Evaluation of Fibrous Feeds for Growing Pigs in Vietnam

Effects of Fibre Level and Breed

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Abstract

The aim of this study was to evaluate the effects of fibre level and source in the diet on the digestive physiology, growth performance and carcass traits of different genotypes of pig, and the efficiency of supplementation of an exogenous enzyme mixture to fibrous diets for weaned piglets.

The first experiment showed that the coefficient of total tract apparent digestibility (CTTAD) of nutrients in the diet was negatively affected by fibre level. Irrespective of fibre level, the local growing pigs (Mong Cai (MC)) had the highest CTTAD, followed by F1 (crossbred of Mong Cai and Yorkshire) and Landrace x Yorkshire (LY). Nitrogen retention versus nitrogen intake was negatively affected by fibre level. Nitrogen utilization and retention was highest for LY, lowest for MC and intermediate for F1. In the second experiment, the weight and length of the gastro-intestinal tract (GIT) were not different between MC and LY piglets at the age of 10 and 30 days but were higher for MC at 63 days. MC had longer caecum and colon+rectum than LY at 10 and 30 days. At 63 days MC had heavier visceral organs and GIT and longer intestines on fibrous diets than LY. The CTTAD of nutrients was lower for LY than MC, and for fibrous diets than for the control diet. Performance was lower for the sweet potato vine meal diet than other diets. In the third experiment, dry matter (DM) intake (g/kg BW0.75) was not affected by fibre level but was higher for MC than LY. The negative effects of fibre level on performance were seen clearly in the growing period, while effects were small in the finishing period. The MC had the lowest average daily gain (ADG) and highest feed conversion ratio, followed by F1 and LY. Carcass and dressing percentage was highest for LY and for the pigs given low fibre diets. The final experiment showed that the coefficient of ileal apparent digestibility (CIAD) and CTTAD of nutrients in piglets given a high fibre diet was lower than those given a low fibre diet. The CIAD of nutrients and amino acids was similar between MC and LY but CTTAD of nutrients was lower for LY than for MC. Supplementation of an exogenous enzyme mixture to a high fibre diet for piglets improved ADG, CIAD and CTTAD.

Keywords: Carcass traits, Digestibility, Digestive physiology, Enzyme supplementation, Fibre level, Fibre source, Growing pigs, Growth performance, Landrace x Yorkshire, Mong Cai, Piglets, Vietnam.

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Dedication

To my parents
My husband Nguyen Van Thuc
My son Nguyen Phi Hoang
My daughter Nguyen Thi Mai Phuong

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text

I Len, N. T., Lindberg, J. E. and Ogle, B. 2007. Digestibility and nitrogen retention of diets containing different levels of fibre in local (Mong Cai), F1 (Mong Cai x Yorkshire) and exotic (Landrace x Yorkshire) growing pigs in Vietnam. *Journal of Animal Physiology and Animal Nutrition* 91 / 2007, pp. 297-303.

II Len, N. T., Hong, T. T. T., Ogle, B. and Lindberg, J. E. 2008. Comparison of total tract digestibility and development of visceral organs and digestive tract of Mong Cai and Yorkshire x Landrace piglets fed diets with different fibre sources. *Journal of Animal Physiology and Animal Nutrition* (In Press).

III Len, N. T., Lindberg, J. E. and Ogle, B. 2008. Effect of fiber level in the diet on the performance and carcass traits of Mong Cai, F1 crossbred (Mong Cai x Yorkshire) and Landrace x Yorkshire pigs. *Asian-Australasian Journal of Animal Science* 21 / 2008, pp. 245-251.

IV Len, N. T., Ngoc, T. B., Ogle, B. and Lindberg, J. E. 2008. Ileal and total tract digestibility in local (Mong Cai) and exotic (Landrace x Yorkshire) piglets fed low and high-fibre diets, with or without enzyme supplementation. (Submitted).

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Abbreviations

AA	Amino acid
ADCG	Average daily carcass gain
ADF	Acid detergent fiber
ADG	Average daily gain
$BW^{0.75}$	Metabolic body weight
CF	Crude fibre
CIAD	Coefficient of ileal apparent digestibility
CP	Crude protein
CReM	Cassava residue meal
CTTAD	Coefficient of total tract apparent digestibility
DM	Dry matter
DMI	Dry matter intake
EBW	Empty body weight
EE	Ether extract
FBW	Final body weight
FCR	Feed conversion ratio
GE	Gross energy
GIT	Gastro intestinal tract
HF	High fibre
IBW	Initial body weight
LF	Low fibre
LY	Landrace x Yorkshire
MC	Mong Cai
ME	Metabolisable energy
MF	Medium fibre
NDF	Neutral detergent fiber
OM	Organic matter
RB	Rice bran
SPVM	Sweet potato vine meal

1 Introduction

Vietnam is located in South East Asia and is bordered by China in the North, Laos in the West, Cambodia in the South West and the Pacific Ocean in the East and South East. The total area of the country is 332 000 km^2, with a total population of 84 million, of which more than 54 million are farmers (GSO, 2006). Before 1989, Vietnam was a country that regularly experienced chronic food deficiency. Since 1990, however, the Vietnamese economy has developed rapidly owing to government policies that opened the economy and stimulated innovation. Since then, Vietnam has not only provided enough food for domestic consumption but has also become a major exporter of agricultural products such as rice, pepper, coffee etc. Currently, Vietnam is the second most important exporter of rice in the world after Thailand. Agricultural production contributes around 22% of GDP, of which animal production accounts for 22% of agricultural GDP (GSO, 2006). It is estimated that this value will reach 30% in 2010 and 35% in 2015 (Livestock Department, 2006). Although the GDP of agriculture in general and of animal production in particular makes up a relatively small proportion of total GDP, it plays an important role in the economic development of small-farmer families, who are the major part of the population of the country.

Although animal production in Vietnam has developed rapidly, it does not as yet meet the demand for animal protein for human consumption. At present, the average annual meat consumption per capita of the Vietnamese people is 34.3 kg (Livestock Department, 2006), whereas it was on average 88 kg in developed countries (FAO, 2003). Of the livestock species, pig production is dominant, as pork accounts for around 80% of total meat consumption (Livestock Department, 2006). More than 80% of the pig population in Vietnam is traditionally kept by small farmers, and pigs are usually integrated with rice and crop production (Lapar *et al.,* 2003).

Rearing pigs in the traditional system results in low production performance and revenues, but requires low investments, resulting in a low level of risk due to unstable pork prices.

There is a chronic shortage of animal feed in Vietnam, especially concentrate feeds, which explains why around 30% of feed materials are imported (Livestock Department, 2006), resulting in high prices of commercial concentrate feeds. This has a strong impact on pig and poultry production, because their growth performance depends primarily on the quantity and quality of concentrate feeds available. Therefore, in the rural areas, where farmers cannot afford to buy concentrates and commercial mixed feeds, agricultural by-products have become an important feed resource, in particular for pigs. Roughage feeds and crop by-products are used in almost all households for feeding pigs and at relatively high levels (Viet *et al.*, 2003). The combination of the high level of roughage and by-products such as sweet potato vines and rice bran has resulted in diets being very high in fibre. However, increased utilization of by-products, which are high in fibre content but which also have relatively high energy or protein contents, can be an alternative strategy to reduce feed costs and increase economic benefits. Various techniques, such as pelletting or/and supplementation of exogenous enzymes to diets can be applied to improve nutrient value and utilization of these feed resources (Brufau *et al.*, 2006).

During recent years, improved breeds of pig (Landrace, Yorkshire, Duroc etc.) have been found to be less suitable in extensive farming systems because they require high investment and are not well adapted to tropical climates and poor diets. Traditionally, the people in rural areas prefer to keep indigenous breeds such as Mong Cai, I and Ba xuyen because they are considered to be well-adapted to poor conditions of feeding, housing and management. In addition, indigenous breeds can meet the demand for meat with a higher fat content, which is generally preferred by people in the rural areas (Lemke *et al.*, 2002). However, nowadays as a result of the development of animal production in general and the improvement of living standards of rural people in particular, highly productive breeds have been introduced gradually to rural households and raised under similar feeding conditions as indigenous breeds or crossbreds (indigenous sow x exotic boar). This raises in number of issues: (1) different breeds probably have a different response to diets with respect to nutrient digestibility and growth performance, (2) the different breed responses could be related to differences in development of the digestive physiology and also the chemical composition of diets, especially dietary fibre level and fibre source, and (3) these responses can be changed by providing diets supplemented with additives such as exogenous enzymes.

Objectives of the study:

- To compare nutrient digestibility, nitrogen utilization, feed intake, growth performance and carcass traits of local (Mong Cai), F1 crossbred (Mong Cai x Yorkshire) and improved (Landrace x Yorkshire) growing-finishing pigs when given diets with different fibre levels.
- To compare the development of the gastro-intestinal tract and related visceral organs of local (Mong Cai) and improved (Landrace x Yorkshire) piglets before and after being given diets containing different fibre sources.
- To compare nutrient digestibility and growth performance of local (Mong Cai) and improved (Landrace x Yorkshire) weaned piglets when given diets with different sources of fibre, with and without supplementation of fibre-degrading enzymes.

Hypotheses of the study:

- Local (Mong Cai) growing-finishing pigs can utilize high fibre diets better than F1 crossbred (Mong Cai x Yorkshire) and improved (Landrace x Yorkshire) pigs.
- Mong Cai piglets have a larger gastro-intestinal tract and related organs and thus can utilize high fibre diets better than improved piglets.
- Fibre degrading enzyme supplementation to high fibre diets can improve nutrient digestibility at different sites of digestion (ileum and rectum) in Mong Cai and Landrace x Yorkshire piglets after weaning.

2 Background

2.1 Pig production in Vietnam

2.1.1 Numbers and distribution

Pig production plays very important role in livestock production in Vietnam, because pork contributes around 80% of total meat consumption (Livestock Department, 2006). The pig population in the country has increased rapidly in recent years, from 21.8 million in 2001 to 27.4 million in 2005, of which the breeding herd accounts for 14% and fattening pigs 86%. Average live body weight at market (6 months old) is around 63 kg, of which exotic breeds reach about 83 kg, crossbreds (local sows x exotic boars) 60 kg and local breeds 39 kg. The distribution of pig production varies between the different ecological regions, depending on socio-economical and other factors and also due to the meat consumption habits in the different regions. Table 1 shows the development of pig production in the main ecological regions and overall between 2001 and 2005 (GSO, 2006).

2.1.2 Production systems

Based on the number of animals raised and housing and management, pig production in Vietnam can be broadly defined and divided into three different systems.

Intensive system: This system has developed most rapidly in the last five years and now accounts for around 30% of total pork production (Livestock Department, 2006). In this system, by definition a farm markets at least 100 fatteners per year or maintains at least 20 breeding sows (GSO, 2006). Normally, this system is mainly located in the areas that are close to major towns or cities, particularly in the South East Lands and the Red River Delta, because of the higher per capita meat consumption in Ho Chi Minh and Hanoi City. In addition, owing to the government's open policies, joint-stock and private feed companies have invested heavily in pig production in these regions. The intensive system is based on the use of commercial feeds and advanced equipment, housing and management techniques. In addition, improved (exotic) breeds are normally reared, which also contributes to higher productivity.

