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FEED NOT FOOD: ALTERNATIVE FEEDSTUFFS FOR GROWING-FINISHING PIGS

A thesis presented in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

in

Animal Science

at Massey University, Manawatu, New Zealand

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GRADUATE RESEARCH SCHOOL

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The pandemic has directly impacted my ability to collect pig meat samples for quality analysis during the trial period for Chapter 4. Due to the second lockdown in New Zealand, I was unable to go to the slaughterhouse to obtain the samples for meat quality analysis. This analysis was critical to the research as the Lucerne diet was expected to achieve better meat quality, including reducing boar taint in pork.

Furthermore, the pandemic-related lockdowns and other restrictions significantly delayed my experiment schedule and slowed down my writing process, which extended the duration of my entire PhD research.

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ABSTRACT

Conventional diets used in the swine production sector, which rely heavily on soybean meal (SBM) and cereal grains, do not align with sustainable development goals. Hence, exploring alternative feedstuffs that are inexpensive, environmentally friendly, and do not compete with human food sources is essential to meeting future expectations around sustainability. As pigs are omnivores, they can efficiently convert many types of feed into a nutritious protein source for human consumption. Therefore, research and development in alternative feedstuffs for pigs are ongoing, and farmers are encouraged to adopt these options to enhance the sustainability of their operations. However, incorporating alternative feedstuffs in the diets of grower-finisher pigs requires proper risk management as they can contain high levels of insoluble fibre and other anti-nutritional factors that may affect pig growth performance, pork quality, and welfare.

This thesis aimed to investigate alternative ingredients for inclusion in growing-finishing pig diets. The first experiment (Chapter 3) examined the effect of replacing barley, SBM and soybean oil with dried distiller's grains with solubles, canola meal, wheat middlings and tallow on pig growth performance and meat quality. There were no negative effects of the alternative diet on overall pig growth or carcass performance, however, skatole levels of backfat were significantly lower in pigs fed the alternative diet.

The second experiment (Chapter 4) investigated the effect of lucerne as an ingredient in grower-finisher diets and as manipulable enrichment material on pig growth performance and behaviour. Feeding the lucerne diet reduced average daily feed intake, live weight gain, feed intake per feeder visit, and feeding rate, but increased feed efficiency. Despite these effects, overall performance was not significantly different between treatments when considering feed conversion ratio, final slaughter weight, dressing out percentage and backfat thickness.

The third experiment (Chapter 5) investigated the effect of replacing SBM with Poultry by-product meal (PBM) in growing-finishing pig diets on growth performance, carcass yield and meat quality. Four experimental diets were formulated, in which SBM was replaced with PBM at the increasing level of 0%, 33%, 77% and 100%. The diets were then fed to growing-finishing pigs. The results clearly demonstrate that PBM can be used as the primary protein source in pig diets without compromising the performance of growing pigs, as long as the diets are properly formulated to meet their nutritional requirements.

A meta-analysis (Chapter 6) was conducted to assess the impact of substituting SBM with alternative oilseed meal, including canola meal, camelina meal, cottonseed meal, sunflower meal and rapeseed meal, on the performance of growing-finishing pigs. The findings indicate that this replacement adversely affected pig's daily weight gain while maintaining daily feed intake, resulting in an increased feed conversion ratio for both growers and finishers. Furthermore, the use of alternative oilseed meals led to reducing carcass and loin yield, although there was no significant impact on meat quality. However, the heterogeneities of the analysis for most parameters were substantial, possibly due to the variation in the nutritive value of the alternative oilseed meal.

Overall, the results showed that substituting conventional feed ingredients with alternative feedstuffs had no or minor impacts on pig growth performance and meat quality. Additionally, several benefits of using alternative feedstuffs ingredients in growing pig diets were identified: reducing skatole in pork from entire males and improving feed conversion efficiency. The present research indicates that using alternative feedstuffs can be a viable option for pig feed, with possible benefits for pig production, meat quality and animal welfare.

The field of alternative feedstuffs for pigs has much to explore, with numerous undiscovered options, such as legumes, brassicas, insects, and by-products, which can offer valuable nutrients and support sustainable pork production. These alternative feedstuffs may have multiple benefits, such as improved gut utilization, support for pig health, lower production costs, and reduced environmental impact. Furthermore, using feed additives to enhance the utilization of low-nutritive-value alternative feedstuffs is a viable option. As such, further research should focus on integrating these feedstuffs into pig diets while promoting sustainable development.

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ABBREVIATIONS

AA	Amino acid
ADF	Acid detergent fibre
ADFI	Average daily feed intake
ADG	Average daily gain
ADL	Acid detergent lignin
AID	Apparent ileal digestibility
ANFs	Anti-nutritional factors
ATTD	Apparent total tract digestibility
BFD	Backfat depth
CDS	Condensed Distillers Solubles
CF	Crude fibre
CM	Canola meal
CP	Crude protein
CSM	Cottonseed meal
DDGS	Distiller's Dried Grains with Solubles
DE	Digestible energy
DM	Dry matter
EAA	Essential amino acid
EE	Ether extract
FCR	Feed conversion ratio
FM	Fish meal
GE	Gross energy
ME	Metabolizable energy
MUFAs	Monounsaturated fatty acids
NDF	Neutral detergent fibre
NE	Net energy
NEAA	Non-essential amino acid
NSP	Non-starch polysaccharides
OM	Organic matter
PBM	Poultry by-product meal
PUFAs	Polyunsaturated fatty acids
RSM	Rapeseed meal
S	Sulphur
SBM	Soybean meal
SCFAs	Short-chain fatty acids
SFAs	Saturated fatty acids
SFM	Sunflower meal
SID	Standardized ileal digestibility
UFAs	Unsaturated fatty acids
WDG	Wet Distillers' grain
WMD	Weight mean difference

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I.
INTRODUCTION

"End hunger, achieve food security and improved nutrition and promote sustainable agriculture." - ***The sustainable development goal 2***

Pork is the second most consumed meat worldwide, following poultry meat. It provides a high-quality protein food source for humans (Pereira & Vicente, 2013). Due to a fast-growing population, together with the improvement of living standards and expansion of urbanization, the demand for meat is increasing (Babinszky et al., 2019). These motivations encourage the development of pig production. Pork production is projected to increase by 25% during the next decade, accounting for 38% of global meat production growth (OECD/FAO, 2022).

Conventional diets for pigs are based on cereal grains and soybean meal (SBM) (Myer & Brendemuhl, 2004; Stein & Lange, 2007). Cereal grains are highly appetizing and digestible, rich in starch, supplying most of the energy to support growth, maintenance, and fat deposition. They generally account for 60-80 per cent of growing-finishing pig diets (Stein et al., 2016). Around 20 per cent of growing – finishing pig diets during the grower-finisher period comprises SBM. It is a popular protein source for pigs as it has a high protein level and an amino acid (AA) profile close to ideal for growing pigs to support building tissue, predominantly muscle (van Kempen et al., 2006). The complement of amino acids (AA) from SBM for cereal grain is believed to be the best formulation to maximize pig growth. Therefore, precision feeding using grains and SBM for pigs has been applied worldwide since the 1950s (Stein et al., 2016).

However, conventional diets for growing-finishing pigs may present sustainability challenges for the pig industry (Mottet et al., 2017; Myer & Brendemuhl, 2004). Pigs are considered as competitors of humans for staple food ingredients, while nearly 10% of people worldwide suffer from hunger (FAO, 2022a). Therefore, sharing human food with pigs counteracts Sustainable Development Goal 2 of the United Nations, which aims to achieve "zero hunger”. At the same time, using SBM as a universal protein source for animal feed goes against the sustainable management forest’s objective of Goal 15 because the high demand for SBM for animal feed drives soybean production, resulting in biodiversity loss and deforestation in high-volume soybean-producing countries in Amazon area (Lathuillière et al., 2017; Ritchie & Roser, 2021). Above all, the heavy dependency on a few sources of cereal grains and SBM makes the pig industry vulnerable to commodity price volatility, trade distortions and the accessibility of the feed source.

Furthermore, the pig industry has significant indirect impacts on the world's agricultural resources and climate change due to the use of conventional feedstuffs. A significant portion of arable land, approximately 85 million hectares globally, is utilized for growing crops to produce cereal grains and oilseed meals for pig feed (Mottet et al., 2017). Moreover, feed production for the swine sector substantially contributes to the water footprint since it involves intensive agriculture systems that require high levels of irrigation for cereal grains and soybeans, which serve as feed for pigs(de Miguel et al., 2015; Mekonnen et al., 2019). Therefore, the dependency on conventional feed for pigs indirectly puts pressure on using the limited cropland and freshwater resource on our planet. On the other hand, the primary source of greenhouse gas emissions in pig production comes from feed production and feed transportation (Basset-Mens & Van Der Werf, 2005; Van der Werf et al., 2005). Transporting imported feed contributes substantially to eutrophication, acidification and energy use (Van der Werf et al., 2005). Therefore, using local ingredients or other alternative feedstuffs for pigs is recommended to reduce the ecological footprints (Van der Werf et al., 2005).

In summary, the use of traditional feedstuffs in the pig industry poses significant challenges for producers seeking profitability and sustainable development. Therefore, it is apparent that there is a need for alternative feedstuffs to reduce competition for food with humans whilst being readily available and less expensive for pig producers, and friendly to the environment. These ambitions are feasible because pigs are omnivores. They are ideal biological organisms capable of converting many feedstuffs into high-quality animal protein for human consumption (Moon et al., 2004; Zijlstra & Beltranena, 2013). Historically, pigs used to scavenge human food leftovers and forage plants around villages (Lutwyche, 2019). The use of cereal grains and SBM does not come from pig necessity, but because of the human wish to maximize the productivity of pig farms based on existing knowledge. Many studies have attempted to find novel feedstuffs for pigs to replace conventional feed ingredients. Some research successfully provides evidence that modern pig breeds can be fed agri-industrial co-products (Zijlstra & Beltranena, 2013), food waste (Salemdeeb et al., 2017) or forage plants (B. Kambashi, C. Boudry, et al., 2014) without any impairment on growth performance, carcass traits and meat quality. However, there are still a vast number of alternative feedstuffs that are unutilised.

In addition, alternative feedstuffs commonly contain anti-nutritional factors (ANFs) that might impact pig production. Therefore, proper risk management must be applied when using alternative feedstuffs for pigs to ensure pig growth, animal welfare and profit. The investigations on the nutritive values of alternative feedstuffs and their effects on pig growth performance and carcass quality need to be published as references for farmers.

The alternative feedstuffs investigated in the present research included:

1) Co-products from biofuel production, food and oil processing: Distiller's dried grains with soluble, canola meal, and wheat middling. These co-products have been studied as feed sources for pigs for many years. The experiment in Chapter 3 aimed to increase the inclusion of these co-products in the finisher diet beyond the levels recommended in previous studies to maximize replacing conventional ingredients with co-products for pigs.
2) Forage plants: Lucerne (*Medicago sativa*), also known as alfalfa, has the potential to serve as a nutritious feed ingredient in pig diets and a source of roughage for the enrichment of grower-finisher pens. In Chapter 4, the inclusion of 10% lucerne in pig diets and the provision of lucerne chaff as enrichment material were supplied for pigs during the growing and finishing stages. This study aimed to investigate the effect of dietary fibre from lucerne on pig production and behaviour.
3) By-products from poultry processing: Poultry by-product meal is a potential protein source for pigs due to its availability and quality. However, a long-lasting ban on using poultry by-products in livestock diets has led to a lack of information on optimal inclusion levels and their effect on pig performance. In Chapter 5 of this study, poultry by-product meal was used to replace SBM in grower-finisher diets at increasing levels of 0%, 33%, 77% and 100%. The objective was to provide precise information on how PBM can be included in growing-finishing pig diets.
4) Alternative oilseed meals: Numerous studies have investigated the impact of substituting SBM with alternative oilseed meals on pig growth performance. However, many of these studies failed to incorporate alternative oilseed meals into pig diets. On the other hand, other studies have proved that including alternative oilseed meals in grower-finisher diets

did not have a negative effect on pig growth traits. The conflicting reports might result from the varying quality of oilseed meals, replacement levels, and growing stages of pigs. These different results can perplex farmers who want to include alternative oilseed meals in pig diets. To address these inconsistencies, Chapter 6 presents a meta-analysis that systematically reviews the effects of replacing SBM with alternative oilseed meals on growing-finishing pigs. The meta-analysis can provide more precise recommendations for farmers who are interested in incorporating alternative oilseed meals into their pig diets.

