threshold levels could be explained by the masking effects that fibrous ingredients have on non-fibrous feed components that hindered exposure of nutrient to enzymatic digestion and absorption (Glisto *et al.*, 1998; Mikkelsen *et al.*, 2004). Gastrointestinal organs have high rate of energy expenditure relative to their sizes, implying that a proportion of the decreased FCE observed when the fibre level is increased could be due to increase basal heat production resulting from increased growth of gut organs (Pluske *et al.*, (2003). The finding that an increase in the CF level in the diet caused a decrease in the FCE confirms that replacement of the conventional feed components with the fibrous ingredients reduced the digestible proportion of the diet that could be used to promote potential growth (Nyachoti *et al.*, 2004).

5.5. Conclusions

The SFI decreased with an increase in WHC, CF and NDF content. These physicochemical measurements of bulkiness, however, do not provide relationships that can be used to determine the gut capacity of finishing pigs.

5.6 References

Allen, M.S. (2000). Effects of diet on short-term regulation of feed intake by lactating dairy cattle. *Journal of Dairy Science*, 83: 1598-1625.

Anguita, M., Canibe, N., Perez, J.F. and Jensen, B.B. (2006). Influence of the amount of dietary fibre on the available energy from hindgut fermentation in growing pigs: use of cannulated pigs and *in vitro* fermentation. *Journal of Animal Science*, 84: 2766-2778.

Anguita, M., Gasa, J., Nofrarias, M., Martin-Orue, S.M. and Perez, J.F. (2007). Effect of coarse ground corn, sugar beet pulp and wheat bran on voluntary intake and physicochemical characteristics of digesta of growing. *Livestock Science*, 107: 182-191.

Bindelle, J., Sinnaeve, G., Dardenne, P., Leterme, P. and Bulgen, A. (2005). A rapid estimation of nitrogen bound to neutral detergent fibre in forages by near infrared reflectance spectroscopy. *Proceedings of the XXth International Grassland Congress*, University College Dublin, Dublin: 259-271.

Bindelle, J., Leterme, P. and Buldgen, A. (2008). Nutritional and environmental consequences of dietary fibre in pig nutrition: review. *Biotechnology, Agronomy, Society and Environment*, 12: 69-80.

Cole, D.J.A., Hardy, B. and Lewis, D. (1972). Nutrient density of pig diets. In Cole D.J.A., Editor, Pig Production, Butterworths, London: 243-257.

Dierick, N.A., Vervaeke, I.J., Demeyer, D.I. and Decuypere, J.A. (1989). Approach to the energetic importance of fibre digestion in pigs. I. Importance of fermentation in the overall energy supply. *Animal Feed Science and Technology*, 23: 141-167.

Ferguson, N.S. and Gous, R.M. (1997). The influence of heat production on voluntary food intake in growing pigs given protein-deficient diets. *Animal Science*, 64: 365-378.

Glisto, L.V., Brunsgaard, G., Hojsgaard, S., Sandstrom, B. and Bach Knudsen, K.E. (1998). Intestinal degradation in pigs of rye dietary fibre with different structural characteristics, *British of Nutrition*, 80: 457-468.

Henry, Y., Seve, B., Colleaux, Y., Ganier, P., Saligaut, C. and Jego, P. (1992). Interactive effects of dietary levels of tryptophan and protein on voluntary feed intake and growth performance in pigs, in relation to plasma free amino acids and hypothalamic serotonin. *Journal of Animal Science*, 70: 1873-1887.

Jorgensen, H., (2007). Methane emission by growing pigs and adult sows as influenced by fermentation. *Livestock Science*, 109, 216-219.

Kyriazakis, I and Emmans, G.C. (1995). The voluntary feed intake of pigs given feeds based on wheat bran, dried citrus pulp and grass meal, in relations to measurements of bulk. *British Journal of Nutrition*, 73: 191-207.

Le Goff, G., Noblet, J. and Cherbut, C. (2003). Intrinsic ability of the faecal microbial flora to ferment dietary fibre at different growth stages of pigs. *Livestock Production Science*, 81: 75-87.

McDonald, D.E., Pethick, D.W., Mullan, B.P. and Hapson, D.J. (2001). Increasing viscosity of the instestinal contents alters small intestinal structure and intestinal growth, stimulates proliferation of enterotoxigenic *Escherichia coli* in newly-weaned pigs. *British Journal of Nutrition*, 86: 487-498.