Table 1. *Pig population (millions) and annual growth rate (%) for the whole country and the main ecological regions*

Region	Year					
	2001	2002	2003	2004	2005	Annual growth, %
Whole country	*21.77*	*23.17*	*24.88*	*26.14*	*27.43*	*6.0*
Red River Delta	5.07	5.40	6.76	6.90	7.42	10.0
North West Lands	4.72	4.92	4.24	4.39	4.57	-0.8
North East Lands	1.03	1.05	1.10	1.18	1.25	5.1
North Central Coast	3.35	3.57	3.80	3.85	3.91	3.9
South Central Coast	1.92	2.03	2.14	2.22	2.24	3.9
Central Highlands	0.91	0.95	1.33	1.49	1.59	14.9
South East Lands	1.85	2.10	2.07	2.40	2.62	9.1
Mekong River Delta	2.91	3.15	3.45	3.71	3.83	7.1

Semi-intensive system: This system is popular at household-level, especially in the Red River Delta, and recently the development of the system has been comparable to that of the intensive system. By definition, it includes farms which keep 10-20 sows or market 10 to 50 fatteners per annum (GSO, 2006). Feed sources are mainly agro-industrial by-products, which account for up 60% of the diet, with the remaining 40% coming from commercial feeds (Livestock Department, 2006). The most common breeds kept in this system are 3-way crossbreds (exotic x [exotic x local]) or 2-way crossbreds (exotic x local). Housing and management are of a fairly high standard in this system. Average market live body weight is normally 70-75 kg for fattening pigs. In common with the intensive system, the semi-intensive system requires investments and is strongly affected by variations in the price of pork in the markets, but is less sensitive to variations in commercial feed costs.

Extensive system: This traditional system has existed for thousands of years in Vietnam, and is found in rural areas throughout the country. The pig population in this and the semi-intensive system includes over 80% of the total pig population of the country (Lapar *et al.* 2003), but only accounts for about 70% of the total pork production (Livestock Department, 2006). Pig numbers range between 1 and 10 heads per farm, and production is integrated with crop production. The main characteristics of this system are an inefficient utilization of inputs and technologies, resulting in low productivity and incomes. This is generally the case of poor farmers, in particular ethnic minorities and those living in remote areas. The main feeds used in this system are based on locally available resources purchased in local markets or produced on-farm with low dietary nutrient value (Viet *et al.*, 2003; Lemke *et al.*, 2006). In addition, as the main breeds of pig raised in this system are indigenous breeds or F1 crossbreds between local breeds and improved breeds, typical growth rates of fattening pigs, especially in remote areas, are very low (136-177 g/head/day) (Lemke, *et al.*, 2006). However, where the households are located near to towns or have access to improved technology the productivity can be improved, as for example was shown by Peters (1998), who supplemented ensiled sweet potato vines and Loc *et al.* (1996), who provided protein supplements to cassava root silage based diets for growing pigs. In general, the productivity in this system is highly variable, according to the availability of local feeds, feeding and management system, breeds kept etc.

2.1.3 Breeds of pig raised in Vietnam

Indigenous breeds: In Vietnam, local pig breeds are very diversified, with about 60 genotypes categorized, distributed across the different regions of the country (Duc, 2006). The main characteristics of the indigenous breeds of Vietnam are small size and slow growth. However, they often have fairly large litter size, good meat quality in terms of taste, and especially good adaptation to local environments and management systems. They are kept mainly in the rural areas and their diets are based on agro-industrial by-products. Often these breeds are allowed to range freely and to find a high proportion of their feed from scavenging, especially in remote or mountainous areas. Local pigs constitute around 26% of the national pig herd and are mainly kept in the rural areas (Huyen *et al.*, 2005). However, in recent years a few genotypes have been promoted while others have almost disappeared. For example, the Mong Cai breed has been promoted the most widely in the North, and the Ba xuyen in the South, replacing other lower yielding local breeds. Compared to exotic breeds, Mong Cai pigs have lower carcass and lean meat percentage and higher back fat thickness (Thien *et al.*, 1995; Van *et al.*, 2000). Compared to other local breeds, Mong Cai pigs have superior reproductive characteristics and growth performance. Therefore, Vietnam has introduced programs for maintaining Mong Cai genes and extending the use of Mong Cai sows in the Northern and Central provinces for crossing with exotic boars. In general, the growth performance of the Mong Cai is very variable and depends on diet and farming system. Mong Cai pigs appear to have comparative advantages over exotic breeds when the need is to be able to consume large quantities of a voluminous feed such as duckweed (Rodriguez and Preston, 1996). Phuoc and Ngoan (2005) reported that the Landrace is more sensitive to changes in the external environment than the Mong Cai breed.

Improved (exotic) breeds: Animal production in Vietnam has been based on the utilization of local genotypes for a long time. However, because of their disadvantages with respect to slow growth, poor feed utilization efficiency and early onset of obesity, the improved breeds, which were introduced to Vietnam in early years of last century, are considered as a part of the government strategies to meet the increasing demand for high lean meat carcasses. The improved breeds imported to Vietnam include Berkshire, Landrace, Large White/Yorkshire, Duroc and Pietrain. However, in comparison to parent stock in the countries of origin, their performance in Vietnam has been 20 to 30% poorer, and the mortality higher (Ly, 1999). More recently, official non-government and government owned commercial companies and breeders' organizations have started to introduce higher-yielding exotic breeds to Vietnam. It is estimated that the population of exotic sows in 2005 was 372 000, and they accounted for 9.6% of the total sow herd in the country. The annual increase in the rate of exotic sow herds was 14.5% in the period 2001-2005 (Livestock Department, 2006). The proportion of exotic fattening pigs in the country was 17.8 % in 2005, and is projected to be 31.6% in 2010 and 40% in 2015.

Crossbreds of local sows and exotic boars: The F1 crossbred is the most common type of fattening pig in the rural areas throughout the country. Local breeds raised under improved conditions have lower performance than exotics, but under poor conditions of feeding, housing and management may be comparable to exotic pigs (Rodriguez and Preston, 1996). Therefore, local breeds have been partly replaced or crossed with exotic high yielding breeds to improve productivity. Artificial insemination (AI) was introduced to Vietnam in 1958 (Thien, 2002) to increase the number of crossbred herds. At the moment, the F1 crossbred of Mong Cai sow and Landrace or Yorkshire boar is the most popular type of fattening pig in the North, while the cross between Ba xuyen sow and Yorkshire or Landrace boar is more common in the South. The F1 offspring (1/2 blood from each local and exotic breed) is dominant in small-scale extensive and semi-intensive systems, while the F2 (3/4 blood from exotic and 1/4 from a local breed) is more common in medium-size and large farms. The main characteristics of crossbreds are better growth rates and higher carcass lean than indigenous breeds and better adaptation to poor feed and management conditions than purebred exotics. However, the productivity of crossbred pigs is very variable, depending not only on the type of cross but also on the feeding, housing and management conditions. Although current government policy is aimed at replacing F1 fattening crossbred pigs with purebred exotics, it is projected that F1 crosses will still account for around 55% of the total pig population in 2015, compared with 73% in 2005 (Livestock Department, 2006).

2.1.4 Feed resources used for feeding pigs in Vietnam

As mentioned previously, more than 80% of pigs are kept in the rural areas, and the availability and utilization of feedstuffs is very variable geographically. Farmers tend to use whatever is available and reasonably palatable, including commercial feed, crop products and by-products, kitchen waste and fresh forages. Based on their origin and chemical composition, the main feed ingredients used can be categorized into the different groups below.

Energy feeds: The most common energy feedstuffs used in Vietnam are maize, cassava root, sweet potato root and broken rice. However, although these contain high concentrations of digestible energy they are also important human foods, and increasing quantities of maize are used by the ethanol industry. Around 20% of the energy feeds for monogastrics in Vietnam is imported, mainly maize (Livestock Department, 2006), and the current high world market price of maize is reflected in the increasing cost of pig feed. Maize is ranked as the second crop in Vietnam (after rice) with a total production of 3.8 million tons/year (GSO, 2006). The government policies are aimed at increasing the area of maize cultivation and decreasing import taxes.

Cassava is the main cash crop of the small-scale farmers. Annually, Vietnam produces 6.6 million tons of cassava root, which is multi-purpose and used for human food, animal feed and starch processing. However, the utilization of cassava root is limited due to its low protein and high HCN contents. Several studies have been carried out in Vietnam on processing fresh cassava root at household level to improve its nutrient value and preserve it as animal feed for long-term use (Loc *et al.*, 1997), and results with respect to pig performance have generally been successful.

In addition to maize and cassava, sweet potato root also contributes considerable amounts of energy feed, especially at household farm level, where the sweet potato-pig system has traditionally been important in the rural economy (Peters *et al.*, 2005). As with cassava root, the nutritive value of sweet potato root can also be improved by different processing methods, as shown by Giang *et al.* (2004) and Peters *et al.* (2005).

Protein feeds: This group consists mainly of feedstuffs such as soybean meal and cake, groundnut cake, cottonseed cake and fishmeal. The domestic production of protein feeds in Vietnam is very limited, and 60-70% of the total consumption is imported, of which soybean meal accounts for 80% (USDA, 2006). Approximately 90% of fish meal in the animal feed industry is imported (Edwards *et al.*, 2004) and the imported fish meal is usually of higher quality but more expensive than that produced locally. Household level producers prefer to use local fish meal or fish silage because of their lower price. Local production of soybean seed is very low, only around 0.3 million tons/year (GSO, 2006), and this is used mainly for human food. At present, cottonseed meal, rubber seed meal, coconut meal and groundnut meal, which are local by-products after oil extraction, are non-conventional protein sources used to a limited extent in animal diets in Vietnam (Liem *et al.*, 2000).