The goal of this thesis is to contribute new insights and information on alternative feedstuffs for pig diets, with the aim of advancing pork production towards sustainability. The thesis findings may serve as a foundation for further exploration of alternative feedstuffs, including their optimal inclusion levels and impact on pig performance, meat quality and behaviour. The results can also function as a catalyst for future studies on alternative feedstuffs for pigs. This research can provide valuable information for farmers on the benefits and limitations of incorporating alternative feedstuffs into their pig feed composition. By offering information on the potential sustainability benefits of alternative feedstuffs, this research can inspire farmers to explore new options for pig diets.

CHAPTER II.

LITERATURE REVIEW

2.1. Why use alternative feedstuffs for pigs?

2.1.1. Increasing pork demand

The demand for pork is inevitably increasing, driven by the rapid growth of the population and improved living standards. The burgeoning population has spurred increased demands for food (Chakraborty & Newton, 2011; Vos & Bellù, 2019) while improving living quality has boosted meat consumption (Boland et al., 2013; Henchion et al., 2014; Mottet et al., 2017).

Food is the most basic need for any living creature to provide energy and nutrients for its existence. Therefore, ensuring enough food for everyone on Earth is a fundamental precursor of humankind for a good life, as one of the UN's Millennium Development Goals. In 2021, the total population reached 7.8 billion; nearly one billion people have been added this century (OECD/FAO, 2022). The population is projected to increase to 9.7 billion by 2050 (UN, 2019). Therefore, food production will need to increase in the coming decades to feed nearly 10 billion people (UN, 2019).

Population size determines food requirements but improved living standards and lifestyle shift diets towards animal-based products like dairy and meat. This significant human diet replacement can obviously be seen in developing countries. For example, Vietnam's daily rice consumption declined from 458g/capita/day in 1985 to 373 g/capita/day in 2010 (Harris et al., 2020). Over the same period, meat consumption increased 8 times due to higher average incomes and population growth (Hansen, 2018; Harris et al., 2020). Globally, the average meat consumption per person increased by 25%, while total global meat consumption rose by 60% from 1990 to 2009 (Henchion et al., 2014). Moreover, expenditure on meat will likely continue growing in the future (OECD/FAO, 2020).

The nutrition transition occurs in developing countries as the population becomes wealthier and can afford more nutritious and flavourful animal-based foods. While plant-based foods often have lower levels of essential amino acids (EAA) and bioavailable minerals (Young & Pellett, 1994), animal-sourced foods are rich in high-quality protein and other essential micro-nutrients (Reig et al., 2013). Evidence shows that meat contributed to human evolutionary heritage (Stanford, 1999). As shown in Figure 2.1, pork accounts for the second highest proportion of meat production, even though much of the world's population does not consume pig meat due to their religious and cultural beliefs. The reasonable price of pork meat and its palatable flavour results in a highly desirable product for the customer (Resano et al., 2011)

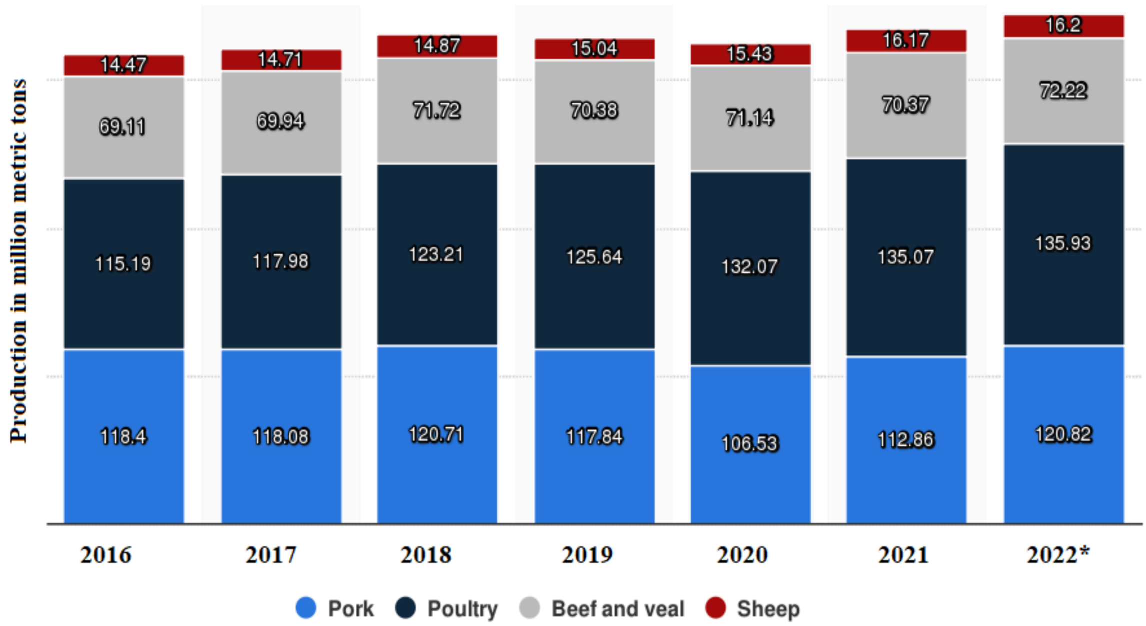

Figure 2.1. Production of meat worldwide from 2016 to 2022

** The data in 2022 were estimated*

Source: OECD/FAO (2022)

Furthermore, the popularity of pork production is related to the close relationship between human society and pig production (Bai et al., 2019; Lutwyche, 2019). With a long history of domestication, the pig is an important farmed animal as a source of income, employment, food, and fertilizer (Chauhan et al., 2016; Ebata et al., 2020). China, the greatest pork producer in the world, implemented a national "shopping basket program", which significantly increased pig production in the country (Bai et al., 2014). Over almost 60 years, pork production increased approximately 5-fold (Figure 2.2) (Mayorga et al., 2019). The annual world production of pig meat is over 100 million metric tons (OECD/FAO, 2022). Pig production is projected to continue growing in the next few decades with increases in population and the standard of living (Mottet et al., 2017; OECD/FAO, 2022).

Figure 2.2. Pig meat production per area across 60 years

Source: Mayorga et al. (2019)

2.1.2. Conventional feedstuffs for pigs are unsustainable.

2.1.2.1. Conventional feedstuffs for pigs

Diets for growing pigs are traditionally formulated using cereal grains (primarily maize and other grains) and soybean meal (SBM) (Myer & Brendemuhl, 2004; Stein & Lange, 2007). Table 2.1 illustrates a standard diet for growing pigs, where cereal often comprises up to 80% of a pig ration. The second largest proportion in growing pigs' diet is SBM.

Table 2.1. Example of conventional grower pig diets based on cereal grains.

Ingredient (%)	Maize	Barley	Wheat
Maize	74.48	—	—
Barley	—	83.27	—
Wheat	—	—	83.04
Soybean meal (dehulled)	22.21	13.62	14.01
Tallow	1.00	1.00	1.00
Limestone	0.85	0.85	0.85
Dicalcium phosphate	0.80	0.60	0.27
Trace mineral salt	0.30	0.30	0.30
Vitamin mix	0.10	0.10	0.10
L-Lysine•HCl	0.16	0.16	0.33
L-Threonine	0.05	0.05	0.05
DL-Methionine	0.05	0.05	0.05

Source: Carr et al. (2005)

a. Conventional energy source for pigs

Cereal grain has been cropped for thousands of years and is the dominant crop in world agriculture. Cereal grains, rich in starch, highly appetizing and digestible, supply the majority of energy in pig rations (Stein et al., 2016). Moreover, they also supply up to 60% of the amino acid (AA) requirements for growing pigs (Myrie et al., 2008). Maize, wheat, and barley are the most common cereal grain used as pig feed.

Maize (or corn) is the leading cereal grain fed to pigs worldwide, thanks to its availability and low market price, as illustrated in Figure 2.3. Having high starch concentration and starch that is likely almost 100% digestible, maize is one of the best sources of metabolizable energy (ME) among the grains for monogastric animals (McGhee & Stein, 2018; Stein et al., 2016; Wiseman et al., 1982). However, the crude protein (CP) concentration in maize is relatively low (McGhee & Stein, 2018). Moreover, maize protein is deficient in tryptophan and lysine, which are EAA for pigs (Baker et al., 1969). In addition, significant phosphorus in maize is unavailable as it is present as phytate (Lei et al., 1993). Therefore, maize-based diets for growing pigs require supplemental minerals and AA to meet requirements for optimal growth (Loy & Lundy, 2019).

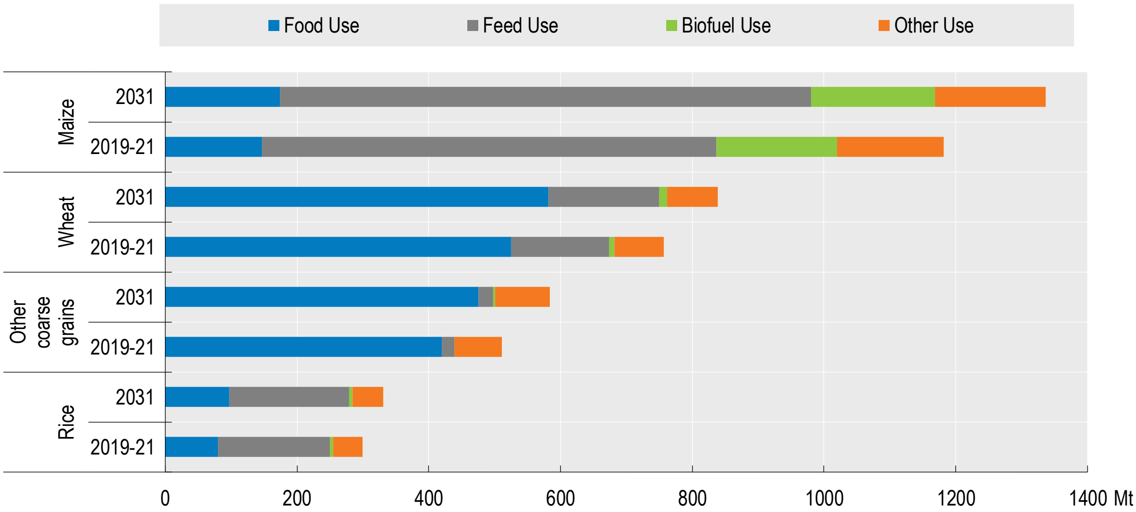

Figure 2.3. Worldwide cereal production and use in 2019-2021 and projected in 2031.

Source: OECD/FAO (2022)

Wheat is the second most commonly used cereal grain in pig feed after maize, with similar concentrations of starch, fibre, and energy. However, wheat has higher protein content and quality due to its better amino acid profile (Loy & Lundy, 2019; McGhee & Stein, 2018; Rosenfelder et al., 2013). Therefore, pigs fed wheat-based diets grew as fast and had equal meat quality as maize-based diets, providing that the two diets were formulated equally to meet requirements (Han et al., 2005). The decision to use wheat or maize is based on the cost of these ingredients. Wheat is generally more expensive than maize in the international market (Figure 2.3). Therefore, wheat is used as animal food mainly in the parts of the world close to where it is grown, such as Canada, Australia, and some Northern European countries, when the price gap between maize and wheat is close (Stein et al., 2016)

Barley is the fourth highest grain produced worldwide after maize, wheat and rice (OECD/FAO, 2020; Statista, 2019). While rice is commonly supplied for human consumption because of its high price (OECD/FAO, 2020), barley is the third most popular animal feed. CP and starch in barley are similar to that of wheat. The AA quality in barley is higher than in maize (Stein et al., 2016). Unfortunately, barley has a higher fibre content than wheat and maize, which results in lower metabolizable energy (ME) and standardized ileal digestibility (SID) of most essential amino acids (EAA) (Stein et al., 2016). Despite that, many researchers have shown that barley can be included in weaner, grower and finisher diets without negatively affecting pig growth performance (Stein et al., 2016).

Furthermore, the high presence of beta-glucans in barley benefits gut microbiota (Weiss et al., 2016).

b. Conventional protein sources for pigs

Feeding a diet based solely on cereal grain cannot sustain growth for growing pigs, especially the weaner diet, since protein quality is insufficient for optimum growth. Therefore, most cereal grain-based diets are supplemented with other types of protein-rich feed.

SBM is the most dominant protein source in pig diets because it has a high protein level and AA profile close to ideal for growing pigs. The use of soybean meal (SBM) in animal feed gained popularity following the European Commission's (EC) directive 999/2001, which banned the use of meat and bone meal in farmed animal diets as a measure to prevent infectious diseases. Nutritional values of SBM are relatively constant due to uniform processing conditions and homogeneous soybean varieties used in the process (Ferket et al., 2002). CP ranges from 48.3 to 52.1% on an as-fed basis, while the apparent ileal digestibility (AID) of CP is from 80.6 to 84.6% (van Kempen et al., 2006). The AID of AA is also very high, up to 90% (van Kempen et al., 2006). As heat treatment destroys antinutritional factors in the original soybean, such as trypsin inhibitors, saponin, and isoflavones, SBM is a safe feed source (Anderson & Wolf, 1995). However, the inadequacy of methionine, vitamin B, and unavailable phytate-phosphorous in SBM needs to be considered when including SBM in pig diets. SBM is rich in lysine, tryptophan, threonine, and isoleucine (Cho & Kim, 2011), becoming an excellent AA complement for cereal grains.