Mikkelsen, L.L., Naughton, P.J., Hedemann, M.S. and Jensen, B.B. (2004). Effects of physical properties of feed on microbial ecology and survival of *Salmonella enterica* serovar *Typhimurium* in the pig gastrointestinal tract. *Applied Environmental Microbiology*, 70: 3485-3492.

Nyachoti, C.M., Zijlstra, R.T., de Lange, C.F.M. and Patience, J.F. (2004). Voluntary feed intake in growing-finishing pigs: A review of the main determining factors and potential approaches for accurate predictions. *Canadian Journal of Animal Science*, 84: 549–566.

Pluske, J.R., Black, B., Pethick, B.P., Mullan, B.P. and Hampson, D.J. (2003). Effects of different sources and levels of dietary fibre in diets on performance, digesta characteristics and antibiotic treatment of pigs after weaning. *Animal Feed Science and Technology*, 107: 129-142.

Renteria-Flores, J.A., Johnston, L.J., Shurson, G.C. and Gallaher, D.D. (2008). Effect of soluble and insoluble fiber on energy digestibility, nitrogen retention, and fibre digestibility of diets fed to gestating sows. *Journal of Animal Science,* 86: 2568-2575.

Robertson, J.A. and Eastwood, M.A. (1981). A method to measure the water holding properties of dietary fibre using suction pressure, *British Journal of Nutrition*, 46: 247-255.

SAS, (2008). SAS User’s Guide: Statistics, Version 9.1. SAS Institute, Cary, NC, USA.

Tsaras, L.N., Kyriazakis, I. and Emmans, G.C. (1998). The prediction of the voluntary food intake of pigs on poor quality foods. *Animal Science*, 66: 713-723.

Wellock, I. J., Emmans, G. C. and Kyriazakis. I. (2003). Modelling the effects of thermal environment and dietary composition on pig performance: model testing and evaluation. Animal Science, 77: 267-276.

Wenk, C. (2001). The role of dietary fibre in the digestive physiology of the pig. *Animal Feed Science and Technology*, 90: 21-33.

Whittemore, E.C., Kyriazakis, I., Emmans, G.C. and Tolkamp, B.J. (2001a). Tests of two theories of food intake using growing pigs. 1. The effect of ambient temperature on the intake of foods of differing bulk content. *Animal Science*, 72: 351-360.

Whittemore, E.C., Emmans, G.C., Tolkamp, B.J. and Kyriazakis, I. (2001b). Tests of two theories of food intake using growing pigs. 1. The effect of a period of reduced growth rate on the subsequent intake of foods of differing bulk content. *Animal Science*, 72: 361-373.

Whittemore, E.C., Emmans, G.C. and Kyriazakis, I. (2003a). The relationship between live weight and the intake of 'bulky' foods in pigs. *Animal Science*, 76: 89-100.

Whittemore, E.C., Emmans, G.C. and Kyriazakis, I. (2003b). The problem of predicting food intake during the period of adaptation to a new food: a model. *British Journal of Nutrition*, 89: 383-398.

Chapter 6: General discussion, conclusions and recommendations

6.1 General discussion

Prediction of gut capacity using the physicochemical measurements of bulkiness is fundamental in the understanding of pig nutrition. The physical properties of feed components which define the bulkiness of the feed, and hence the amount of feed that can be consumed by growing pigs, are often ignored during feed formulations. It is crucial to determine the physicochemical measurements of bulkiness so that consumption of sufficient nutrients by growing pigs is achieved without restricting nutrients to achieve potential growth and reduce nutrient losses to the environment through excretion. Understanding the influence of bulkiness of feeds on feed intake solely depends on characterisation of physicochemical properties of feed ingredients.

The physicochemical properties and fermentation parameters of common fibre sources were determined in Chapter 3. The chemical composition, physical properties and fermentation parameters of feed ingredients varied widely. The variation in the physicochemical nature and fermentation parameters of feed ingredients indicated that monomeric composition and structural arrangements of building blocks is not uniform and might impose complex physiological effects on gut fill, digestibility and performance. To understand the influence of bulkiness on gut capacity, it is essential that a variety of fibre sources are used so that conclusions on relationships between intake and bulkiness can be made over a wide range of physicochemical properties. Saw dust was used in this study as an indigestible material that would impose the effects of a filler on voluntary feed intake.