Agro-industrial by-products: Agro-industrial by-products are one of the most important feed resources for smallholder pig production, especially in the rural areas. They include milling by-products (rice bran), food processing by-products (shrimp by-products, cassava residue and tofu residue) and alcohol processing by-products (brewers' grains and distillers' grains). The chemical composition of this group is very variable, and for example rice bran, cassava residue and brewers' grains have high fibre content, while the protein content in tofu residue and shrimp by-products, and the energy concentration in rice bran and cassava residue are relatively high. In several surveys on the utilization of feedstuffs in pig diets in rural areas, by-products from crop production occurred at the highest frequency, particularly rice bran (Viet *et al.*, 2003; Tra, 2003). The use of rice bran is very common because wet and rain-fed rice cultivation is practiced throughout the country. On average, Vietnam produces about 36 million tons of rice per year (GSO, 2006), resulting in about 3.6 million tons of rice bran. Cassava residue is a by-product from the processing of cassava root for starch. After processing, the proportion of starch to residue is about 1:1 (personal observation), and the residue has quite a high metabolisable energy content and high fibre content (2800 Kcal ME and 200 g CF/kg DM, NIAH, 2001). Processing cassava root for starch is carried out both on a large scale (in factories) and small scale (at household level). Utilization of cassava residue as animal feed contributes to the development of sustainable agriculture due to the decrease in pollution from the decomposition of the residue, which contains a high level of moisture (80%). Owing to its relatively high energy value, cassava residue meal is also used in the feed industry to reduce feed costs. Shrimp by-product is used as a protein feed for pigs (Ngoan *et al.*, 2001) and poultry (Dong, 2005). Other by-products, such as tofu residue from processing soy bean curd for human food, brewers' grains and distillers' grains are also valuable feed resources, as demonstrated by Dung and Uden (2002) and Dong (2005).

Forages: Cassava leaves, sweet potato vines, water spinach and water hyacinth are typical representatives of this class of feed. The main characteristics of this group are a high fibre content and sometimes a relatively high content of crude protein (Dung and Uden, 2002; Dung *et al.*, 2002). They are all commonly used in the rural areas at household or small farm level, but not by the animal feed industry. In the North, the use of fresh sweet potato vines (SPV) for pigs is more common than in the South. A survey published by Viet *et al.* (2003) showed that the roughage level in pig diets in the rural areas on average is more than 50%, and average provision of fresh SPV is around 4.5 kg/head/day (Peters *et al.*, 2005). Traditionally, the farmers plant sweet potato in their gardens and harvest the vines for their pigs on a daily basis. In addition, sweet potato vines can be collected as a by-product at harvesting time of the root then processed and preserved by ensiling or sun- drying for later use as animal feed. Similarly, in the regions where cassava is a major crop the leaves can be harvested and processed and used as a protein source, and the leaves of both cassava and sweet potato have been shown to be good protein sources for pigs (Phuc and Lindberg, 2000; An *et al.*, 2005). In addition, water spinach is a valuable protein feed for growing pigs and sows in the Mekong Delta (Men *et al.*, 2000). Phuc and Lindberg (2000) suggested that under tropical conditions, forage feeds can be supplied at low levels to increase dietary protein supply for growing pigs. According to Men *et al.* (2006), using water hyacinth to supplement to rice based diets increases the economic efficiency under household conditions.

2.2 Utilization of high fibre feeds by pigs

2.2.1 Definition and chemical and physical properties of dietary fibre

Many attempts have been made to define dietary fibre, but all definitions have their limitations because components of plant cell walls are variable and complex in chemical and physical composition and their metabolic effects. However, two definitions of dietary fibre appear to be useful: "the sum of lignin and polysaccharides that are not digested by the endogenous secretions of the digestive tract" (Trowell *et al.*, 1976, cited by Low, 1993) or "non-starch polysaccharides and lignin" (Low, 1993). However, the former definition combined both chemical and physiological aspects of dietary fibre and is not easily measured by practical analytical methods, while the latter may be a more practical definition and can be analysed by existing methods. It is most important when describing dietary fibre to understand its chemical and physical properties in as much detail as possible. There are several methods for analysing fibre that can be used to determine the fibre content in animal diets:

- Crude fibre (CF): The method to analyse CF content was developed many years ago as a way of measuring the indigestible fraction in animal feeds. Crude fibre consists mainly of cellulose and lignin, but their recovery is not always complete.
- Neutral detergent fiber (NDF): The method to analyse NDF content makes use of a neutral detergent solution to extract soluble components in the sample. The residue obtained after filtering contains hemicelluose, lignin and cellulose, of which lignin and cellulose are usually fully recovered but there may be some loss of hemicellulose.
- Acid detergent fiber (ADF): An acid detergent solution is used to extract the sample before filtering. The residue contains mainly cellulose and lignin, while almost all other components of the fibre fraction are lost during treatment.
- Non-starch polysaccharides (NSP): To analyse total NSP content, enzymic hydrolysis is applied to remove the starch from the sample. The residue is then subjected to acid hydrolysis, uronic acid determination and gas chromatographic determination of the component sugars.
- Soluble and insoluble NSP: Insoluble NSP is determined by extraction of the NSP fraction with phosphate buffer at neutral pH, followed by acid hydrolysis and gas chromatographic determination of the component sugars. Insoluble NSP is obtained by subtracting insoluble NSP from the total NSP content.

In practical animal nutrition, CF, NDF and ADF continue to be used, as well as NSP because there is a good negative correlation between them and the digestible and metabolisable energy content of the diet. However, in some comparative studies, the individual soluble and insoluble components gave a more accurate interpretation of the results obtained.

2.2.2 Effect of high fibre level in diets

The pig is a monogastric species, which does not produce endogenous enzymes to digest fibre. However, digestion of fibre can be achieved by including enzymes in feeds or by enzymes produced by intestinal bacteria, which are abundant in the large intestine. Therefore, pigs have different responses to high fibre feeds with respect to differences in digestive physiology, utilization of energy and nitrogen, feed intake, growth performance, feed efficiency and health status.

Effects on nutrient digestibility, size of digestive tract and utilization of nitrogen and energy in pigs

It is accepted that feeding high fibre diets tends to reduce nutrient digestion and absorption in pigs. The main explanations are that dietary fibre increases the flow rate of digesta, increases gastric and pancreatic secretions in the small intestine, enhances mucosity in the intestine, increases losses of endogenous nitrogen, and decreases nutrient absorption (Low, 1993; Varel and Yen, 1997). However, volatile fatty acids (VFAs), which are the end products of dietary fibre fermentation, can provide 15-24% of the total energy requirement of growing and finishing pigs (Dierick *et al.,* 1989)

Measurement of mean retention time (MRT) is a method for evaluating the flow of digesta, which is a factor affecting the digestion of nutrients. Retention time is assumed to be reduced when a diet contains a high level of fibre. The reduction in retention time is mainly caused by the higher viscosity and water-holding capacity of the digesta, and higher quantities of digestive juices being secreted when feeding high fibre diets. However, the effect of high fibre diets on MRT appears to be different between sites of the digestive tract, depending on level and fraction of fibre. Wenk (2001) indicated that an increasing fibre content in the diet led to reduced retention time in the colon, while in the precaecal digestive tract it was not influenced. In contrast, in other reports, daily flow rate of digesta at both small and large intestine was higher in pigs fed high fibre diets than that in those on diets with low fibre levels (Jørgensen *et al.*, 1996a; Wilfart *et al.*, 2007). Cherbut and Ruckebusch (1985) measured MRT in pigs fed diets with and without indigestible particles of polyethylene (2 mm in diameter), resembling grains of rice, and found that MRT was 94 and 129 h for diets with and without indigestible particles, respectively. Thus, a decreased MRT of digesta from high fibre diets in the small intestine could be an explanation for decreased digestibility at terminal ileum, while the decreased total tract digestion could have been due to decreased MRT in small intestine or/and in large intestine. This hypothesis is supported by the findings of Stanogias and Pearce (1985a) and Partanen *et al.* (2007) that increased levels of dietary fibre decreased the overall MRT of digesta, and consequently decreased ileal and/or total tract apparent digestibility of nutrients.

Mucus production is an index of the influence of high fibre diets on digestibility. Mucus contributes to the apparent thickness of the unstirred layer in the intestine and affords protection to the mucosal surface. However, if animals produce more mucus, it could reduce absorption rate and apparent digestibility. Several studies showed that fibre in the diet increases mucosal excretion at terminal ileum of pigs and rats (Mariscal-Landin *et al.*, 1995; Monagne, 2003). Goblet cells, which are the mucus producing cells in the intestine of monogastrics, increased numerically in a group of rats given a wheat bran diet compared to a group fed fibre-free diets (Schneeman *et al.*, 1982). In addition, the protein content in digesta of rats fed a wheat bran diet was higher than in those given a fibre-free diet, implying a slower rate of digestion and absorption of nitrogen in the animals fed the fibrous diet. Moreover, increase of mucus also implied a higher loss of endogenous nitrogen, and as a result apparent digestibility of nitrogen is depressed. This is supported by the findings of Lenis *et al.* (1996) and Schulze *et al.* (1994), who showed that addition of NDF to growing pig diets increased losses of endogenous and exogenous protein, causing a decrease of ileal and total tract digestibility of nitrogen and most amino acids.

The other mode of action of high fibre diets on digestibility is due to the fact that fibre can adsorb amino acids and peptides and withhold them from absorption (Sauer *et al.*, 1991). Moreover, fibre reduces the diffusion of digested products towards the mucosal surface owing to the high water holding capacity of fibre (Dierick *et al.*, 1989; Jørgensen *et al.*, 1996a) and increases the erosion of mucosal surfaces, leading to a loss of endogenous materials.

There is a close relationship between fibre level in the diet and digestibility and utilization of nitrogen and energy. As the level of fibre in diets increases, digestibility of nitrogen and energy decreases, particularly digestibility measured at terminal ileum (Reverter and Lindberg, 1998; Partanen *et al.*, 2007). The decrease in nitrogen digestibility is due to increased endogenous nitrogen loss and also exogenous nitrogen losses (Schulze *et al.*, 1994). As a result, the nitrogen content in digesta increases and apparent digested nitrogen decreases. This is confirmed by several reports. For example, Galassi *et al.* (2004) fed finishing pigs diets with high levels of wheat bran and beet pulp and showed that total tract apparent digestibility of nitrogen was 3.0 and 5.5% lower than on a control diet. However, the higher level of fibre in the diet did not increase nitrogen excretion in urine as much as in faeces, resulting in a compensation for the decrease in nitrogen utilization in terms of nitrogen retention versus nitrogen intake and digested nitrogen. The improvement of nitrogen retention and utilization in pigs fed a lucerne leaf diet compared to those fed a control diet (Lindberg and Cortova, 1995) was attributed to higher nitrogen consumption and a similar amount of urinary nitrogen. However, according to Kanengoni *et al.* (2002) addition of maize cobs to growing pig diets decreased not only nitrogen digestibility but also nitrogen retention. This is possibly due to the difference in nitrogen digestion between diets being larger than that for urinary nitrogen excretion, and consequently reduced nitrogen retention.