Before soya products were commonly used as a high protein source for pig diets, fish meal (FM) was historically used to supply protein for pigs (Asche et al., 2013). The nutritional value of FM is well documented by Cho and Kim (2011). FM is not only rich in protein but also energy and minerals. CP in FM ranges from 60 to 72%, dry matter (DM) basis, and AA profile is very favourable, making it an attractive protein source for pigs. While SBM is low in methionine, FM is abundant in this essential sulphur-containing AA (Cho & Kim, 2011). Additionally, FM is rich in vitamins, essential trace elements, and long-chain polyunsaturated omega-3 fatty acids. Including FM in the diets fed during the growing period can improve growth performance. Moreover, pigs fed FM had better meat quality, which was richer in omega 3 (Cho & Kim, 2011). Unfortunately, the soaring price of FM due to the lack of supply pushed pig producers to seek cheaper protein sources (Asche et al., 2013). On the other hand, a high concentration of FM in the grower-finisher diets causes pork rich in polyunsaturated fats and increases the intensity of off-flavour and rancid flavour after long storage (Jónsdóttir et al., 2003). In addition, fishmeal fed to pigs also potentially contains persistent, bioaccumulative toxic substances (Dorea, 2006). Therefore, FM is predominantly used in weaner diets as it positively affects the growth of weaners (Asche et al., 2013).

2.1.2.2. Issues related to conventional diets in the pig industry.

Traditional diet formulations for growing pigs based on cereal grains and SBM raise concerns about food security and environmental problems.

The three main uses of cereal grains are for human food, animal feed and biofuels (Figure 2.3). Animal feed accounts for one-third of worldwide cereal grain consumption (OECD/FAO, 2022). The use of grains as animal feed is projected to increase due to the increasing demand for food and animal protein, specifically by a growing population (OECD/FAO, 2022). Cereal grain consumption as animal feed is driven mainly by non-ruminant production, as ruminants can rely on forages and pasture for nutrition (Mottet et al., 2017). For example, cereal grains comprise 60-80% of growing pig diets (Myer & Brendemuhl, 2004). Mottet et al. (2017) estimated that it takes approximately 4 kg (DM) of human-grade feed (i.e., cereal grains, pulses, soybeans, and root vegetables) to produce 1 kg of boneless pig meat in industrial pig production systems in OECD countries. In developing countries, particularly China, intensive pig farming replaces the traditional backyard raising system, increasing demand for high-energy concentrate feeds (OECD/FAO, 2022). The inevitable expansion of pork production puts more pressure on the so-called 'feed-food' competition since pork is produced mainly from food that is edible to humans (Van Zanten et al., 2018). Meanwhile, over 820 million people worldwide still suffer from hunger, mostly concentrated in subregions of Africa, Latin America and Asia (FAO, 2019). With the rise of grain prices due to greater demands for cereal grain for food, feed, and biofuel, developing countries are more vulnerable to access food for their citizens through world trade.

Moreover, the universal use of SBM for animal feed drives soybean production, which raises concerns about the impact on the sustainability of the economy and the environment. Although SBM is the co-product of soy oil processing, only a small portion of worldwide soy is utilized directly for human consumption and other industries, while more than three-quarters (77 per cent) of soy is processed as SBM for livestock feed (Ritchie & Roser, 2021). However, most soybean production is produced in the USA and Brazil, accounting for more than two-thirds of global soybean production (Ritchie & Roser, 2021). Therefore, the world's livestock protein heavily depends on the leading soybean production countries. The expansion of soybean production indirectly impacts the tropical rainforest's deforestation (Lathuillière et al., 2017; Ritchie & Roser, 2021). At the same time, many countries heavily depend on exportation from the leading soybean production countries. Livestock production in these countries is impacted by SBM price volatility, trade distortions and the accessibility of the feed source (European Parliament, 2011). Covid-19 is a learned lesson of logistic disruption and increasing feed prices, which affected whole farm production due to the lack of feedstuffs and increasing feed prices (Hashem et al., 2020). Many countries are taking proactive actions to deal with protein feed concerns, such as The European Parliament called for research on substituting soy-based feeds with local protein sources to resolve the protein deficit in Europe (European Parliament, 2011).

Besides, using conventional feedstuffs for pigs consumes significant agricultural sources. The total global land producing cereal grain for pigs is 45.1 million ha (Mottet et al., 2017), which accounts for about 28% of worldwide cropland. Current feeding practice also causes a high water footprint of pig production (de Miguel et al., 2015; Mekonnen et al., 2019). The water footprint to produce meat is driven by conversion efficiencies, feed composition and feed origin (Gerbens-Leenes et al., 2013; Mekonnen & Hoekstra, 2012). Cereal grains and soybeans are typically produced in intensive agriculture that entails innumerable nutrients, irrigation water and arable land. The consumptive water footprint relative to grains and oilseed meals is 20,504 and 9,001 million m3/y, accounting for approximately 90% of the total water footprint of swine production in the USA (Mekonnen et al., 2019). Industrial pork production systems often rely on concentrate feed, which is typically composed of grains and soybeans, resulting in a high-water footprint due to the water required for the crop production used in the feed and the water used in the feed production process.

In addition, the environmental impact of the pig industry is raising public concern, particularly regarding its carbon footprint. Currently, feed production is the primary contributor to greenhouse gas emissions in pig production (Van der Werf et al., 2005) and pig excreta (Aarnink & Verstegen, 2007). Feed crop and feed production per kg pig comprised 54 to 73% of the total carbon footprint from pig production (Basset-Mens & Van Der Werf, 2005). With the impact of fertiliser for crop-based ingredients and feed processing, transporting feed contributes substantially to climate change, eutrophication of surface water, soil acidification and energy use (Van der Werf et al., 2005). Imported feed ingredients emit around 200 kg CO2-eq./1000 kg feed (Van der Werf et al., 2005). Thus, the use of imported SBM represents a potential for environmental damage. Using local ingredients for pigs, both edible and inedible feedstuffs, is recommended to reduce the ecological footprint (Van der Werf et al., 2005).

Finally, conventional diets for pigs are a significant economic input for growing-finishing pigs (Lewis et al., 2000; Niemi et al., 2010). Therefore, reducing feeding costs is a crucial preoccupation to enhance competitiveness for the pork industry. Unfortunately, the price of coarse grain and soybean products globally has fluctuated wildly and generally increased as the demands rise, as shown in Figure 2.4. Therefore, the inclusion of unstable price feedstuffs in pig diets brings pig producers a challenge to maintain profitability while handling the competitive pig world market.

Figure 2.4. Monthly cereals price index worldwide from January 2000 to August 2022
Source: FAO (2022b)

The pig sector has been a vital source of meat for humans and is projected to increase steadily due to population growth and higher living standards. However, traditional feedstuffs in the pig industry have created challenges for producers to gain high profits and respect a friendly environment. Therefore, it is apparent to request alternative feedstuffs that are inedible to humans, cheap for producers and pleasant for the environment.

2.1.3. Alternative feedstuffs for pigs: a sustainable solution for pig industry development

2.1.3.1. Pigs are suited to convert unsuitable food for humans into pork – evidence from pig biology and evolution.

Pigs are naturally omnivorous animals eating both plants and animals. "Omnivore" comes from 2 words of Latin: "Omni" means "everything", and "vore" means "swallow". Their unique digestive system allows them to digest various feedstuffs. In the past, pigs were raised as garbage disposers of humans.

Digestion and absorption occur over the whole digestive tract, illustrated in Figure 2.5 (Wenk, 2001). Feeds are digested mechanically and chemically. The feed structure is disrupted and combined with saliva in the mouth to form a bolus for easier swallowing. Next, the mass travels through the oesophagus to the stomach. The stomach squeezes, churns and mixes the bolus with gastric juice to form chyme (Heda & Tombazzi, 2020). Most digestion and absorption occur in the small intestine by digestive enzymes secreted from the pancreas and epithelial cells in the small intestinal wall (Wenk, 2001). Undigested feed components and endogenous secretions are moved down to the large intestine, then fermented by micro-organisms (Rérat, 1978; Wenk, 2001). The final beneficial products of fermentation in the hindgut are short-chain fatty acids (SCFAs). SCFAs are rapidly absorbed, metabolized by the intestinal epithelium, and enter the mesenteric vein (den Besten et al., 2013). SCFAs are substrates for metabolic energy production (Bindelle, Buldgen, et al., 2008; den Besten et al., 2013; Rérat, 1978). The energy produced from hindgut fermentation contributes substantial energy for the host but varies depending on feed ingredients, fibre type and age of the pigs (Rérat, 1978; Wenk, 2001). Anguita et al. (2006b) reported that the contribution of absorbed SCFAs to the total available energy for growing pigs of the low-fibre diet, the standard-fibre diet and the high-fibre diet were 7.1%, 13.6% and 17.6%, respectively. In other studies, Friend et al. (1964) reported higher values. The energy produced from acetic, propionic, and butyric acids in 30 kg live weight pigs was between 184 and 330 kcal daily, equaling 15 and 28% of the maintenance energy requirement.

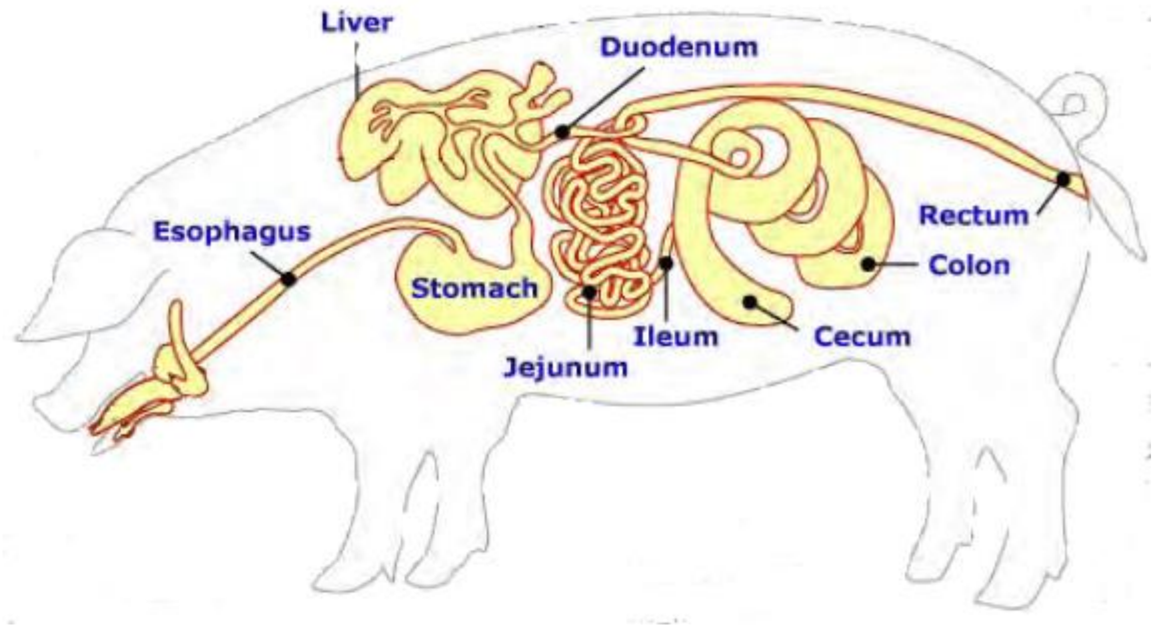

Figure 2.5. Pig digestive tract

Source: Wenk (2001)

On the other hand, pigs have traditionally been fed according to human decision-making and perspectives rather than their own biological needs and preferences. Historically pigs were domesticated and used to scavenge food (Lutwyche, 2019). This tradition is still kept in minority groups in some developing countries, where local pig breeds are raised instead of genetically improved high-performance breeds (Boro et al., 2018; Kumaresan et al., 2007), illustrated in Figure 2.6. Indigenous pigs adapt well to harsh conditions and poor-quality feeds (Lukić et al., 2020). Nowadays, pork is produced mainly through industrial systems (McGlone, 2013), in which pigs are produced in large and modern intensive farms (Bai et al., 2019; Lutwyche, 2019). Industrialized farms only rear genetically improved pigs selected for fast growth, with high lean meat and carcass yields. Precision feeding using grains and high-quality protein sources is applied worldwide to support high-performing breeds' nutrition requirements. However, recent studies have shown that modern pig breeds can be fed diets of low-cost materials without any impairment in their productivity, such as agro-industrial co-products (Zijlstra & Beltranena, 2013), food waste (Salemdeeb et al., 2017) or forage plants (B. Kambashi, C. Boudry, et al., 2014). Furthermore, moving pigs from indoor facilities to outdoor environments and allowing them to graze on pasture has generated customer interest in animal welfare (Früh et al., 2014). Few studies reported that grazing had no difference in growth performance compared with indoor pigs, however, the former exhibited better value in pork quality (Park et al., 2017).