The objective of Chapter 4 was to determine physicochemical properties of a feed that best describe the bulkiness of the feed, such that the gut capacity of weaner pigs can be predicted.

Based on the physicochemical analyses reported in Chapter 3, six fibre sources were selected. These were lucerne hay, maize cob, maize stover, sunflower husk, saw dust and vermiculite. The selection criterion was based on the difference of the chemical composition and range in their physicochemical measurements of bulkiness. For weaners, increasing the WHC, ADF and NDF content in the diet increased SFI up to an equilibrium intake, suggesting that the pigs increased intake to compensate for the digestible nutrient that were replaced by the indigestible fibrous ingredients. The maximum SFI indicated the gut capacity of the pigs. Weaner pigs have minimum abilities to digest fibres, hence, increase in WHC beyond the break point caused a decrease in SFI (Tsaras *et al.*, 1998, Whittemore *et al.*, 2001). The constraining effects of ADF and NDF could be a result of the masking effect imposed on digestible non-fibrous ingredients from enzymatic digestion. Pigs, therefore, attempt to consume more feed to increase the amount of nutrients available for digestion.

It was hypothesised that the relationship between physicochemical properties and SFI in weaner pigs would also be present in finishing pigs. In finishing pigs, WHC and NDF, ADF and bulk density could not be used to estimate gut capacity (Chapter 5). In these pigs, increase in WHC of diets caused a linear decrease in SFI, whilst increase in NDF and CF content decreased SFI up to equilibrium intake. These observations suggest that the mechanism with which physicochemical measurements of bulkiness influence gut fill in weaner pigs could be different for finishing pigs. A point of equilibrium intake was reached with increasing NDF and CF, suggesting that the finishing pigs could have developed mechanisms to cope with the physical bulk of the diets. The CP content of the diets was inversely proportional to CF and NDF contents. The quadratic increase in SFI as the CP content in the diet increased attest that increase in CP content increase the palatability of fibrous feeds. Alternatively, intake for diets with low CP content was inhibited, suggesting that other physicochemical properties of the feed limited intake. Research on the influence of stage of harvesting of fibre sources with high protein contents, such as lucerne hay, on gut fill can possibly provide plausible explanations.

In finishing, the reduced SFI as bulkiness increased could be ascribed to the development of gut organs of finishing pigs, particularly the enlargement of large intestines and caeca, which influence the behaviours of physicochemical properties of feeds during gut transit in a different way as with weaner pigs. The decrease in capacity for bulk in finishing pigs strongly suggests a link between size of the gut organs and body weight.

6.2 Conclusions

Fibrous ingredients have variable chemical and physical properties that additively influence feed bulk. In weaner pigs, WHC, ADF, NDF and bulk density of the food, allows a constrained feed intake to be predicted. A quadratic regression was found to provide an accurate description of when maximum SFI is reached that could be used to estimate gut capacity in weaner pigs using WHC, ADF and NDF. In finishing pigs, SFI decreased with increase in CF and NDF. The way in which physicochemical properties influenced gut fill in weaner pigs was different from that in finishing pigs.

6.3 Recommendations and further research

Physicochemical measurements of bulk provide predictive relationships describing changes in feed intake with bulkiness that could be used to estimate the gut capacity of growing pigs. Feed compounders should also consider the influence that physical properties of feed ingredients have on gut fill when formulating diets. If pig producers decide to make use of bulky ingredients when they are available at a reasonable cost, selecting fibrous ingredients with low WHC, such as maize cob and sunflower husks, is recommend for these impose minimum constraining effects on gut fill. Furthermore, due to lightness and fluffiness in most fibrous ingredients, pelleting the bulky feeds would help to reduce blockages in feeders and feed spillages. Feed formulation strategies involving mixing of fibrous ingredients with variable physicochemical properties are recommended to ensure that constraining effects of other fibrous ingredients with high nutrient values can be masked by those with low physical capacity for bulk.

There is need, therefore, for further research to characterize physicochemical properties of digesta in different sections of the gut. Furthermore, the capacities of compartments of the gut of growing pigs given fibrous feeds with a wide range of physicochemical properties need to be measured. These properties should be measured in conjunction with transit time within each section of the gut. Research on the effect of physicochemical properties of bulky diets on feeding, drinking and stereotypic behaviours of pigs is recommended to establish the effects of satiety levels on pig welfare. It is also important to assess the influence of feed bulk on water intake and nutrient excretion from a wide of variety fibrous sources.