It is well known that fibre has direct negative effects on energy digestibility in pigs, and it can also affect energy metabolism. Firstly, a high fibre level in the diet has a disproportionate influence on the digestible energy value of diets because it reduces the digestibility of organic components (starch, protein, ether extract and dietary fibre). Secondly, because energy for fermentation by bacteria in the hind gut comes mainly from carbohydrates which are not digested and absorbed in small intestine, especially from non-starch carbohydrates. After being ingested, the fibrous components of the diet pass through the digestive tract and are fermented by bacteria to generate VFAs and gases (H_2, CH_4 and CO_2), which are lost by faecal excretion. It was found that methane is mostly generated in the hindgut, while hydrogen is produced in the small intestine (Jensen and Jørgensen, 1994). According to these authors, the production of methane increased from 1.4 l/day in animals fed low NSP diets to 12.5 l/day in those on high NSP diets. For animals given low fibre diets, energy loss was 0.2% of total digestible energy, while it was about 1.3% for those fed high fibre diets (Jørgensen *et al.*, 1996a). Similarly, results obtained from Noblet and Shi (1993) and Le Goff *et al.* (2002a) showed that methane lost by fermentation was linearly correlated to fibre level in the diet. Heat production is also affected by fibre level in the diet (Ramonet *et al.*, 2000, Le Goff *et al.*, 2002a) and there is a positive linear relation; consequently the net energy value of high fibre diets is reduced (Noblet *et al.*, 1994).

In almost all cases when pigs are given high fibre diets, the size of the gastrointestinal tract, particularly the large intestine, increases relative to that of pigs on low fibre diets. The mechanism of the increase is not clearly understood, although it is probably due to the prolonged presence of fibre in the gut stimulating an increase of mucosa weight and hypertrophy of the gut, which facilitates the development of bacterial mass (Eastwood, 1992), and/or due to the production of VFAs, which stimulate the development of the intestine (Montagne *et al.*, 2003).

Effects on feed intake, growth performance, feed efficiency and health in pigs

In general, the effect of high fibre diets on feed intake, growth rate and feed conversion efficiency is variable, depending on several factors, such as level of fibre, ratio of soluble/insoluble fibre, nutrient balance in the diet, feed processing method and age of the pig.

Naturally occurring fibrous feedstuffs have the main characteristics of low energy content, bulkiness and high water holding capacity (WHC). With respect to energy concentration, as the dietary fibre content of diet increases, the voluntary feed intake of pigs increases, as they try to maintain a constant metabolisable energy intake (NRC, 1998). With respect to bulkiness, fibre causes decreased feed intake because of the limitation of the capacity of the digestive tract and the WHC property of fibre. Both these mechanisms were confirmed in the study of Kyriazakis and Emmans (1995) on pigs given diets in which the basal diet was diluted by wheat bran, leading to decreasing digestible energy (DE) concentration in the diets with progressive dilution. The results showed that daily feed intake increased proportionally with progressive dilution between 0% and 50%, which would have been a result of energy compensation by the animals, and then inversely in proportion with progressive dilution between 75 and 100%, which would have been due to the limitation of bulkiness. According to these authors, the WHC of fibrous feeds can be one of the experimental criteria to characterise the bulkiness of feed and which may be responsible for their limiting feed intake. Whittemore *et al.* (2003) indicated that intake of high fibre diets was affected by the body weight of pigs and that for young pigs fed high fibre diets the daily and scaled feed intakes (g/kg body weight/day) were higher than in those on a control diet, but were not different for growing pigs.

In all cases of feeding high fibre diets to pigs, the increase of growth rate was found to be due to an increase of weight of digestive tract and digesta (Kyriazakis and Emmans, 1995; Whittemore *et al.*, 2003). Therefore, the measurement of carcass ADG gives a more accurate interpretation than of ADG with animals fed high fibre diets. This was confirmed by Jørgensen *et* *al.* (1996a), who showed that pigs given high fibre diets had higher daily gain than those on low fibre diets, but there was no difference between the two types of diet in the final weight or in daily gain when the body weight was corrected for gut-fill. Feed efficiency is directly affected by growth rate and feed intake and in all cases of feeding high fibre diets, feed conversion efficiency decreased, with the decrease being more pronounced in young pigs (Whittemore *et al.*, 2003).

Although high fibre diets are well known to reduce nutrient digestibility and growth performance, they can have benefits with respect to animal health, especially for weaned piglets (Hedemann *et al.*, 2006). Some components of dietary fibre may improve gut health and reduce diarrhoea in young piglets (Montagne *et al.*, 2003; Mateos *et al.*, 2006; Mateos *et al.*, 2007). The VFAs, which are the main products of fermentation are almost completely absorbed from GIT, and consequently stimulate the absorption of sodium with water from the colon (Montagne *et al.*, 2003), thus reducing the potential for non-pathogenic diarrhoea. Moreover, VFAs promote the proliferation of beneficial bacteria species, which can limit the development of pathogenic species (Bauer *et al.*, 2006). Adding fibre to the diet may also protect animals from gastric ulcers (Lee and Close, 1987; Montagne *et al.*, 2003).

2.2.3 Effect of fibre source in diets

Digestibility of high fibre diets depends very much on the botanical origin, especially on the fibre components in cell walls (Chabeauti *et al.*, 1991). Different feed sources have different levels and proportions of fibre components, such as lignin and soluble/insoluble hemicellulose (Graham *et al.*, 1985), cellulose and lignin (Dung *et al.*, 2002). In general, soluble fibre is better fermented than insoluble fibre (Bach Knudsen and Hansen, 1991; Montagne *et al.*, 2003). Soluble fibre consists mainly of pectins and to a lesser extent hemicelluloses, while insoluble fibre consists mainly of cellulose, lignin and hemicelluloses. As discussed previously, depressed digestibility of high fibre diets is partly due to decreased MRT, which is related to fibre origin. Decrease of MRT of digesta in pigs fed different fibrous diets has been shown by Freire *et al.* (2000). According to these authors, retention time and digestibility of an alfalfa diet decreased to a greater extent than other diets (wheat bran, soy bean hull and sugar beet pulp). Similarly, Le Goff *et al.* (2002b) indicated that pigs given a sugar beet pulp based diet had longer MRT and higher nutrient digestibility than those on diets based on wheat bran or maize bran. This could have been a result of increased fibre degradation in sugar beet pulp owing to the increase in retention time. It has been found that the lignin and NSP content was lowest in flour (maize, wheat), followed by bran (maize and wheat) and was highest in hull meals and grass and alfalfa meal (Bach Knudsen, 1997). In contrast, the starch content was highest in flour, followed by bran, and was lowest in hull and grass meals. The variation in the proportions of starch and the fibre components is the main reason for the difference in nutrient digestibility between different fibre sources, because almost all starch is completely digested in the small intestine, irrespective of diet (Andersson and Lindberg, 1997a and b; Zhang *et al.*, 2004; Högberg and Lindberg, 2004). In a review by Fernandez and Jørgensen (1986), it was evident that the different fibre sources depressed digestibility to varying degrees. Crude fibre which originated from cereals depressed energy digestibility to a larger extent than that from leguminous plants (2.1-3.5% vs. 0.5-2.2%, respectively). However, the decrease in energy digestibility influenced by NDF level showed a different trend, with a larger depression in leguminous plants than cereals (0.4-1.8% vs. 0.9-1.0%, respectively). It is difficult to interpret this difference because data quoted in the papers were results from different experiments with different objectives, experimental design and techniques. Chabeauti *et al.* (1991) found that the higher digestibility of energy and NSP in diets with soy bean hull (SBH) and sugar beet pulp (SBP) compared to that in a wheat bran diet could be related to differences in chemical composition and physical form of the plant cell walls. SBH and SBP contain higher concentrations of pectic substances, which are highly digestible, while cereals (wheat bran) are very poor in pectins (Graham *et al.*, 1985). Moreover, different fibre sources contain varying amounts of lignin. For example, wheat straw and wheat bran were found to be high in lignin (Agosin *et al.*, 1986), while lignin was low in SBH and SBP (Carre and Brillouet, 1986). Source of fibre was also a major factor influencing the length and weight of the colon in pigs, resulting in differences in fermentation capacity in the hindgut (Stanogias and Pearce, 1985b) and fermentation in the total gut (Wang *et al.*, 2004a & b; Christian *et al.*, 2006). Additionally, digestibility values of fibre fractions are variable among parts within a plant. For example, the digestibility of cellulose in whole wheat flour was 60%, while it was 24% in wheat flour plus pericarp and testa (Bach Knudsen and Hansen, 1991). According to Eastwood (1992) different fibre sources have different viscosities, which inhibits the access of nutrients to the epithelium and decreases the absorption of nutrients. Nitrogen utilization of fibrous diets is also affected by the nature of the fibre in the diets. For example, pigs given a sugar beet pulp (SBP) diet had higher utilization of digested nitrogen than those on soybean hull (SBH) or pectin residue diets, even though nitrogen digestibility in SBP was lower (Hansen *et al.*, 2006). With respect to growth performance, Freire *et al.* (2000) found that piglets fed a diet with SBH had 20% lower growth rate and 17% poorer feed conversion ratio than those fed diets with SBP, wheat bran and alfalfa meal.

2.2.4 Effect of age and body weight on the utilization of high fibre diets

Table 2. *Effect of age on digestibility of nutrients in pigs fed high fibre diets*

TTAD	CF level in diets			Source
	3%	**8%**	**16%**	Fernandez and
CF at 25 kg	36	39	32	Jørgensen, 1986
CF at 78 kg	57	59	57	
GE at 25 kg	90	85	74	
GE at 78 kg	92	88	79	
	4.1%	**10.8%**	**10.5% + oil**	Noblet and Shi (1994)
CF at 45 kg	45	36	41	
CF at 100 kg	48	46	47	
GE at 45 kg	85	72	75	
GE at 100 kg	87	75	77	
CP at 45 kg	84	69	73	
CP at 100 kg	88	75	77	
	2.7%	**4.6 %**		Le Goff *et al.* (2002b)
NDF at 33 kg	57	48		
NDF at 77 kg	59	54		
GE at 33 kg	87	79		
GE at 77 kg	89	82		

The ability of pigs to digest nutrients, especially fibre components, increases with age and body weight, and this is especially pronounced with diets with high fibre contents (Noblet and Shi, 1994; Le Goff *et al.*, 2002a; Noblet and van Milgen 2004). It is clear that the size of the gastrointestinal tract (total mass) of the pig is directly proportional to the age or body weight of the pig (Kyriazakis and Emmans, 1995; Whittemore *et al.*, 2003), and consequently the ability to store feed is increased, and this facilitates digestion. This is confirmed by the finding of Le Goff *et al.* (2002b) that the digestibility of a fibrous diet in finishing pigs was better than in growing pigs, because the MRT in finishing pigs was higher (37h vs 33h, respectively). However, the effect of age on the digestibility of high fibre diets can sometimes be negative if soluble NSP levels in the diet are higher than insoluble NSP (Jørgensen *et al.*, 2007). Moreover, improvement in the digestibility of dietary fibre has also been attributed to increased fermentation of bacteria in the hind gut of the pig. In piglets fed a high fibre diet the number of viable bacteria/g dry faeces increased with age (Varel and Yen 1997; Yen *et al.*, 2004). The effect of age or body weight and dietary fibre level on the digestibility of crude fibre, crude protein and energy is summarized in Table 2.