Figure 2.6. A pig consuming food waste at a market in Jayapura, West Papua, New Guinea, Indonesia, in 2016

Source: Lutwyche (2019)

2.1.3.2. Alternative feedstuffs for a sustainable development

There is no official definition of alternative feedstuffs. In the chapter "Alternative feedstuffs in swine diets" of the book "Sustainable Swine Nutrition", Zijlstra and Beltranena (2013) only list alternative feedstuffs as co-products from food processing, biofuel and fractionation industries. In the current research, feeds are alternatives when a feed is inedible to humans (such as by-products and food processing waste) or produced from land unable to be used for other purposes (i.e., grass biomass from permanent grasslands where annual cropping is unfeasible), or feed that locally available but not regularly included in commercial animal diets due to undefined nutritional value and optimum inclusion levels. Therefore, alternative feeds are not necessarily inedible for humans but rather unsuitable. It is noted that the term "alternative" is relative, varying by geographical region and time period, making it confuse to distinguish between conventional and non-conventional feed ingredients.

Overall, the target of feed formulations for pigs is to maximize profit while optimizing pig performance (Niemi et al., 2010; Pomar & Remus, 2019). Alternative feeds are generally less costly than conventional feeds. Hence replacing expensive grains and SBM with cheaper alternative feeds possibly reduces feed costs (Woyengo et al., 2014). Since feed represents the largest expense in pig production, lowering feed costs can substantially enhance the profit margin for pig producers. Unfortunately, alternative feeds are not generally as nutritious as conventional feeds. Therefore, care must be taken when formulating diets with alternative feeds to prevent poor performance (Stein & Shurson, 2009; Woyengo et al., 2014). Recent advancements in feed technology have greatly improved the opportunities for using low-quality feedstuffs for pigs through enhanced feed quality evaluation and diet formulation, feed processing and feed supplementation (Hendriks et al., 2019). Therefore, it is possible to increase profit for pig production by replacing traditional diets with cheaper alternatives.

Using alternative feedstuffs for pigs addresses the argument that pigs compete with humans for food and reduce the environmental impact. Pigs are ideal biological organisms capable of converting human-inedible waste from crop production, food processing, and biofuel industries into high-quality animal protein for human consumption (Moon et al., 2004; Zijlstra & Beltranena, 2013). Therefore, alternative feedstuffs are a promising solution to mitigate the impact of waste on the environment. Moreover, consuming pork from pigs fed by-products might reduce land use per person, even compared to a vegan diet (Van Kernebeek et al., 2016). On the other hand, nutritious diets for pigs waste a considerable amount of undigested nutrients through excreta (Kornegay, Harper, Jones, & Boyd, 1997). These excretions significantly contribute to a pig farms' nuisance odour, eutrophication of surface waters, soil acidification, and global warming potential (Aarnink & Verstegen, 2007). Meanwhile, alternative feedstuffs often contain high fibre content, which might reduce nitrogen excretion, ammonia emissions, and concentrations of odorous compounds in manure (Jha & Berrocoso, 2016).

Applying a "feed not food" approach to pigs requires deep knowledge of pig nutrition and feed nutritive value. Alternative feedstuffs commonly contain anti-nutritional factors that might impact pig health, growth performance or meat quality. Therefore, proper risk management must be applied when using alternative feedstuffs for pigs to ensure pig welfare and farm profit. So far, many efforts have been conducted to find alternative feedstuffs for pigs. The nutritional value, inclusion level, effect on pig growth performance and carcass quality are investigated for many new feedstuffs. However, there are still many alternative feedstuffs that are undiscovered. More information about the nutritional quality and impact on growth performance and carcass traits of alternative feedstuffs is needed to investigate so that pig producers have more options to feed their pigs when conventional feedstuffs' market price fluctuates.

2.2. Alternative feedstuffs for pigs

2.2.1. Distiller's Dried Grains with Soluble (DDGS)

The enormous growth of biofuel production has occurred in the last two decades (OECD/FAO, 2019). The industry creates biofuel for green energy generation and produces valuable co-products for livestock feed (Cooper & Weber, 2012). While massive demand for biofuel directly affects feed market price, biofuel co-products that can be substituted for traditional feedstuffs mitigates price volatility (Farzad Taheripour, 2011; Taheripour et al., 2010). Approximately 30% of the total grain input for biofuel production is estimated to be converted into animal feed at the end process (Cooper & Weber, 2012). The co-product types formed depend on the specific agricultural inputs and biofuel refining processes. Originally, ethanol co-products were marketed for ruminant feed due to their high fibre content (Kalscheur et al., 2012). Recently, many studies have shown that pig and poultry can utilise ethanol co-products (Graham et al., 2014; Shurson et al., 2012; Stein & Shurson, 2009; Tsai et al., 2017; Wiseman et al., 2017; Yoon et al., 2010). However, the nutritive value of ethanol co-products varies according to raw material input and processing methods (Spiehs et al., 2002). As such, accurate determination of nutrient composition for the various co-products is required for effective use in pig diets.

DDGS is the dominant co-product of ethanol production. Ethanol from starch-based crops is produced by dry grind or wet mill processing. Only the starch portion of the grain kernel in both processes is fermented to produce ethanol, leaving other nutrients in their co-products, such as ash, protein, and fibre. While the dry grind process ends up with distiller's grains, wet milling generates gluten feed and gluten meal. Due to the lower capital requirement, the dry-grind process is predominant nowadays. Approximately half of distiller's grain produced is DDGS type which is convenient for handling, transportation, storage and shelf-life (RFA, 2020). Thus, DDGS dominates the other bio-fuel co-products in the market (RFA, 2016, 2020). According to the Renewable Fuels Association (2020), the world's leading ethanol-producing country, the USA, has produced around 35 million metric tons of distiller's grains and 4 million metric tons of gluten feed and gluten meal annually since 2010.

Conventionally, DDGS is produced by blending and drying after ethanol production (Figure 2.7). After distillation, the whole stillage portion is separated into wet distillers' grain (WDG) and thin stillage by centrifugation. The thin stillage is condensed at about 35–40% solids content by removing water using evaporators. At this point, it is called condensed distillers solubles (CDS). WDG containing 65–70% moisture is then blended with CDS. The mixture is dried in rotary drum dryers to produce DDGS with 10–13% moisture range. Many new and emerging technologies have been implemented to maximise the profit of biofuel production. These technologies include back-end extraction and front-end fractionation. The process to produce DDGS in back-end extraction is the same as the traditional process, except oil is extracted from thin stillage, resulting in low-fat DDGS. In front-end fractionation, germ and bran fractions are separated with endosperm removed from the fermentation process, resulting in a lower fat and fibre DDGS type. Moreover, the distillers' grains that remain after yeast fermentation in the front-end fractionation process are dried with steam instead of direct heat like the traditional process, which significantly affects AA content. The different ethanol technologies result in additional distillers' co-products with different nutritional profiles (Martinez-Amezcua et al., 2007; Saunders & Rosentrater, 2009).

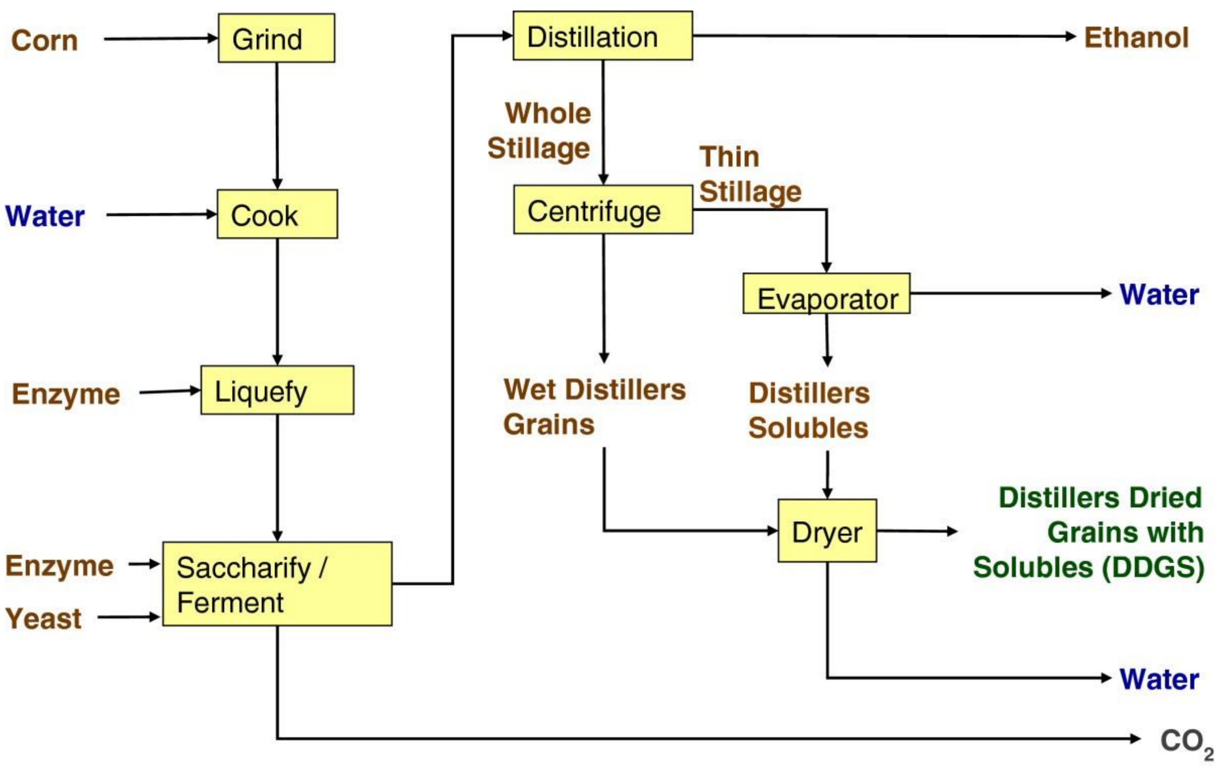

Figure 2.7. Conventional DDGS production

Source: Mumm et al. (2014)

2.2.1.1. Feeding value of DDGS for growing pigs

A high protein, minerals, and fat concentration is generally found in DDGS. However, the composition varies depending on the starting materials and ethanol production process.

Firstly, the nutritional properties of DDGS directly depend on their parent grains (Mustafa et al., 2000; Stein & Shurson, 2009), as shown in Table 2.2. Theoretically, components not extracted or utilized for the bioethanol process are recovered in co-products. In general, nutrients recovered in co-products are concentrated approximately 3-fold compared to the original grains due to starch removal during fermentation. The differences in nutritional composition among original grains result in the differences of those in their co-products. It can be seen in Table 2.2, DDGS derived from wheat has greater DM, CP, ash, and acid detergent lignin (ADL) but has lower OM and fat than maize DDGS, while DDGS from mixtures of wheat and maize is intermediate. This trend is the same when comparing DDGS produced from sorghum, maize and mixtures of sorghum and maize (Urriola et al., 2009).

Table 2.2. Chemical profile of wheat DDGS, maize DDGS and blended DDGS

Chemical composition	Wheat (W)	Maize (M)	Wheat DDGS	Maize DDGS	Blend DDGS (W:M=70:30)
Dry matter (g/kg)	895.2	887.7	937.6	914.4	916.1
Crude protein (g/kg DM)	142.8	101.3	393.2	320.1	368.2
Organic matter (g/kg DM)	978.8	982.6	948.8	956.7	949.1
Starch (g/kg DM)	603.5	634.1	63.2	43.8	39.9
NDF[1] (g/kg DM)	172.2	144.7	480.7	494.6	515.0
ADF[1] (g/kg DM)	36.8	36.6	109.9	146.8	108.0
ADL[1] (g/kg DM)	9.9	5.4	43.2	28.0	36.6
Hemicellulose (g/kg DM)	135.5	108.2	370.4	347.8	407.0
Cellulose (g/kg DM)	26.8	31.1	66.8	118.8	71.4
Ash (g/kg DM)	21.2	17.3	51.2	43.2	50.9
Calcium (g/kg DM)	0.7	0.2	1.8	0.5	1.5
Phosphorus (g/kg DM)	3.7	2.9	9.1	7.7	9.2

Source: Nuez Ortín and Yu (2009)

[1] *Abbreviation: ADF: Acid detergent fibre; ADL: Acid detergent lignin; NDF: Neutral detergent fibre*

As stated before, the nutritive value of DDGS dramatically varies depending on ethanol technology adoption. Innovation in the ethanol industry produces new types of DDGS with different nutritive characteristics. Oil extraction from thin stillage results in low-fat DDGS or de-oiled DDGS. As fat is removed, CP, fibre, and mineral concentrations in de-oiled DDGS are higher but contain less energy than traditional DDGS (Jacela et al., 2011; Saunders & Rosentrater, 2009). Front-end fractionation technology in the dry-grind method allows ethanol producers to remove bran and germ from the fermentation process resulting in higher fermentation efficiency.