2.2.5 Effect of pig genotype on the utilization of high fibre diets

The ability to utilize dietary nutrients by different breeds of pig is variable between studies, depending on the genotype of pig and the dietary fibre level (Fevrier *et al.*, 1988; Fevrier *et al.*, 1992; Ly *et al.*, 1998). Different breeds have different potential for growth, which is a consequence of differences in their physiological characteristics, including digestive physiology (Freire *et al.*, 2003). In general, improved breeds have higher growth rate, lower daily feed intake, higher lean meat in the carcass and better utilization efficiency of feed than unimproved breeds (Renaudeau *et al.*, 2005; Renaudeau *et al.*, 2007). There are a number of factors that can influence the response of different pig breeds in digestibility of nutrients and growth performance when fed high fibre diets.

The first factor is the development of gut bacterial flora. Normally, the unimproved breeds (hereafter called local breeds) are raised mainly on bulky feeds from by-products and crop residues, and under poor conditions of feeding and management. As a result, development of bacteria in the gut of this type of pig is probably more stable than that of improved breeds. For example, Freire *et al.* (2003) found that local Alentejano pigs in Spain can digest fibrous diets better than improved pigs, and this was a result of enhanced enzymatic activities of the ceacal microflora, in particular xylanase and cellulase, which degrade the cell wall components. Also Varel *et al.* (1982) found that the initial population of cellulolytic bacteria in rectum of a lean meat breed was lower than that of an obese breed (76×10^7 vs 8.2×10^7 cells/g faeces, respectively). However, after 8 weeks of consuming a high fibre diet, the population was increased by 71% in the lean meat breed, while there were only small population changes in the lean breed fed a low fibre diet, and in the obese breed fed the low and high fibre diets. However, Ly *et al.* (1998) and Yen *et al.* (2004) were unable to detect any differences in digestion of a high fibre diet between local or fat type breeds and improved or lean type breeds. Thus, different pig genotypes had different responses to high fibre diets with respect to fermentation potential.

The second factor is the development of the size of the gastro-intestinal tract and related visceral organs. Several reports showed that local breeds have higher nutrient digestibility because they have a greater size of GIT expressed relative to body weight compared with improved breeds, particularly when given high fibre diets. For example, Fevrier *et al.* (1992) found that the Chinese Meishan pig has higher digestibility of nutrients than the Large White. Freire *et al.* (2000) and Freire *et al.* (2003) found that the higher digestive capacity of local Alentajano piglets compared with improved piglets was partly due to a higher capacity of the digestive tract in terms of weight and length. Jørgensen *et al.* (1996b) and Borin *et al.* (2006) also found a similar response of different chicken breeds fed fibrous diets.

Thus, the response of different breeds to high fibre diets varies between experiments. This may be related to differences in the experimental design. For example, in a comparison of digestibility between Meishan and Large White pigs fed a high fibre diet, Yen *et al.* (2004) found that the Meishan pigs had lower digestibility than the Large White, while the opposite was found by Fevrier *et al.* (1988). This difference could have been due to differences between the two studies in the diets, which were based on different fibre sources, and had different proportions of cellulose and hemicelluloses. In agreement with this Ndindana *et al.* (2002) and Kanengoni *et al.* (2002), with a similar experimental design and maize cob based diets, showed that local Mukota pigs in Zimbabwe had higher nutrient digestibility than Large White pigs.

2.2.6 Utilization of high fibre diets supplemented by exogenous enzymes in pigs

Pigs use enzymes produced either by themselves or by the microbes present in the digestive tract to digest feed. In general, diets with high fibre levels are associated with reduced digestibility of nutrients, as discussed above. The negative effect of high fibre levels in the diet on digestibility and performance is more pronounced in piglets. Normally, piglets have immature digestive systems, which may result in inadequate production of endogenous enzymes (Lindemann et al., 1986), and less development of bacterial flora (Graham et al., 1988). Indeed, Varel and Yen (1997) indicated that piglets have smaller populations of cellulolytic bacteria than older pigs when fed high fibre diets. Therefore, supplementation of exogenous enzymes, especially fibre-degrading enzymes, to high fibre diets in order to increase efficiency of digestion can be considered as a strategy to help animals utilize nutrients better. However, the effect of exogenous enzymes in animal feeds has been found to be inconsistent, mainly as a result of differences in experimental design between studies, such as concentration of enzyme (Högberg and Lindberg, 2004 ; Hahn et al., 2006), diet preparation

(Mavromichelis et al., 2000), the weaning age of the experimental animals (Dunshea et al., 2002), the composition of the basal diet (Li et al., 1996) and the number of individual enzymes (Chesson, 1993; Jensen et al., 1998).

The most common fibre degrading enzymes included in animal feed are ß-glucanase, cellulase, xylanase, hemicellulase and pectinase. In general, the mode of action of exogenous enzymes, including fibre degrading enzymes, is to break down anti- nutritional factors that are present in feed ingredients, or to break down specific chemical bonds which are not usually broken down by the host enzymes, and consequently to release nutrients to make them available for absorption or for the activities of host enzymes. In addition, exogenous enzymes can have indirect effects on the response of animals by reducing the viscosity of the digesta, and increasing nutrient absorption. This effect has been more pronounced in poultry. A basic understanding of the activity, stability and substrate specificity are very important in order to qualify the effects of exogenous enzymes in animal feeds. Because enzymes are protein molecules, they are influenced by pH, temperature and proteolytic enzymes in the digestive tract. Therefore, the stability of an enzyme preparation depends on the coating process as well as its proteolytic stability in situ (Morgavi *et al.*, 2000). The coating process is to facilitate secure passage through the acid pH and high proteolytic activity in the upper gastrointestinal tract, as well as to improve storage stability. Mascarell and Ryan (1997) found that some exogenous enzymes are working at a pH of 2-5 in the stomach and at pH 6-8 in the duodenum, with a constant temperature of 38-40^{0}C. Enzymes used in animal feed are almost all of microbial origin, either fungal or bacterial. It has been shown that fungal enzymes require a pH below 5 for optimal activity, while bacterial enzymes require a pH closer to neutrality (Mascarell and Ryan, 1997).

The positive effect of supplementation of fibre degrading enzymes on nitrogen digestibility is explained by the liberation of carbohydrate-bound protein, which otherwise is probably unavailable for the animal and excreted, either directly or after bacterial catabolism. Therefore, with cellulase supplementation of pig diets, a significant increase in the digestibility of NSP and AA was found, of 16.7% and 4.4-9.4%, respectively (Dierick and Decuypere, 1996). Thus, the improvement in AA digestibility could be largely a result of the release of fibre-bound nitrogen. Similar results were reported by Li *et al.* (1996) and Baidoo *et al.* (1998).

3 Summary of materials and methods

3.1 Experimental sites

All the experiments were conducted at the Experimental Farm of the National Institute of Animal Husbandry. The farm is located 15 km from the centre of Hanoi City. Monthly average temperature of the area was 27-28^{0}C (Paper I), 17-21^{0}C (Paper III), and 25-28^{0}C (Paper II & IV), and corresponding monthly average relative humidity was 76-81%, 72-80$^{\%}$ and 81-82$^{\%}$, respectively.

3.2 Experimental diets

Paper I: The experimental diets were formulated to contain three different levels of NDF (Low fibre - LF; medium fibre - MF and high fibre - HF, corresponding to 200, 260 and 320 g NDF/kg DM). The diets were equalized in metabolisable energy (ME, 13.2 MJ/kg DM) and crude protein content (CP, 170 g/kg DM). In Paper II there were four experimental diets: Control diet (basal diet without any fibrous feed) and three fibrous diets (basal diet plus rice bran (RB), sweet potato vine meal (SPVM) or cassava residue meal (CReM)). All the experimental diets were balanced in CP (205 g/kg DM) and ME content (14.6 MJ/kg DM). NDF content in the control and fibrous diets was 88.0 and 177 g/kg DM, respectively. There were two experimental diets in Paper III, with a low and high fibre level (200 and 300 g NDF/kg DM, respectively). Within each feeding period, ME and CP contents in both the diets were balanced to meet the requirements of NRC (1998) for growing-finishing pigs. The experiment in Paper IV had two experimental diets, with either low fibre (LF) or high fibre (HF) content, corresponding to 115 g and 200 g NDF/kg DM, either without or with a supplement of a mixture of exogenous enzymes. The enzyme mixture consisted of cellulase (9007 units/g), β-glucanase (5602 units/g), protease (922 units/g) and α-amylase (788 units/g). All the diets were equal in energy (15.0 MJ ME/kg DM) and CP content (233 g /kg DM).

All the experimental diets were based on maize meal and soybean meal. Fibrous feeds were cassava residue meal, rice bran, non-de-hulled groundnut meal, cassava residue meal, and sweet potato vine meal. The feeds were in powder form in the experiments in Paper I, II and IV and were pelleted into 3-4 mm lengths in Paper III. Chromium oxide was added at a level of 5 g/kg (as fed basis) to the diets in Paper II and IV.

3.3 Experimental design

In Paper I, the experiment had a 3 x 3 factorial arrangements with three breeds of pig (MC, F1 and LY) and three different diets (LF, MF and HF). Within breed, the experiment was conducted according to a double Latin Square. The experiment in Paper II was conducted using two designs. The first had a 2 x 3 factorial arrangement in which one factor was breed (MC and LY) and the second factor was age (10, 30 and 63 days). In the post-weaning period a 2 x 4 factorial arrangement was used, with 2 breeds (MC and LY) and 4 diets (C, RB, SPVM and CReM). In Paper III, the experimental design was a 3 x 3 factorial model with 3 breeds of pig (MC, F1 and LY) and 3 treatments (LF-LF; LF-HF and HF-HF, corresponding to the growing-finishing periods). The experiment in Paper IV was carried out according to a 2 x 2 x 2 factorial design, with 2 breeds of piglet (MC and LY), 2 diets (low and high fibre level) and 2 enzyme supplementations (with and without).

3.4 Animals, management and measurements

The experiment in Paper I included 18 castrated male pigs from three breeds, 6 of each: local (Mong Cai-MC), F1 crossbred (Mong Cai sow x Yorkshire boar) and exotic crossbred (Landrace x Yorkshire-LY) at an initial age of around of 3.5 months. The animals were randomly allocated into individual metabolism cages. The experiment lasted for 36 days and was divided into three periods of 12 days, of which 7 days were for adaptation and 5 days for collection. In Paper II, the experiment was conducted on two breeds, pure local (MC) and exotic crossbred (LY) piglets, with 10 litters of each. The piglets suckled normally between 1 and 10 days old, and then given free access to a commercial feed until weaning at an age of 30 days. At weaning day, within breed, 64 healthy piglets were selected and divided into 4 treatments and into 16 concrete floored pens, with each pen being considered as a replicate. The piglets in each treatment were balanced in litter origin, initial average body weight and sex. The animals in each treatment were offered *ad- libitum* one of the four experimental diets (C; RB; SPVM and CReM) until 63 days of age. The experiment in Paper III included 54 pigs from the same three breeds as in Paper I (MC, F1 and LY). The animals had a similar initial age of about 60 days. Within breed, 18 animals were allocated randomly into individual 1.5 x 0.5 m pens with concrete floors and divided into three groups of 6 pigs (3 males and 3 females). The animals in group 1 were fed a low fibre diet (LF) in both growing and finishing periods, while in group 2 diet LF and a high fibre diet (HF) were given in the growing and finishing period, respectively, and in group 3 HF was given in both periods. At the end of the experiment, four representative pigs (2 males and 2 females) from each breed in each group were slaughtered for measurement of carcass traits. In Paper IV, 32 piglets from each breed (MC and LY) weaned at 30 days old with an initial average body weight of about 4.6 and 7.6 kg, respectively, were allocated to 4 treatments and 16 pens (one male and one female per pen). Within breed, the pigs in each treatment were selected to have similar initial average body weight and were balanced for litter origin. The animals in each treatment were fed one of four experimental diets: LF with (LF+) or without (LF-) enzyme supplementation, or HF with (HF+) or without (HF-) enzyme supplementation.

In Paper II, III and IV the animals were fed *ad-libitum* throughout the experiment, except for the five first days of the experiments in Paper II and IV, in order to avoid post-weaning diarrhoea. In Paper I, the feed was given *ad-libitum* in the adaptation period and restricted to 80% of the *ad-libitum* intake in the collection period. Urine and faeces were collected totally and weighed twice per day, after the morning and afternoon meal (8.00 and 16.00h, respectively) during each 5 day experimental period. In Paper II and IV, the samples of faeces were collected for five consecutive days before the end of the experiment. The live body weight was determined in the morning after 12 hours fasting at the beginning and at the end of each experimental period and overall. The daily samples of faeces and urine were stored in a refrigerator at 4^0 C until analysis. All the animals in the studies had free to access to drinking water via nipple drinkers.

3.5 Slaughter

The animals were slaughtered by exsanguination after 12 hours of feed withdrawal, and hot carcass weight, hot dressed carcass weight, lean meat weight, back fat thickness, crude protein and ether extract content in loin lean meat of the pigs were determined at the end of the experiment (Paper III). In Paper II and IV, the piglets were killed after 4 hours fasting by exsanguination, and then eviscerated. The digestive tract was rapidly removed and segmented into different parts and the measurements of the full and empty weight and the length of the segments were taken (Paper II). Total digesta weight was calculated by subtraction of total empty weight from total full weight of digestive tract. Empty body weight (EBW) was calculated as live body weight at slaughter minus total digesta weight. The size of the digestive tract segments and visceral organs (liver, kidney and heart) was expressed relative to EBW. In Paper IV, after evisceration the ileal digesta were taken from ileum (about 100 and 80 cm of small intestine before the ileo-caecal ostium for LY and MC, respectively). The digesta samples were immediately transferred to plastic bags, and then frozen at -20 ^{0}C until analysis.

3.6 Chemical analysis

Analyses were carried out in the Laboratory of Analysis of Feed and Animal Products of the National Institute of Animal Husbandry. The samples of feed, faeces and ileum digesta were dried for 24 hours at 60^{0}C and ground to pass through a 1 mm sieve before analysis. Urinary samples were analysed in fresh form for nitrogen content. The analysis of chemical components (dry matter, crude protein, ether extract, organic matter and crude fibre, corresponding to OM, CP, EE, OM and CF) was done according to standard methods (AOAC, 1990). Neutral detergent fiber (NDF), acid detergent fiber (ADF) and lignin were analysed using the methods of Goering and Van Soest (1970). Gross energy content was determined using an automatic adiabatic bomb calorimeter (Gallenkamp, London, UK). Amino acids were determined by high performance liquid chromatography (Amino Quant, 1990). Chromium was determined by atomic absorption spectroscopy (NMAM, 1994).

3.7 Statistical analysis

The data were analysed using the Software MINITAB 13.31 (2000). The General Linear Model procedure was used for analysis of variance

(ANOVA) of independent and interaction factors. Tukey pair-wise comparisons was used to determine F-test at the significance level of more than 95% ($P<0.05$) to compare the differences between mean values.

4 Summary of results

4.1 Total tract apparent digestibility and nitrogen utilization of growing pigs: Effect of fibre level and genotype (Paper I)

For growing pigs, irrespective of genotype, as the level of NDF in the diet increased the total tract apparent digestibility (TTAD) of all nutrients decreased ($P<0.001$). On average, each additional 1.0 % unit of NDF in the diet resulted in mean decreases of 0.67 %, 0.75 % and 0.5 % units for TTAD of OM, CP and GE, respectively. However, the average decrease in CF and NDF digestibility with increased dietary NDF was smaller (0.43 % and 0.48 % units, respectively). Overall, there was a negative linear relationship between NDF level in the diet and TTAD of nutrients ($P<0.01$). There was a tendency towards a decrease of urinary nitrogen with increased dietary NDF ($P=0.065$). Nitrogen retention as a proportion of nitrogen intake was lowest in HF ($P<0.05$), while there was no difference between the three diets in nitrogen retention as a proportion of digested nitrogen.

TTAD of all nutrients was highest for MC, lowest for LY and intermediate for the F1 ($P<0.05$). The difference between MC and LY in TTAD of NDF and CF was higher than the difference between them in the TTAD of OM, CP, GE and EE (4.3 and 4.4 % versus 2.3, 2.5, 2.0 and 1.7 % difference, respectively). The regression lines for TTAD of OM and CP, LY had significantly steeper slopes than those of MC ($P<0.05$). The MC had the highest urinary nitrogen and lowest nitrogen utilization, while LY had the lowest nitrogen in urine and the best utilization of nitrogen, with intermediate values for the F1 ($P<0.05$).

4.2 Feed intake, growth performance and carcass traits of growing-finishing pigs: Effect of fibre level and genotype (Paper I and III)

For growing-finishing pigs, when diets were equal in CP and ME content, palatable and similar in bulk volume, the increase of NDF in the diet did not affect DM intake (DMI), irrespective of genotype. Therefore, the increase of NDF intake in HF was solely a result of the increase in NDF concentration in the diet.

During the growing period, there were no differences in average daily gain (ADG) between pigs fed LF and MF or between MF and HF (Paper I). However, ADG of pigs fed LF was significantly higher than of those fed HF (Paper I and Paper III); consequently feed conversion ratio (FCR) of HF was poorer than that of LF. During the finishing period, there were no significant differences in ADG and FCR between LF and HF (Paper III). Overall, ADG and FCR were similar between the animals in treatment LF-LF and LF-HF and were significantly better than those in treatment HF-HF ($P<0.01$). Similarly, the difference in average daily carcass gain (ADCG), which was calculated from measured carcass percentage at the end of the experiment, and estimated carcass percentage at the beginning of the experiment, had a similar tendency to the difference in ADG between the treatments.

Feeding the high fibre diet in both growing and finishing period decreased hot carcass and dressing percentage, while feeding HF in the finishing period only did not significantly affect carcass traits (Paper III). Back fat thickness, lean meat percentage and concentration of crude protein and ether extract in loin lean meat were not affected by feeding LF or HF throughout the experiment.

In both feeding periods in Paper III, MC had the highest nutrient intake (expressed as g/kg metabolic body weight, $BW^{0.75}$) the lowest ADG and the poorest FCR, followed by F1 crossbred and LY ($P<0.001$). The difference between breeds in ADCG was greater than the difference between breeds in ADG (MC had 44.9% lower ADCG and 40.4% lower ADG than LY). Carcass, dressing and lean meat percentage in LY was higher than in F1 and MC, while back fat thickness and ether extract content in loin meat of MC was highest, followed by F1, and was lowest for LY ($P<0.01$).

4.3 Feed intake, performance and nutrient digestibility of piglets: Effect of fibrous feed, enzyme supplementation and genotype (Paper II and IV)

For post-weaning piglets, different fibre levels (Paper IV) and different fibre sources (Paper II) did not affect DMI, expressed as g/kg $BW^{0.75}$ (P>0.05). In Paper II, the piglets given the diet with SPVM had the lowest ADG and TTAD, and poorest FCR. In Paper IV, an increase of NDF in the diet did not affect ADG and FCR of weaned piglets (P>0.05). However, the animals given HF had lower digestibility of OM, CP, EE, CF, NDF and ADF at both ileum and rectum than those given LF (P<0.05). Ileal apparent digestibility (IAD) of amino acids decreased in the piglets given HF.

Supplementation of exogenous enzymes in Paper IV, including fibre degrading enzymes, did not affect feed intake but improved ADG significantly (P<0.01) and numerically improved FCR of weaned piglets, particularly in the case of the HF diet. On average, the piglets fed HF with the enzyme mixture had 18% higher ADG and 10% better FCR compared to those fed HF without enzyme addition. Digestibility of nutrients at both ileal and faecal level increased (P<0.01) owing to supplemental enzymes. There was an interaction between fibre level and enzyme supplementation for IAD and TTAD of nutrients and amino acids (P<0.05). The effect of adding enzymes to the diet on IAD of amino acids showed a similar pattern to the effect on IAD of CP.

Irrespective of fibre level, fibre source and enzyme supplementation, MC piglets had higher DMI (g/kg $BW^{0.75}$) but lower ADG and poorer FCR than LY. In Paper II, among the three fibrous diets, intake of digestible NDF (DNDF) was highest for diet CReM, particularly for MC. The digestibility of nutrients was not different between MC and LY at the ileum in Paper IV (P>0.05), but total tract digestibility was higher for MC in both Paper II and IV (P<0.05). Similar to the results in growing pigs, the difference between MC and LY piglets for TTAD of CF and NDF was greater than the difference between the two breeds for TTAD of other nutrients

4.4 Development of digestive tract and visceral organs: Effect of breed, age and fibrous diets (Paper II)

Development of visceral organs: With respect to the effects of age, between 10 and 30 days old, for both breeds the relative weight (g/ kg EBW) of liver and heart was not significantly changed (P>0.05), while the weight of kidney was significantly decreased (3.0 and 1.8 g for MC and LY, respectively, P<0.05). Similarly, the weight of liver and heart was not different between 30 and 63 days old within breed, while there was a significant decrease in kidney weight for LY (1.2 g, $P<0.05$). Overall, between day 10 and day 63, the weight of liver and heart changed only slightly in MC, but significantly decreased in LY (5.0 g and 1.3 g, respectively), while the weight of kidney decreased in both breeds (3.2 g and 3.0 g for MC and LY, respectively).

When the weaned piglets were given the diets with different sources of fibre, the weight of visceral organs was not affected by diet but was significantly different between breeds, with heavier weights for MC ($P<0.05$).