A large concentration of oil in germ and fibre in the bran of grain kernel is removed from the fermentation process. Consequently, the new DDGS product, referred to as high-protein DDGS (HP-DDGS), has lower fat, starch and fibre content but greater concentration and digestibility of CP and each AA than traditional DDGS (Espinosa & Stein, 2018; Hart et al., 2019). In addition, the technique of drying distiller grain with steam instead of direct heat avoids heat damage of AA, especially lysine (Espinosa & Stein, 2018). Heat-free cold fermentation technique to produce a low-oil DDGS in some ethanol plants results in greater SID of CP and most AA than in conventional DDGS (Rodriguez et al., 2020).

Even in the same production facility, the nutritive content of DDGS is considerably different from batch to batch (Table 2.3). Kingsly et al. (2010) observed that the percentage of CDS blended in during the drying process causes a high variation in the nutritive value of DDGS. Adding CDS during the drying process increases the sugar, fat, and ash content while decreasing the protein, acid detergent fibre (ADF), and neutral detergent fibre (NDF) content. In addition, the nutritive composition of co-products varies depending on the extent of milling, the presence of chemicals from the manufacture, and the amount of yeast remaining from fermentation (Böttger & Südekum, 2018; Han & Liu, 2010). It can explain why the nutrient content of the same type of distiller grains among studies varies widely and differs from official standard reference values in NRC (Belyea et al., 2004).

Table 2.3. Chemical properties of DDGS from different batches of a biofuel plant

Chemical composition, g/100 g	Batch 1	Batch 2	Batch 3	Batch 4
Crude fibre	26.69	28.78	32.33	28.16
Fat	10.80	9.32	7.76	9.04
Ash	4.00	3.12	2.04	2.97
Acid detergent fibre	10.06	12.48	15.98	10.68
Neutral detergent fibre	33.18	39.96	44.49	34.56
Glycerol	7.61	6.01	3.08	5.85

Source: Kingsly et al. (2010)

2.2.1.2. Limited factors of DDGS for growing-finishing pigs

DDGS contains high levels of fibre (non-starch polysaccharides (NSP)), which are resistant to digestion in the small intestine. The fibre from parent grains remains during yeast fermentation and accumulates in the final co-products (Spiehs et al., 2002; Widyaratne & Zijlstra, 2007). The high content of NSP reduces nutrient digestion and absorption (Wenk, 2001). As a result, the digestibility of energy, CP, and most AA in DDGS is lower than in maize, wheat, and sorghum. For grower–finisher pigs, the apparent total tract digestibility (ATTD) of energy in maize DDGS is 76.8% compared with 90.4 % in maize (Stein & Shurson, 2009), or 77.4% in wheat DDGS compared with 84.8 % in wheat (Widyaratne & Zijlstra, 2007). The SID of AA in DDGS is 5-10% less than cereal grains (Widyaratne & Zijlstra, 2007). On the other hand, high fibre in growing pigs' diets might limit ME intake due to reduced feed consumption caused by earlier satiety and greater endogenous energy losses resulting from more digestive fluid secreted (Wenk, 2001). Generally, the current Digestible Energy (DE) and Metabolizable Energy (ME) systems may overestimate the energy value of ingredients high in protein and fibre, which can lead to inadequate net energy supply for growth (Noblet & van Milgen, 2004b).

The other limitations of DDGS could be due to high oxidized lipids. DDGS produced from grains rich in oil, such as maize, typically contains high concentrations of unsaturated fatty acids (UFAs). The drying temperature and UFAs combination cause high lipid peroxidation levels in DDGS. Song et al. (2011) reported that the thiobarbituric acid reactive substances in DDGS could reach 25 times higher than that of maize. Secondary lipid peroxidation products result in lost nutrition, reduced shelf-life, impaired animal health, and reduced growth performance (Boler et al., 2012; Dibner et al., 1996). Therefore, antioxidants should be supplied in DDGS-based diets to minimize oxidation. Song et al. (2014) found that increasing vitamin E concentrations in diets containing highly peroxidised DDGS improved feed conversion in growing pigs.

Furthermore, the presence of sulphur (S) in DDGS comes from sulphuric acid added during dry-grind ethanol production and the concentration of natural S in cereal grains is a limiting factor. Although S is an essential mineral for animals and serves many important biological functions in the animal body, excessive inorganic S in growing pig diets may cause gastrointestinal epithelium damage and odour emission from pig manure (Attene-Ramos et al., 2010; Canh et al., 1998). However, Kim et al. (2012) reported no effect of S in DDGS on feed preference or growth performance of weanling or growing-finishing pigs. The concentration of S in DDGS may benefit growing pigs fed diets containing highly peroxidized DDGS (Song et al., 2014; Song et al., 2013). Little is known about the effect of S in DDGS on growth performance, carcass yield and meat quality.

Another challenge of using DDGS for growing pigs is the presence of mycotoxins. Grower pigs fed mycotoxin-contaminated feed experience growth depression and health problems (Richard et al., 2003). Mycotoxins in DDGS come from the contaminated parent grains. Like other cereal grain components, mycotoxin concentrates in DDGS during production (Bennett & Richard, 1996; Zachariasova et al., 2014). Mycotoxins could be slightly decreased during drying to produce DDGS (Dzuman et al., 2016). However, DDGS are susceptible to mycotoxin contamination due to the high moisture and protein content, hence, improper storage might increase mycotoxin contamination, particularly in moist areas (Li et al., 2014). In a 5 year survey (2005-2010) covering 409 DDGS samples taken from animal farms or animal feed production sites worldwide, 98% of samples were contaminated by at least one type of mycotoxin, and only 2% of samples showed contamination below the detectable limit (Rodrigues & Chin, 2012). Li et al. (2014) found that 15 of 17 DDGS samples from swine farms in Beijing contained concentrations of deoxynivalenol (DON) that exceeded European Regulation No. 401/2006. Although the concentration of mycotoxins in a small inclusion of DDGS for growing pig diets might not be a problem, diets with a high level of DDGS may cause issues.

2.2.1.3. Effect of DDGS inclusion in pig diets on growth performance

The effect of DDGS inclusion in growing pig diets on growth performance and carcass quantity traits varies among studies. In some studies, pig growth performance was impaired linearly with increasing DDGS levels in the diet. Whitney et al. (2006) and Linneen et al. (2008) found a linear reduction in average daily gain (ADG) and dressing percentage in pigs fed inclusions of 10, 20, or 30% DDGS during the grower-finisher stage. In an experiment investigating the effects of different DDGS levels (5, 10, 15, 20, or 25% DDGS in growing pig diets), Thacker (2006) also observed a tendency for decreases in ADG and average daily feed intake (ADFI). Widyaratne and Zijlstra (2007) reported that including 25% DDGS in diets for finisher pigs impaired ADG and ADFI compared with pigs fed the wheat control diet. Feed intake reduction results in the impairment of pig growth rate (Stein & Shurson, 2009). Poor palatability caused by burnt DDGS (Cromwell et al., 1993) or earlier satiety because of fibrous components could explain why pigs preferred diets containing no DDGS (Seabolt et al., 2010).

In contrast, many studies showed no change in the growth performance of pigs fed DDGS (Stein & Shurson, 2009). Wahlstrom et al. (1970) reported that 5 and 10% DDGS in growing pig diets did not affect daily gain, feed intake and feed conversion, but 20% DDGS inclusion caused reductions in these traits. However, pig growth performance was unaffected if the 20% DDGS inclusion was supplemented with 0.15 or 2.5% L-lysine. Xu et al. (2010b) demonstrated that DDGS inclusion up to 30% in a growing-finishing diet did not affect growth performance, provided the diets were formulated on a standardized ileal digestible AA basis. McDonnell (2011) proved that formulated diets based on ileal digestible AA, available P and Net energy (NE) would bring no differences in daily gain, feed intake, feed conversion ratio, backfat depth, carcass yield when increasing levels of DDGS in growing pig diets.

Differences in growth performance among studies using DDGS for pigs were due to high variation in DDGS quality. Nutritive value and physical characteristics of DDGS are noticeably affected by the process of mixing wet distillers grains and condensed distillers solubles (Kingsly et al., 2010). Poor quality of DDGS or overestimated nutritive value of DDGS could lead to decrease growth performance in some studies. Conversely, positive effects of DDGS on pig growth performance were often seen when diets containing DDGS were formulated based on available AA.

2.2.1.4. Effect of DDGS inclusion in pig diets on carcass yield and meat quality

In most research, the inclusion of DDGS in growing pig diets does not impact carcass yield or meat quality. However, some research stated that DDGS negatively affected dressing percentage, belly firmness and fat iodine value; therefore, feeding DDGS for growing pigs needs proper strategies to enhance carcass traits and pork quality.

The reduction in dressing percentage could be explained by the increased gut fill and intestinal mass in pigs fed fibre-rich ingredients in diets (Wenk, 2001). Linneen et al. (2008) showed a linear reduction of carcass weight and percentage yield with increasing levels of DDGS in the diet of grower pigs. Xu et al. (2010b) reported that dressing percentage was linearly reduced with increasing dietary DDGS from 10, 20, and 30% DDGS in grower-finisher diets. Dahlen et al. (2011) reported that the dressing percentage was lower in pigs fed 20% DDGS than in pigs fed a conventional diet. However, Widmer et al. (2008) did not find any effect of adding 10 or 20% DDGS to growing pig diets for carcass weight, dressing percentage, and carcass composition. The reason why no effect of DDGS on dressing percentage has been observed in some experiments is not known, but it may be associated with the quality of DDGS used in different studies (Stein & Shurson, 2009; Widmer et al., 2008; Xu et al., 2010a, 2010b). Backfat thickness, loin depth and belly thickness are likely not affected by the inclusion of maize DDGS in most studies (Widmer et al., 2008). However, the depression in carcass yield likely relates to the negative response of daily weight gain in those experiments that could have diet formulations that did not meet requirements (Stein & Shurson, 2009).

Large quantities of UFAs in DDGS can lead to poor belly firmness and fat quality since dietary fat source significantly affects fat deposition in pork (Madsen et al., 1992; White et al., 2009). Increasing inclusion of DDGS in growing pig diets linearly increased polyunsaturated fatty acids (PUFAs) content but linearly reduced saturated fatty acid (SFAs) and monounsaturated fatty acids (MUFAs) content in backfat and belly fat (McClelland et al., 2012; Xu et al., 2010b). On the other hand, high concentrations of PUFAs in pork fat are closely linked with soft belly (Xu et al., 2010a). However, the adoption of oil extraction in new ethanol production producing less oil in DDGS can reduce this negative effect of feeding DDGS for growing-finishing pigs on pork fat (Graham et al., 2014). In addition, much research on the effect of DDGS on meat quality did not find any impairment of other objective measures of meat quality by the diet, such as meat colour, water holding capacity and tenderness.

To summarise, the high fibre content in DDGS is most likely the limiting factor that reduces feed intake of growing-finishing pigs, reducing growth performance and carcass yield. However, research shows that DDGS can be formulated up to 20% in grower-finisher diets without impairment of pig production.

2.2.2. Forage plants

Using forages in pig diets is prevalent in many tropical countries where pigs are raised on small-scale farms with low agricultural inputs (B. Kambashi, C. Boudry, et al., 2014). These small-scale operations rely on readily available feedstuffs as purchasing imported high-quality feed for pigs is unaffordable. Although the diets are likely to be nutritionally imbalanced and lead to poor pig growth performance, feeding forage-based diets within a smallholder context is more profitable than feeding high-quality feeds (B. Kambashi, C. Boudry, et al., 2014; Lekule & Kyvsgaard, 2003; Men et al., 2006).

In developed countries, forages used to be the basis of pig diets before grain-fed production systems were adopted (B. Kambashi, C. Boudry, et al., 2014). The high fibre content of forages is believed to impair nutrient utilization and growth performance in high genetic merit pigs. Therefore, intensive livestock production systems use substantial amounts of high-protein feed to maximize the growth potential of high-merit breeds. However, recent studies report that fibre is important to gut health and animal welfare (Jarrett & Ashworth, 2018; Jha & Berrocoso, 2015; Montagne et al., 2003). Therefore, forage plants have become an exciting topic for pig nutritionists (Figueroa et al., 2020; Liu et al., 2012; Rattanasomboon et al., 2019).