Development of gastrointestinal tract: With respect to the effect of age, during pre-weaning the weight of the various segments of the gastrointestinal tract (GIT) was neither significantly different between breeds, nor between 10 and 30 days old ($P>0.05$), with the exception of the weight of caecum, which increased ($P<0.05$). However, there was a significant increase post-weaning of GIT segments ($P<0.001$), especially in MC, resulting in heavier weight of all segments for MC at 63 days old ($P<0.05$). In contrast to the development of the weight, the length of intestine (cm/kg EBW) declined with age in both breeds. At 10 and 30 days old, the length of small intestine and total intestine was not different between breeds but was higher for MC at day 63 ($P<0.05$). In general, the length of caecum and colon + rectum was greater for MC than LY ($P<0.001$). The decrease in length of small and total intestine in LY was higher than that in MC between 10 and 63 days (117 and 140 cm vs. 89 and 117 cm/kg EBW, respectively). In contrast, the decrease in length of colon + rectum was higher for MC than LY (28 vs. 24 cm/kg EBW, respectively).

There was an effect of diet on the weight of almost all parts of GIT post-weaning. In general, the weight of GIT parts in piglets fed the three fibrous diets was higher than in those on the low fibre diet ($P<0.05$), with the exception of the small intestine weight. Among the three fibrous diets, the weight of caecum in piglets fed SPVM was numerically lower than in those given RB and CReM, while the weight of stomach in RB was numerically higher than in SPVM and CReM. The length of colon + rectum was significantly higher in CReM than in the other diets ($P<0.05$). In general, MC had heavier weight and greater length of GIT parts than LY ($P<0.05$). There was an interaction between breed and diet with respect to the caecal weight and length ($P<0.01$), with no difference between breeds for SPVM, but heavier caecal weight for MC on diet C, RB and CReM, while there was no difference in ceacum length between breeds on diet C and CReM but a greater length for MC on SPVM and RB.

5 General discussion

5.1 Effect of fibre level and fibre source on nutrient digestibility, nitrogen utilization, growth performance and size of GIT and visceral organs

5.1.1 Effect on nutrient digestibility

It is well known that fibre components are not digested by the endogenous enzymes of monogastrics, while almost all other dietary nutrients are relatively well digested in the gastrointestinal tract. Digestion of fibre is attributed to fermentation by microflora in the digestive tract, especially in the large intestine. The extent of the fermentation in the gut depends on the characteristics of the fibre source, for example the ratio of soluble/insoluble fibre. In theory, the performance of growing and finishing pigs is not reduced if they consume adequate amounts of net energy, ileal digestible amino acids and other essential nutrients from high fibre diets. However, in almost all cases of feeding high fibre diets, this is not the case, because there are interactions between fibre and other nutrients, and consequently, animals have negative responses to high fibre diets through decreases in digestibility. The effects of different fibre levels in the diet on growth performance and TTAD of nutrients in post-weaning and growing pigs in the current study are summarized in Table 3. In general, the results obtained are in good agreement with previous studies that showed that adding fibre to the diet decreased ileal or/and total tract digestibility of nutrients (Schulze *et al.*, 1994; Lindberg and Cortova, 1995; Le Goff *et al.*, 2002a; Partanen *et al.*, 2007). There is no specific evidence to explain the current results. However, a possible explanation could be the well-known effects of fibre in the digestive tract of animals, such as decrease of retention time of digesta

(Jørgensen *et al.*, 1996a; Le Goff *et al.*, 2002a; Wilfart *et al.*, 2007; Partanen *et al.*, 2007) or/and the specific properties of fibre, such as high viscosity or high water holding capacity (Kyriazakis and Emmans, 1995; Whittemore *et al.*, 2003) or/and low degradability (Dung and Uden 2002; Dung *et al.*, 2002). The comparison of TTAD between post- weaning piglets and growing pigs fed a similar level of NDF in the diet (19 % NDF in HF and 20% NDF in LF for post-weaning and growing pigs, respectively) in the present study (Table 3) confirms that digestibility of nutrients increases with age or body weight. This result is in agreement with findings from previous studies that the ability of pigs to digest and utilize diets increases with age, particularly in the case of high fibre diets (Noblet and Shi, 1994; Le Goff *et al.*, 2002a&b). However, the TTAD of CF did not follow this rule (both piglets and growing pigs had a mean CF digestibility of 46 %).

Table 3. *Summary of the effect of different fibre levels on TTAD in post-weaning and growing pigs*

TTAD	Post- weaning*		Growing**		Decrease per %-unit increase in NDF in the diet	
	LF	HF	LF	HF	Post-weaning	Growing
OM	84.7	81.4	86.9	78.5	-0.41	-0.67
CP	81.6	78.1	81.9	73.4	-0.43	-0.73
CF	50.1	46.3	46.0	40.8	-0.37	-0.44
NDF	52.8	48.9	55.8	50.0	-0.45	-0.50
GE	81.7	77.4	83.9	77.9	-0.45	-0.51
ADG, g	257	236	653	589	-2.50	-5.47
FCR,	1.65	1.77	2.69	2.91	-0.01	-0.02
Digestible NDF g/kg DM	54	93	114	162	4.4	4.0

*Calculated from Paper IV (without enzyme supplementation) and Paper II: LF 10.2 % NDF; HF 19.0 % NDF; **Calculated from Paper I: LF 20.5 % NDF; HF 32.3 % NDF.

On average, the decrease in the TTAD of nutrients per %-unit increase of NDF in the diet was numerically higher for growing pigs than weaned piglets. This is probably mainly due to differences in the experimental design between the two studies, particularly with respect to feed ingredients and chemical composition of the diets. For piglets, the NDF content of LF and HF was around 10 and 20%, respectively, whereas it was 20 and 32 %, respectively, for growing pigs. Full fat soybean meal, powdered milk and extruded maize meal are feed ingredients which have quite high digestibility and these were included at a higher level in HF for piglets compared to HF for growing pigs. This could be an explanation for the lower negative effect of fibre on the digestibility of OM, CP and energy for piglets. Nevertheless, as the level of NDF in the diets increased, the amount of digestible NDF increased (4.4 and 4.0 g per %-unit increase of NDF, for piglets and growing pigs, respectively).

The effect of different fibre sources on the TTAD and growth performance of piglets was shown clearly in Paper II. Among the three fibrous diets, there was a tendency towards higher TTAD of nutrients for CReM, followed by RB and SPVM. This is probably related to differences in chemical composition, especially the composition of the fibre sources used to formulate the diets, although no detailed analyses of the composition of the different fibre fractions were carried out in the current study. However, differences in the lignin content in the diet could be a reason for the difference in digestibility, because according to van Wieren (2000) the negative effect of NDF on diet digestibility in pigs could be partly explained by the lignin concentration in the NDF, which was highest in the SPVM diet, followed by RB and was lowest in the CReM diet (14, 11 and 8 %, respectively). Moreover, the composition and properties of the fibre of cassava residue meal, rice bran and sweet potato vine meal could be comparable to those of sugar beet pulp, rice bran and alfalfa meals, respectively, because they originate from tubers, cereals and forages, respectively. Among these fibre sources, a sugar beet pulp diet had higher digestibility of nutrients than wheat bran and alfalfa diets (Freire *et al.*, 2000). In agreement with this hypothesis, Dung and Uden (2002) found that cassava residue had a higher degradation potential of nutrients than other fibrous feeds, such as rice bran.

5.1.2 Effect on nitrogen utilization

The effect of fibre level on nitrogen utilization in growing pigs was investigated in the experiment reported in Paper I. The results obtained are comparable to findings from previous studies that adding fibre to a diet increased the nitrogen excreted in faeces, and decreased both ileal and faecal nitrogen digestibility (Sauer *et al.*, 1991; Schultze *et al.*, 1994; Lindberg and Cortova, 1995; Dilger *et al.*, 2004). In the current study, increasing the concentration of NDF from 20 % to 32 % in the diet did not affect nitrogen retention as a proportion of nitrogen digested, but significantly decreased nitrogen retention as proportion of nitrogen intake, while increasing NDF from 20 % to 26 % did not affect nitrogen utilization at all. In general, in some cases of feeding high fibre diets, the negative effect of fibre on nitrogen retention was depressed because of decreased nitrogen excretion in urine (Scipioni and Martelli, 2001), and nitrogen retention and utilization was even increased in pigs fed a lucerne leaf diet (Lindberg and Cortova, 1995). However, this was not the case when feeding diets with an extremely high level of fibre (Kanengoni *et al.*, 2002), because the large decrease in nitrogen digestibility reduced nitrogen retention and utilization. In addition, losses of endogenous nitrogen were also found to be affected by protein level and protein source in the diet (Souffrant, 2001), which thus may influence the effects of dietary fibre on the retention and utilization of nitrogen.

5.1.3 Effect on growth performance and carcass traits

In general, the effect of dietary fibre on feed intake depends on the level and source of fibre (Kyriazakis and Emmans, 1995), especially with respect to energy concentration (NRC, 1998). In the current study, although fibre level was different between the treatments within experiment, all the diets were balanced in CP and ME, and consequently there was no effect of diet on dry matter intake for piglets and growing-finishing pigs. The fibrous sources used in the study were commonly available feeds, which are palatable and have been used in basal diets in numerous feeding trials with pigs. Moreover, all the diets were prepared in homogenous form (more than 85 % DM) with the same particle size and similar bulk volume, which is a very important factor affecting the capacity of pigs to consume feeds. The results in the current study are in agreement with previous findings by Jørgensen *et al.* (1996a), Freire *et al.* (2000) and Ndindana *et al.* (2002).

The effect of fibre on average daily gain depends on fibre level, fibre source and the age of the animals. As the results in Paper I show, although the MF diet had no effect on daily gain, feeding the HF diet to growing pigs reduced ADG. A similar result was found in Paper III, in that ADG and FCR of growing pigs fed diet LF were better than those on HF. However, when different fibre sources were fed to piglets, the SPVM diet negatively affected ADG and FCR, and to a larger extent than RB, while growth performance on the CReM diet was similar to diet C. Similarly, in Paper IV, ADG and FCR were not affected by feeding a diet with a high fibre level. This lack of effect of feeding a high fibre diet on ADG and FCR in some cases could have been due to an increase in digesta weight owing to the high water holding capacity of fibre in the GIT and/or an increase of GIT weight (Jørgensen *et al.*, 1996a; Whittemore *et al.*, 2003) and/or the specific degradation potential and chemical composition of the fibrous diets (Dung and Uden, 2002; Dung *et al.*, 2002). Thus, when the pigs were fed a high fibre diet for a long time the size of the GIT and digesta weight increased, leading to a decrease in carcass and dressing weight as a proportion of body weight (Paper III).