2.2.2.1. Feeding value of forage plants for growing pigs

Forages used in pigs' diets include grasses, legumes, aquatic plants, and leaves from shrubs and trees. The nutritional value of forage plants varies among species, families, regions, harvesting timing and processing method. Table 2.4 describes nutritive value of some common forage plants.

Table 2.4. Chemical composition of some forages.

Component (g/kg DM)	Chicory[1]	Plantain[1]	Lucerne[2]	Red clover[2]	Pigweed [3]	Congo grass[3]	Calopo[3]	Sweetpotato[3]	Stylo[3]
Ash	167	151	159	61	NR	NR	NR	NR	NR
Crude protein ($N \times 6.25$)	316	159	538	556	225	101	179	225	194
Crude fat	26	17	102	111	21	21	42	37	30
Starch	5	9	9	3	NR	NR	NR	NR	NR
Neutral detergent fibre	332	295	158	156	373	672	489	389	559
Acid detergent fibre	268	179	45	67	208	358	357	334	396
Acid detergent lignin	177	57	24	44	22	31	70	99	77
Gross energy (MJ/kg DM)	17.5	17.4	22.2	24.6	15.1	18.4	19.6	17.6	18.2
Amino acid (g/kg DM)									
Arginine	13.4	7.2	32.8	33.3	10.6	5.7	8.1	10.2	10.2
Histidine	5.6	3.1	12.4	12.7	3.8	2.7	3.6	3.7	4.0
Isoleucine	12.6	7.3	29	28.4	8.9	3.8	7.7	8.8	7.7
Leucine	23	12.7	49.8	51.1	14.0	6.6	12.3	15.0	12.9
Lysine	15.7	8.3	35.7	34.8	9.1	2.2	6.9	7.2	7.0
Methionine + Cysteine	7.8	5	14.6	13.2	NR	NR	NR	NR	NR
Phenylalanine + Tyrosine	23.3	13.6	56.2	59.3	NR	NR	NR	NR	NR
Threonine	12.8	6.8	25.7	27.1	8.8	5.9	7.5	9.8	9.3
Tryptophan	5.7	3.5	11.8	12.5	NR	NR	NR	NR	NR
Valine	17.1	9.2	33.9	35.1	10.8	5.2	9.5	11.5	9.3

NR: Not reported.

[1] Rattanasomboon et al. (2019); [2] Renaudeau et al. (2022); [3] B. Kambashi, P. Picron, et al. (2014)

Forage species are good sources of protein, EAA and minerals for pigs. The CP content of many forage plants meets the requirements for growing pigs (B. Kambashi, C. Boudry, et al., 2014; Martens et al., 2012), especially protein in legume forages such as lucerne and red clover reach up to 50% DM (Table 2.4). The protein content of chicory and plantain is comparable with that of maize DDGS, wheat and triticale (Rattanasomboon et al., 2019). AA in forage plants closely matches the ideal AA balance for growing pigs. Particularly, lysine content in most forage plants (Table 2.4), except calopo, is richer than in cereal. Furthermore, many forage plants are rich in macro-and micro-minerals (B. Kambashi, C. Boudry, et al., 2014). Sweet potato leaves (Ipomoea batatas), cocoyam leaves (Colocasia esculenta) and erythrina leaves (Erythrina glauca) are common feedstuffs that can be the primary ingredients of pig diets in developing countries (Ly et al., 2010; Regnier et al., 2012). High yield forage plants in such as chicory, plantain, lucerne and red clover are potential protein source for growing-finishing pigs that recently reported.

Forage plants are a source of dietary fibre for pigs as cell walls in forage plants are mainly composed of polysaccharides, cellulose, hemicelluloses, pectin, and lignin. In addition, fibre can partially provide energy to growing pigs through gut fermentation (as mentioned in section 2.1.3.1). Fibre in chicory and plantain is more digestible than cereal fibre due to the more readily degradable polysaccharides present in these herbs than cereals (Ivarsson et al., 2011; Rattanasomboon et al., 2019). In addition, the high digestibility of chicory fibre can be attributed to the presence of inulin, which positively impacts bacterial flora and the synthesis of SCFAs in the colon (Loh et al., 2006). Therefore, chicory can be present in pig diets without negative consequences for pig growth (Ivarsson, 2012).

Apart from their nutritional benefits, bioactive compounds found in plants offer a range of benefits for animal health and well-being, as well as the potential to improve production efficiency and reduce environmental impact. Many studies showed the possibility of using the extract from herbal plants as alternatives to antibiotics for weaned piglets at a time when they experience physiological and immunological stressors. For example, supplying Eucommia ulmoides leaf extracts improved growth performance, jejunal morphology and function, and reformed colonic microbial composition and diversity of piglets (Peng et al., 2019). The same positive effect on piglet intestinal health was found in Psidium guajava L. and Eucommia ulmoides leaf extracts (Ding et al., 2020; Wang et al., 2020). In growing pigs, garlic and dandelion supplementation promoted growth performance and improved carcass traits (Samolinska et al., 2020). The Achyranthes Japonica Nikai root extract improved the growth rate of pigs during the 36-70 day finisher period, reduced meat drip loss, and decreased faecal ammonia emission, leading to a better overall barn environment (Dang et al., 2020). Inulin, which is found in chicory, jerusalem artichokes, and dandelions, has been shown to enhance the mineral concentration in the plasma of pigs (Samolinska et al., 2019) and reduce skatole levels in adipose tissue of entire male pigs (Kjos et al., 2010). In addition, the inclusion of inulin in pig diets may mitigate ammonia emissions from pig production (Hansen et al., 2007).

Overall, including forage plants in grower-finisher diets can have potential benefits for pig health and production, making it a promising practice for pork producers to consider.

2.2.2.2. Limiting factors of forages for growing pigs

The fibre content of forages is probably the main limitation to their exploitation as a feed ingredient for growing pigs (Noblet & Le Goff, 2001). The digestibility of high lignin and insoluble fibre is almost zero in pigs (B. Kambashi, C. Boudry, et al., 2014; Noblet & Le Goff, 2001). In addition, high-fibre diets are associated with reduced digestibility of almost all nutrients and energy of pigs. In fibrous diets, nutrients are trapped in a voluminous chyme within the intestine, and the transit time of feed in the gastrointestinal tract is faster, reducing opportunities for nutrient breakdown and absorption (Wenk, 2001). The ileal and total tract digestibility of OM, CP, nitrogen-free extract and energy of the diets significantly declined with the inclusion of cassava leaves, leucaena leaves and groundnut foliage in growing pig diets (Phuc & Lindberg, 2000). In addition, a high-bulk diet causes earlier satiety resulting in lower voluntary intake. The consequence of the low digestibility and low feed intake of pigs fed forage-based diets are low growth performance and reduced carcass quality (Phengsavanh & Lindberg, 2013).

Poor bioavailability of EAA also results in inefficient use of forage for pigs. Nitrogen stored in plant tissues is primarily in the form of nitrate, AA, and protein. Monogastric animals are not able to convert nitrate into protein. As the traditional method of evaluating protein content in feedstuffs is based on the N content (N × 6.25) (AOAC, 2005), this calculation might overestimate the actual protein value of a forage species for pigs. For example, Rattanasomboon et al. (2019) found that the total AA in chicory was 20% lower than that calculated using total N content × 6.25. Therefore, formulating forage diets based solely on CP is likely to underestimate the protein provided to growing pigs, which may result in lower lean tissue growth. Moreover, the high content of NDF-bound protein prevents hydrolysis by the digestive enzymes of monogastric animals. Protein-bound to NDF in samples taken from twenty-eight plant species consisting mainly of leaves from leguminous browse trees is about 30% of CP on average, ranging from 6 to 72%, with the highest values for Makhamia zanzibarica (Shayo & Udén, 1999). Protein digestibility in vitro decreased linearly with the increase of NDF:CP proportion in the total CP (Shayo & Udén, 1999).

Highly complex compounds in many plant species act as antinutritional factors (ANFs). ANFs may be defined as those substances generated in natural feedstuffs by the normal metabolism of species and by different mechanisms (e.g., inactivation of some nutrients, diminution of the digestive process or metabolic utilization of feed) which exert effects contrary to optimum nutrition (Kumar, 1992). The most recognized ANFs in plant roots and tubers or leaves are cyanogenic glycosides, saponin, phytate, oxalate, enzyme inhibitors and total alkaloids (Gemede & Ratta, 2014). Besides reducing growth performance, cyanogenic glycosides might cause sudden death in animals consuming a high level of cyanogenic glycoside-rich plants (Vetter, 2000). However, it is difficult to conduct systematic and comprehensive evaluations of primary and secondary plant metabolites in animal health and production because of their complex biological mechanisms in plants and animals.

One plant cannot cover the complete nutrient requirements of pigs but combining forage(s) with other ingredients can provide sufficient nutrition. Moreover, mixing forage with other conventional feed ingredients perhaps alleviates these harmful effects. The level of ANFs may be reduced through feed processing, such as drying, heating, and pelleting (B. Kambashi, C. Boudry, et al., 2014). Therefore, finding a proper inclusion level and processing method to support the use of forages in pigs' diets at different growth stages is very important.

2.2.2.3. Effect of forage inclusion in growing pig diets on growth performance, carcass yield and meat quality

The efficiency of using forages in growing pig diets depends on the type of forage, the inclusion level, feed preservation, feed supplementation and pig breed. Studies on forage plants for growing pigs have primarily been conducted in developing countries for small household farming. Therefore, most results listed below are related to the context of small-scale pig production in which local pig breeds or crossbreeds between local pigs and exotic pigs are reared.

Bulky forage-based diets usually reduce digestibility and energy intake (Ngoc et al., 2013; Noblet & Le Goff, 2001). Hence, increasing forage inclusion in growing pig diets impairs pig growth performance and carcass quality. Replacing SBM protein with legume leaf meal protein decreased total feed intake, protein intake, ME intake, final body weight ADG and carcass yield in Moo Lath Lao pigs (Phengsavanh & Lindberg, 2013). Forage legume had the same effect on growth performance for growing Large White × Duroc pigs. Therefore, pigs fed a forage-based diet had lower slaughter and hot carcass weights (Kambashi et al., 2016). Nhu Phuc et al. (2000) demonstrated that the apparent digestibility of OM, CP, ether extract (EE) and crude fibre (CF) diminished linearly with increasing inclusion levels of cassava leaves in the diet. This digestibility impairment may explain the decreasing growth rates of pigs fed increasing ensiled cassava leaves (Ly et al., 2011). However, the results might be biased by the high hydrogen cyanide (HCN) level in the cassava diet. Ly et al. (2010) found no impact of replacing 70% of the protein from fish meal with protein from ensiled or dry cassava leaves and sweet potato vines on growth performance and carcass traits. The level of HCN in this study was lower than in the former.

Nonetheless, a proper forage-based inclusion would not be detrimental to growing pig performance (B. Kambashi, C. Boudry, et al., 2014; Martens et al., 2012). Halimani et al. (2005) reported higher feed intake, digestibility, and daily live-weight gain of pigs fed 100g of Acacia karroo or Acacia nilotica added in 1kg DM of the conventional diet. This study also reported that the inclusion of more than 100g of leguminous leaf meal per 1kg DM of the conventional diet negatively affected animal performance, resulting from a higher quantity of proanthocyanidins. This conclusion agrees with Anyanwu et al. (2021). The ANFs in Leucaena leucocephala leaf meal diets might influence tubular diameter and epithelial cell thickness of the thyroid glands, feed intake and growth rate of growing pigs. The recommended maximum inclusion level of Leucaena leucocephala leaf meal is up to 70.5 g/kg in pig diets. Leterme et al. (2009) recommended that the acceptable inclusion of aquatic ferns in fattening pig diets is 100-150 g/kg DM due to low digestibility from high fibre content. According to Kaensombath and Lindberg (2012), protein from ensiled taro leaves could replace protein from SBM up to 50% without impairing growth performance or carcass traits.

It is important to acknowledge that the processing and preservation methods used can significantly affect the feeding value of forage ingredients, as anti-nutritional factors in fresh forage can be effectively eliminated when certain processing methods are used. The high-water holding capacity of some forage plants results in high bulkiness, and a high-water content of fresh forage limits feed intake. Adding bulky ingredients to pig diets increases gut fill, thereby reducing DM intake and important nutrients for the growth development of growing pigs (Kaensombath et al., 2013). Drying or ensiling forage substantially decreases water content and partially reduces the fibre content due to the degradation of cell wall polysaccharides (McDonald et al., 1991), increasing feed intake. Borin et al. (2005) experimented with the effect of cassava leaf variety and preservation methods on diet digestibility. The results showed that both ensiling and drying significantly reduced HCN in fresh cassava leaves. Although ensiling, as opposed to sun-drying, was more effective at reducing HCN levels resulting in higher digestibility of DM and other dietary components, the higher bulk of silage limited intake. For non-toxic forages like sweet potato leaves, the sun-drying method significantly increased daily DM intake compared with fresh and ensiled, however the processing method did not have an effect on ileal and total tract digestibility coefficients of nutrients (An et al., 2004). The effect of forage plants on growing pig productivity is controversial, due to the variation of forage species, processing methods, rearing conditions, and breeds.

Much research stated that indigenous pigs could utilize forage better than genetically improved breeds (Borin et al., 2005; Len et al., 2009; Ngoc et al., 2013). However, environmental issues in hot tropical climates could bias the effect of feeding forage plants on high-performance of genetically improved breeds in low-income countries. Recent studies including forage plants in growing-finishing diets of commercial high-merit breeds in developed countries showed some benefits to the pigs. For example, Ivarsson et al. (2012) found that chicory may benefit commercial genotypes as chicory stimulated the hindgut development of 7-week-old Yorkshire pigs. Including forage plants in pig diets can be up to 25% of growing pig diets (Rattanasomboon et al., 2019). Nonetheless, the research on forage for growing pigs in developed countries is limited. More studies are needed to investigate whether forage plants can be included in the diets of fast-growing commercial genotypes.

2.2.2.4. Effect of grazing pigs on growth performance, carcass yield and meat quality

In some countries, pigs can be farmed commercially outdoors (Park et al., 2017; Picardy et al., 2019). Approximately half of New Zealand's pig industry has an outdoor-based breeding herd, and an estimated 3% of production is free-range, where breeding and growing pigs are outside. Free-range pig farms have a lower capital outlay if suitable land is available and offers market differentiation possibilities and a premium based on animal welfare. Indoor systems require higher capital for housing, equipment and maintenance than an outdoor system (Guy et al., 2012), but better control and, thus, efficiency concerning inputs (e.g., feed and other resources) and outputs (e.g., effluent). The effect of outdoor or organic farming on growing pig productivity and pork quality has been well documented (Hansen et al., 2006; Honeyman, 2005; Kelly et al., 2007; Millet et al., 2005; Park et al., 2017). However, little is known about the growth performance, carcass yield and pork quality of growing – finishing pigs reared on pastures.

A potential benefit of grazing pigs is the opportunity for pigs to consume extra nutrients from fresh forage on pastures (Edwards, 2003). Restricted feeding of concentrates to grazing pigs improved feed conversion (concentrated feed/gain) since forage contributed to the energy supply of pigs (Kongsted et al., 2015). Protein-rich pastures like lucerne can partly fulfil protein and AA requirements for growing pigs (Jakobsen et al., 2015). Moreover, natural foraging possibly meets the mineral and vitamin requirements of growing pigs (Edwards, 2003; Kongsted et al., 2015). In other words, it may not be necessary to supply a synthetic premix or AA in a forage-based free-range system depending on the forages used. Grazing pigs on pasture is compliant with organic farming practices. According to Council Regulation (EC), No 834/2007 on organic production, growth promoters and synthetic AA are banned, and animals must have access to open-air areas and pasture land where appropriate in organic farms.

In contrast, rearing pigs outdoor is considered to reduce production efficiency. Given a larger space allowance, outdoor pigs spent more time physically active than indoor pigs (Terlouw et al., 2009; Tozawa et al., 2016). Thus, pigs reared outdoors require more energy for maintenance which stimulates pigs to consume more feed to gain the same weight as those kept indoors (Gentry et al., 2004; Lebret et al., 2006; Oksbjerg et al., 2005). Moreover, exposure to extreme weather conditions impacts pig growth rate, feed conversion and pig health and welfare (Bee et al., 2004; Kelly et al., 2007; Pietrosemoli & Tang, 2020). Adopting appropriate management strategies can reduce the negative effects of a harsh environment on the productivity of grazing animals, including pigs (Pietrosemoli & Tang, 2020). Gentry et al. (2004) found that weight gain and feed conversion of pigs kept on alfalfa pasture in winter (temperature range: −3 to 15°C, humidity: 70%) were not impaired. Nonetheless, the productivity of growing pigs reared on pasture-based systems with different feeding regimes, forage types, pasture rotation, pig genotypes, seasons, and interactions need further investigation.

Expectations of healthy and high-quality meat are the reasons customers purchase animal-friendly products (EC, 2007). Sather et al. (1997) reported that free-range pigs had a higher proportion of dissected lean meat in the picnic (2.0%), butt (4.0%), loin (4.5%) and ham (2.0%) compared with conventionally reared indoor pigs. Thus, the apparent value of wholesale price was increased from 5.7 to 8.1%. Bee et al. (2004) found a similar trend regarding lean yield of free-ranging pigs, while Gentry et al. (2002) found no difference in carcass yield between the two systems. Carcass traits perhaps are confounded by pig growth rate, which was largely influenced by the climatic conditions, genotype and feeding management. Meanwhile, pork from pigs reared on pasture has consistently been shown to have better quality characteristics compared to that of pigs reared indoors. Pork from pigs that were born or reared outdoors was found to have a redder colour compared to pork from pigs raised indoors (Gentry et al., 2004; Terlouw et al., 2009). Pigs reared on pasture have higher blood hemoglobin concentrations than pigs reared indoors (Kleinbeck & McGlone, 1999). Blood haemoglobin concentrations correlate highly with muscle iron and heme pigment concentrations (Miltenburg et al., 1992). Furthermore, increasing spontaneous exercise on large pastures results in more type IIA fibres and fewer type IIB/X fibres in the longissimus and semimembranosus muscles of free-range pigs than in those of pigs reared indoors (Gentry et al., 2004). Kim et al. (2013) found that the high composition and size of type IIB fibres results in lighter colour and lower water holding capacity, which suggests pale soft exudative meat.

Value-added is another advantage of free-range pork. Many studies have found that pigs reared on pasture had higher levels of polyunsaturated fatty acids in the intramuscular fat (Bee et al., 2004; Lebret & Guillard, 2005; Nilzén et al., 2001). The high concentration of polyunsaturated fatty acids benefits human health (Simopoulos, 1999). However, this makes the tissue more susceptible to lipid oxidation, and carcass fat is softer (Wood et al., 2004). Fortunately, the concentration of vitamin E, a powerful antioxidant able to inhibit lipid oxidation in the cell membranes, was higher in pigs fed green feed on pasture (Lebret & Guillard, 2005; Nilzén et al., 2001). There may be strategies to manipulate the meat quality of pigs not raised on pasture to achieve similar benefits, such as supplying dietary silage for indoor pigs to enhance pork vitamin A content (Argemí-Armengol et al., 2020). Dry-cured loin of Iberian pigs reared in a free-range production system was higher in α-tocopherol concentration than pigs reared in confined housing on concentrate feed (Soto et al., 2008). Meanwhile, Kongsted et al. (2015) found a decline of vitamins E and A in pig plasma where free-range pigs reared on diverse pasture swards were not supplied synthetic vitamins. These conflicting results may be explained by the variation in vitamin concentrations among forage species (Elgersma et al., 2013).

The information about the feeding value of forages for growing pigs is inconsistent across studies. This inconsistency results from the variation in pig breeds, types of forages and processing methods, and rearing conditions. Moreover, reports on the effect of feeding forages for growing pigs are scarce. However, many studies demonstrated the benefit of feeding forage plants for growing pigs on growth performance, carcass quality and pig well-being. Therefore, more research investigating the effects of forage-based diets on growing production performance and welfare is vital. In addition, further assessment of the opportunity costs of cultivating, collecting and processing forages need calculating. Ideally, a lifecycle assessment and economic evaluation of feeding forage-based diets to pigs would be conducted.

2.2.3. Vegetable oil extraction by-products

2.2.3.1 Oilseed meal/cake production

Vegetable oil extraction is one of the key industries worldwide. Nearly half of the global agricultural commodity trade share is vegetable oils (OECD/FAO, 2022). It is produced for the human diet and material for other industrial applications such as soap production, chocolate, margarine, and biodiesel (Kumar et al., 2016). The demand for vegetable oil continues to increase due to population growth and the expanding biodiesel industry. The global vegetable oil production has steadily increased by 100% over the past two decades since the 2000s (OECD/FAO, 2022). Oil production is expected to increase in the future.

Extracting oil from oilseeds produces valuable co-products that serve as protein sources for farm animals. Traditionally, oil is extracted via screw presses or solvents (Dunford, 2016) (Figure 2.8). Oil-bearing seeds, nuts, or kernels contain high-fat content and moderate protein and fibre levels. Oil content can reach up to 70% of their total weight (Nde & Foncha, 2020). After the oil is removed, the whole nutrients of oilseeds are recovered in meal/cake. Therefore, oilseed meal/cake is generally rich in protein or fibre. The protein level in oilseed meals/cake can be up to 50% (Bernard, 2011; Florou-Paneri et al., 2014; Ma et al., 2019). “Cake” refers to the co-product of the mechanical expelled process, whereas "meal" comes from the solvent method (Arrutia et al., 2020). Since chemical extraction has higher oil extraction efficiency than mechanical extraction, the co-product from the solvent method has lower oil content but a higher protein level than the latter (Bernard, 2011; Oryschak et al., 2020). However, the most significant difference in the nutritional value of cake/meal depends on the original ingredients.

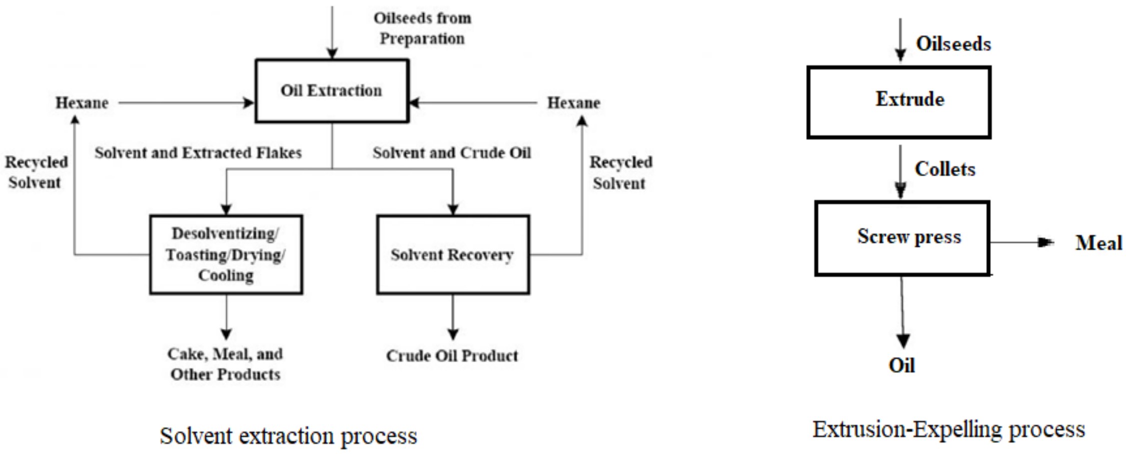

Figure 2. 8. Simplified flow diagram of oilseed meal/cake production

Source: Dunford (2016)

Vegetable oil can be extracted from a wide range of oilseeds, with soybean being the most commonly produced. However, palm oil is the world's leading oil product. Following palm oil and soybean oil is rapeseed oil. Rapeseed oil is the primary source of biodiesel produced worldwide (Tan et al., 2009). Sunflower seed oil, peanut oil, coconut oil, cottonseed oil, and groundnut oil account for a small proportion of global vegetable oil production (OECD/FAO, 2022).

Interestingly, only a small proportion of worldwide soy is utilized directly for human consumption and other industries since more than three-quarters (77%) of soy is processed as SBM for livestock feed (Ritchie & Roser, 2021). The high protein content and excellent quality of the AA profile for monogastric animals make SBM the most significant protein source in farm animal diets (Dei, 2011). For example, the soy content of compound feedstuffs is about 21% of pig diets (European Parliament, 2011). However, most soybean production is produced in the USA and Brazil, accounting for more than two-thirds of global soybean production (Ritchie & Roser, 2021). Therefore, the world's livestock protein production heavily depends on the top soybean-producing countries.

This dependency raises concerns about the impact on the sustainability of the economy and the environment (Krimpen et al., 2013; Ritchie & Roser, 2021). The ongoing increased price of SBM leads to livestock farmers' production costs, reducing their profitability (European Parliament, 2011). On the other hand, the expansion of soybean production indirectly impacts the tropical rainforest's deforestation (Ritchie & Roser, 2021). While China chose to reduce protein content in pig and poultry diets, the European Parliament adopted a resolution on 'the EU's protein deficit by calling research on substituting soy-based feeds with alternative protein sources' (European Parliament, 2011). Extending the use of other vegetable oil extraction by-products (called alternative oilseed meal) to replace SBM in animal diets is necessary to balance protein supplies.