5.1.4 Effect on size of gastrointestinal tract and visceral organs

The effect of fibrous diets on the size of the digestive tract was investigated in Paper II. The results from this experiment support the conclusion in Paper III that feeding HF increased the size (weight and length) of the digestive tract, and consequently decreased carcass and dressing percentage. This finding is in good agreement with previous reports that pigs given a high fibre diet had heavier weight of GIT than those fed a low fibre diet (Stanogias and Pearce 1985b; Jørgensen *et al.*, 1996a, Pluske *et al.*, 2002; Freire *et al.*, 2003; Whittemore *et al.*, 2003). However, the effect of fibre on the size of the various GIT segments was different between the different fibre sources, especially for the weight of caecum and length of colon + rectum. This could have been related to differences in the physical properties of the fibre, which affect the retention time of digesta, as discussed by Bach Knudsen and Jørgensen (2001). In addition, the different fibre sources may result in a variable production of VFAs, which have direct effects on the growth of the gut. The caecum and colon are the main sites of fibre fermentation, and an enlargement of the caecum and colon is a common result of feeding high fibre diets. There was no difference between the fibrous diets and the control diet in weight and length of small intestine, which implies that fibre mainly affects the large intestine. However, effects of dietary fibre on the development of visceral organs were not found in the current study. This is in agreement with previous studies by Jin *et al.* (1994) and Ma *et al.* (2002).

5.2 Effect of breed on digestive physiology, nitrogen utilization and growth performance

It is generally believed that indigenous pigs can utilize high fibre diets better than improved breeds, because they have developed under poorer conditions of environment, feed and management for a long time. The Mong Cai (MC) pig, which is the most common indigenous breed in Vietnam, has been reared for many years by poor smallholder farmers. Therefore, it is commonly accepted that that MC pigs can perform better than exotic pigs on diets of extremely low quality and high fibre content (Rodriguez and Preston 1996). However, this was not completely confirmed in the current study, even though the evaluation of nutrient digestibility in Paper I, II and IV indicated that the MC digested nutrients, particularly the fibre components, better than F1 crossbred and LY, irrespective of fibre level and source. Although the MC had higher DM intake (relative to $BW^{0.75}$), ADG was lower and FCR poorer than in improved breeds, irrespective of diet. Also the evaluation of the development of the visceral organs and GIT indicated that the response of MC to high fibre diets was higher than that of LY, which further emphasised the inferior performance of the MC in terms of carcass gain. Moreover, the evaluation of diet digestibility and growth performance of the two breeds fed diets with and without enzyme supplementation showed that the MC had higher digestibility of nutrients than LY only at faecal level.

Table 4. *Summary of the effect of breed on digestibility and growth performance of post- weaning and growing pigs*

Item	Post-weaning				Growing		Difference between MC and LY			
	IADpw*		TTADpw*		TTADg		IADpw	TTADpw	TTADg	**
	MC	LY	MC	LY	MC	LY				
DOM	74.5	72.5	84.2	81.2	84.2	81.9	2.0	3.0	2.3	0
DCP	73.5	72.9	80.9	78.2	78.6	76.1	0.6	2.7	2.5	-2
DGE	–	–	79.5	77.0	82.1	80.1	–	2.5	2.0	0
DCF	16.7	16.5	50.6	44.6	45.5	41.1	0.2	6.0	4.4	17
DNDF	21.1	20.3	52.9	47.9	55.8	50.5	0.8	5.0	5.3	5
ADG, g	–	–	197	293	374	659	–	-96	-285	-
FCR, kg	–	–	1.91	1.56	3.3	2.51	–	0.4	0.8	-

* Calculated from Paper IV (without enzyme supplementation) and Paper II.
**From Borin *et al.* (2005): pw is post-weaning; g is growing

Although there was no interaction between breed and fibre level for TTAD of nutrients, the difference between breeds in TTAD of fibre components was higher than the between breed difference in TTAD of other nutrients (Table 4). However, the IAD of nutrients was not different between breeds, although there is no specific explanation for this result. The higher TTAD for MC could be mainly attributed to the difference between the breeds in digestion in the large intestine due to its larger size (weight and length) and/or higher number of bacteria in MC. No measurements of bacterial populations were taken in the current study but the greater size of the large intestine in MC piglets (Paper II) could be an explanation for the better digestibility in MC at faecal level. The results in Paper II are comparable to the findings of Borin *et al.* (2005) that growing MC pigs had higher TTAD of fibre components than LY when fed a diet with a high level of cassava leaves. However, according to the authors, there was no improvement of TTAD of GE, OM, CP and EE for MC compared to LY. The explanation for the difference between the two studies is possibly the difference in the diets and body weight of the animals used. In the study of Borin *et al.* (2005) the difference in body weight between LY and MC was 24.3 kg, while in the current study it was only around 7 kg for piglets and 10 kg for growing pigs. In addition, in the study of Borin *et al.* (2005) NDF level in the diets ranged between 348 and 378 g/kg DM, while in the current study it was 100 to 200 g/kg DM for piglets and 200 to 300 g/kg DM for growing pigs. Nevertheless, results from the two studies indicate that the MC had better digestibility of fibre components than the improved breed. The higher digestibility in MC compared to LY in the current study is comparable to the findings from previous studies, such as those of Fevrier *et al.* (1992) in a comparison between Chinese Meishan pigs and LY, Freire *et al.* (2003), who compared Alentejano (Portuguese) and Duroc x Landrace piglets, and Ndindana *et al.* (2002) in a study on Zimbabwean Mukota and Large White pigs.

Although the MC pigs had higher digestibility of CP than LY, their nitrogen retention and utilization were lower than LY. This is a result of the higher genetic potential of exotic pigs in terms of protein deposition, as confirmed by Kyriazakis *et al.* (1993), who showed that there was an interaction between breed (Chinese Meishan and LY pigs) and dietary protein content (low, medium and high) for protein deposition. According to these authors, the indigenous breed pigs fed a high protein diet had lower protein deposition than those fed a low protein diet, while the improved breed had superior deposition of protein on the medium and high protein diets compared to the low protein diet. The lower nitrogen retention and nitrogen utilization is related to the lower lean meat percentage and higher back fat thickness for MC than for F1 and LY (Paper III).

In general, ADG and FCR are proportional to diet digestibility in pigs. However, in spite of higher nutrient digestibility, in the current study ADG and FCR in MC were poorer than in LY, as a result of the genetic differences between the breeds. The better FCR in LY was due to the lower feed intake and higher ADG, which is a result of selection and improvement of lean meat lines. The current results are in accordance with findings from previous studies (Freire *et al.*, 2003; Ndindana *et al.*, 2002; Renaudeau *et al.,* 2005) on comparison of ADG and FCR between indigenous and improved breeds. The changes in the digestive tract and related visceral organs of MC and LY piglets in response to fibrous diets were investigated in Paper II. At 10 days, the sizes of almost all parts of the GIT and organs were not different between the two breeds, except for longer caecum, colon + rectum (relative to EBW) of MC. There is no specific explanation for this result, with the exception of different genetic characteristics. However, after 20 days of free access to concentrate feed, the weight of visceral organs had a tendency to decrease, while the weight of the GIT tended to increase in both breeds. This result is in accordance with the normal development of the digestive tract, as indicated by Adeola and King (2006). In other words, there was an effect of solid feed on the development of the GIT and this is probably related to mechanical stimulation (Cranwell, 1995). There was no difference in the size of the various sections of the GIT between the two breeds at 10 and 30 days of age, except for a greater length of colon + rectum in MC. Thus, both breeds had quite similar responses to creep feed before weaning. After weaning, there was difference in the change of weight and length of the GIT segments between breeds, and this can probably be attributed to the effect of diet. According to Cera *et al.* (1988), a higher proportion of nutrients is used for tissue development of the digestive organs compared to other tissues of the body and there is also an adaptive component of gut development associated with the amount of diet consumed (Kelly *et al.*, 1991a&b). The more rapid development of GIT (weight) in MC on fibrous diets explains its superior ability to consume and digest fibrous feeds.

5.3 Effect of exogenous enzyme supplementation to diets on digestibility and growth performance of weaned piglets

In the present study (Paper IV), the mixture of enzymes used included mainly fibre-degrading enzymes (cellulase and ß-glucanase) and improved nutrient digestibility at both ileal and total tract level, particularly in weaned piglets given the high fibre diet. This can be attributed to the enzyme preparation matching the substrates in the diet or/and the age of piglets. The positive effect of enzyme addition in the current study is confirmed by Chesson (1993), who concluded that multi-enzyme preparations are more effective than mono-enzyme preparations, and that a small amount of protease and amylase in the enzyme mixture could further improve nutrient digestibility. According to Mulder *et al.* (1991), the release of protein from the aleurone layer was improved with a preparation of multi-enzymes which contained a high concentration of enzymes active against cellulose and arabinonxylan. The multi-enzyme preparation in the current study, particularly the fibre-degrading enzymes, was targeted at the substrates in the diets, which resulted in greater improvement of nutrient digestibility in the high-fibre diet. Several previous studies indicated that the effects of exogenous enzyme addition on the digestibility of nutrients mainly occurs in the small intestine of young pigs, and thus enhances both ileal and total tract digestibility (Yin *et al.*, 2000; Yin *et al.*, 2001a&b).

6 General conclusions and implications

6.1 Conclusions

- The high fibre content in the diet had a negative influence on energy and nutrient digestibility in both piglets and growing pigs, and on nitrogen retention as a proportion of nitrogen intake in growing pigs. In addition, feeding high fibre diets increased the size of the gastro-intestinal tract of weaned piglets.
- Growth performance in growing pigs, carcass percentage and dressing percentage were negatively affected by the fibre level in the diet, while growth performance, back fat thickness, lean meat percentage (relative to dressed weight), and protein and fat content in loin meat of finishing pigs was not affected.
- Growth performance of weaned piglets was less affected by fibre level in the diet, and was influenced by fibre source. Cassava residue meal is a better source of fibre than rice bran and sweet potato vine meal in terms of growth performance and digestibility.
- Supplementation with an exogenous enzyme mixture improved digestibility and performance of weaned piglets, particularly those given a high fibre diet.
- Local Mong Cai piglets had higher digestibility of dietary nutrients than improved breeds, especially of fibrous components. Furthermore, the Mong Cai had a more rapid development of the size of the GIT, particularly of the large intestine, compared to exotic breeds when given high fibre diets.
- Irrespective of level and type of fibre in the diet, in comparison with improved pigs (F1 and LY) MC pigs had lower ADG, poorer FCR, higher feed intake (expressed as g/kg metabolic body weight), lower

6.2 Implications and further research

By-products and forages which are rich in fibre are sometimes the only feed ingredients available to smallholder pig producers, resulting in relatively high concentrations of fibre in the diet. The response of pigs to fibrous diets is different depending on factors such as fibre level, fibre source, and the age and breed of pig. From the current study, it is suggested that piglets can be fed diets containing up to 20% NDF with supplementation of fibre degrading enzyme mixtures, and results can be comparable to those on conventional diets. In practical pig production, the NDF concentration in the diet can range between 20-32 %, depending on the availability and price of fibre sources. However, diets at the high end of the range are more suitable for finishing pigs. High fibre diets are more suitable for indigenous breeds such as the Mong Cai than exotic breeds, particularly during the post-weaning and early growing periods.

The feeding extremely high fibrous diet and the interaction between fibre level and other chemical composition (metabolisable energy, crude protein and amino acids) in the diet should be further studied in different genotypes to evaluate their response with respect to feeding behaviour, digestive physiology and growth performance.

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