2.2.3.2. Feeding value of some alternative oilseed meals in comparison with SBM for growing pigs

Like SBM, alternative oilseed meals are excellent protein sources for growing pigs as they have high concentrations of protein and EAA. Protein content in alternative oilseed meals is from 30 to 40%. The AA in oilseed meals exceeds AA requirements of growing pigs (Table 2.5). They are much greater than in maize. Therefore, oilseed meals can be a good source of AA to mix with maize in growing pig diets (Table 2.5).

However, the nutritive value of alternative oilseed meals is still not comparable with SBM. Oilseed meals are lower in protein and AA content but higher in fibre than SBM (Table 2.5 & Table 2.6). NDF and ADF in SBM are around 5% and 8%, respectively. These values are 3 times lower compare to cottonseed meal (CSM) and canola meals (CM) and 5-times lower compare than sunflower meal (SFM). The higher fibre concentration in oilseed meals results in the lower digestibility of all nutrients. According to González-Vega and Stein (2012), the AID and SID of CP and all AA of CM, CSM and SFM were significantly lower than SBM, except those of methionine, cysteine, and proline. Berrocoso et al, (2015) reported that ATTD of gross energy (GE) of CM in growing pigs was 70-80%, which is 10-20% lower than in SBM. ME in SBM is approximately 3700 kcal/kg as-fed basis. This figure is greater than ME of CM (2998 kcal/kg as-fed), SFM (2725 kcal/kg as-fed), and CSM (2459 kcal/kg as-fed) (Rodríguez et al., 2013). Therefore, adding fat when using alternative oilseed meals is required to achieve constant DE or ME for pigs.

The feeding value of alternative oilseed meals can be enhanced through dehulling or plant breeding programs. Dehulling involves removing the fibrous outer layer of the seed, which contains most of the insoluble fibre. This process increases the nutrient density of the remaining meal and improves its digestibility for pigs. For example, compared with SFM, dehulled SFM has higher concentration of CP and AA but lower fibre content (Table 2.5 & Table 2.6). In addition, plant breeding programs can be utilized to develop oilseed varieties that offer superior feeding value for pigs. These programs focus on selecting traits such as lower fibre content, higher protein content, and improved amino acid profiles. By targeting these traits, breeders can create oilseed varieties that are easier to digest and possess higher nutritional value for pigs. Having higher levels of crude protein, essential amino acids, and energy content but lower NDF and ADF, high-protein CM supplies more ME and SID of AA for growing pigs than conventional CM (Berrocoso et al., 2015)

Table 2.5. Essential amino acids of alternative oilseed meals compared with SBM, maize and growing pig requirement (as fed basis)

Essential AA (%)	CSM[a]	SFM[a]	SFM-DH[a]	SFM-HP[b]	CM-HP[c]	CM-CV[c]	SBM[c]	Maize[d]	AA requirement of growing – finishing pigs [e]
Arginine	4.25	2.08	2.69	4.04	2.87	2.09	3.43	0.38	0.47
Histidine	1.07	0.68	0.90	1.34	1.23	0.91	1.24	0.24	0.36
Isoleucine	1.29	1.15	1.47	1.6	1.89	1.35	2.32	0.28	0.55
Leucine	2.31	1.74	2.26	2.85	3.31	2.53	3.73	0.96	1.05
Lysine	1.71	1.01	1.25	1.74	2.67	2.02	3.07	0.26	1.04
Methionine	0.63	0.58	0.76	0.82	0.91	0.68	0.69	0.17	0.3
Phenylalanine	2.09	1.23	1.60	2.03	1.90	1.38	2.45	0.39	0.63
Threonine	1.21	0.92	1.23	1.59	1.84	1.49	1.82	0.28	0.67
Tryptophan	0.33	0.32	0.43	NA	0.71	0.46	0.68	0.06	0.18
Valine	1.79	1.43	1.82	2.05	2.48	1.72	2.50	0.38	0.69

CM-CV: conventional canola meal; CM-HP: high protein canola meal; CSM: cottonseed meal; SBM: soybean meal; SFM: sunflower meal; SFM-DH: dehulled sunflower meal; SFM-HP: high protein sunflower meal

[a] González-Vega and Stein (2012);[b] Dadalt et al. (2016); [c] Berrocoso et al. (2015); [d] Stein et al. (2016)

[e] Amino acid requirements (%, total basic) of growing pigs with live weight range 50-75kg when allowed feed ad libitum (90% DM)

Table 2.6. Analysed proximal chemical composition of alternative oilseed meals compared with SBM and maize (as-fed basis)

Item	CSM[a]	SFM[a]	SFM-DH[a]	SFM-HP[b]	CM-HP[c]	CM-CV[c]	SBM[c]	Maize[d]
GE, kcal/kg	4,307	4,194	4,218	4183	4,442	4,145	4,257	3,991
DM, %	89.3	89.9	91.1	91.2	92.60	91.22	87.49	88.2
CP, %	42.3	29.4	37.3	48.7	47.54	36.79	48.27	8.1
Ash, %	8.1	6.3	7.6	9.2	6.52	8.14	5.57	1.4
AEE, %	3.8	1.6	2.1	-	3.28	3.77	2.48	2.9
ADF, %	17.1	29.2	21.9	9.1	10.95	17.53	4.81	2.9
NDF, %	24.6	39.3	30.3	15	17.90	25.04	8.23	10.2
GLS, µmol/g	-	-	-	-	14.22	8.69	-	-

CM-CV: conventional canola meal; CM-HP: high protein canola meal; CSM: cottonseed meal; SBM: soybean meal; SFM: sunflower meal; SFM-DH: dehulled sunflower meal; SFM-HP: high protein sunflower meal

[a] *González-Vega and Stein (2012)*

[b] *Dadalt et al. (2016)*

[c] *Berrocoso et al. (2015)*

[d] *Stein et al. (2016)*

[e] *Amino acid requirements (%, total basic) of growing pigs with body range 50-75kg when allowed feed ad libitum (90% DM)*

2.2.3.3. Limiting factors of the alternative oilseed meal

Apart from higher fibre content compared with SBM, aspects such as ANFs in oilseed meals must be considered when incorporating oilseed meals into growing pig diets. They are chemical compounds containing secondary plant metabolites produced by oilseed plants. These compounds, such as phenolic in SFM, and gossypol in CSM, bind with AA, vitamins, and minerals, impairing nutrient absorption in the gastrointestinal tract. High consumption of free gossypol (over 146 ppm) causes depression in feed intake and weight gain in growing pigs (Fombad & Bryant, 2004). Similarly, the glucosinolates present in canola varieties impact the appetite and growth mechanisms of animals. Although glucosinolates in current commercial canola seed is almost eliminated, total residual glucosinolates in CM can be up to 21 µmol/g (So & Duncan, 2021). Glucosinolates taste bitter, leading to feed consumption reduction in pigs (Tripathi & Mishra, 2007). Glucosinolate metabolites interfere with the synthesis of thyroid hormones by impairing the uptake of iodine by the gland. The thyroid hormone reduction slows down the growth rate of animals (Schöne et al., 1997). Grower pigs can tolerate up to about 2.2 µmol/g glucosinolates in their diets without adverse effects. Finisher pigs are more sensitive to glucosinolates than grower pigs. Therefore, the glucosinolate level in finisher diets should be lower than 0.9 µmol/g (D. A. Roth-Maier et al., 2004).

2.2.3.4. Effect of replacing SBM with alternative oilseed meals on pig growth performance, carcass yield and meat quality

Numerous researchers have explored the potential of alternative oilseed meals as a substitute for SBM in pig diets. However, there is a lack of consensus on the effects of replacing SBM with alternative oilseed meals on pig growth performance. Some studies have found no negative impact on pig growth traits, while others failed to include alternative oilseed meals in their diets, leading to inconsistent results. The disparate outcomes may be due to varying oilseed meal quality, replacement levels, and pig growing stages, which can confuse farmers seeking to incorporate alternative oilseed meals into their pig diets.

To address this issue, a meta-analysis should be conducted to systematically review the effects of substituting SBM with alternative oilseed meals on growing-finishing pigs. Such a meta-analysis can overcome the inconsistencies across individual studies and provide clearer recommendations for farmers regarding the use of alternative oilseed meals in pig diets. Chapter 6 presents the findings of this meta-analysis.

2.2.4. Poultry by-product meal (PBM)

2.2.41. Poultry by-product meal production

Meat processing by-products are the portion of slaughtered animals that cannot be sold as meat, such as blood, bones, trim, skins/hides, adipose tissue, horns, hooves, and offal. The by-product mass is around 30% of the live weight of poultry or 50% of cattle (Jayathilakan et al., 2012). Regarding meat production, poultry is the most popular meat consumed worldwide as it is reasonably priced for low-income people, is convenient for cooking, and is perceived as healthier than red meat. In 2020, 134 million tonnes of poultry meat was produced, representing almost 40 per cent of global meat production (OECD/FAO, 2022). This figure will increase in the next few decades since poultry is projected to dominate meat production (OECD/FAO, 2022). Over 55 million tons of poultry by-products will be generated annually. If not utilized, these by-products will contribute to landfills, environmental issues, and public health risks (Hamer, 2003; Mozhiarasi & Natarajan, 2022; Salminen & Rintala, 2002).
Processing meat by-products into animal feed efficiently reduces pressure upon solid waste management whilst increasing livestock production. Poultry meat processing by-products can be converted into PBM. PBM also has other names, like poultry meal, poultry offal meal, and poultry viscera meal. Like other animal protein by-product meals, PBM is highly digestible in AA, minerals, and energy (Kerr et al., 2019). In aquaculture feeds, PBM is well-documented and regarded as an excellent alternative feedstuff to replace fishmeal (Galkanda-Arachchige et al., 2020; Hong et al., 2021; Rossi & Davis, 2012). However, the use of protein derived from farm animals was banned in Europe due to the risk of spreading disease according to Regulation (EC) No 1774/2002) (European Community, 2002). The ban, lasting over 20 years, led to a lack of research on using poultry by-products for pigs. The limited information on PBM feeding values and its effect on pig production prevented farmers from incorporating these feedstuffs for their pigs.

2.2.4.2. Feeding value of PBM in comparison with SBM and limitation of its usage

The nutritive value of PBM has been reported in many publications related to the aquaculture sector. Most reports confirmed that PBM is a high protein feed source for fish and shrimp, potentially replacing fish meal (Galkanda-Arachchige et al., 2020). However, the nutritive value of PBM is not uniform across articles. Collecting, storing, and processing meat by-products significantly affects the proximal analyses of PBM (Kerr et al., 2017; Ribeiro et al., 2019; Volpato et al., 2022). In this literature review, a systematic review was conducted based on data from 81 publications that were written in English to evaluate the nutritive value of PBM. The mean, standard deviation, minimum and maximum of proximal nutrients and AA were calculated and shown in Table 2.7.

Table 2.7. Proximate components in PBM compared with SBM (g/100g DM, unless noted)

Protein source		DM	CP	EE	Ash	CF	Ca	P	DE (MJ/kg)[c]
PBM[a]	N	95	118	109	111	20	29	95	-
	Mean	94.38	65.10	15.52	14.57	1.40	4.18	2.25	12.93
	SD	1.99	5.81	3.87	4.61	0.64	1.90	0.77	-
	Min	88.80	47.80	7.72	6.30	0.21	1.34	0.25	-
	Max	98.34	82.65	34.78	31.08	2.57	9.23	4.15	-
SBM[b]	N	55	58	46	44	40	32	32	-
	Mean	89.1	52.73	1.89	7.4	5.28	0.39	0.73	17.61
	SD	1.31	2.06	0.57	0.5	1.13	0.08	0.06	-
	Min	86.9	47.5	0.94	6.41	3.9	0.18	0.64	-
	Max	92.8	56.82	3.34	8.94	8.01	0.53	0.87	-

N: Number of extracted studies; CF: crude fibre; CP: crude protein; DE: digestible energy; DM: dry matter
[a] Data calculated by this systematic review. [b] Data extracted from Ibáñez et al. (2020).
[c] Data of DE extracted from NRC (2012).

Compared with SBM, PBM is more favourable in macronutrients. On average, CP in PBM is around 65% DM, with a maximum of 82.65% DM, while those figures in SBM are around 53 and 57% DM, respectively. Fat content in PBM is around 15.5%, greater than in SBM due to soybean oil extraction. Nonetheless, fat content in PBM ranges considerably, from 8 to 35%. Similarly, ash content in PBM is 30 times higher than in SBM (14.6 vs 0.5%, respectively). In some high-ash PBM, the ash concentration is up to 31% DM, as raw materials of PBM are associated with bone tissues (Hatlen et al., 2015). The proportion of ash in PBM is mainly composed of phosphorus and calcium, which account for 2 – 4% DM of PBM. However, DE in PBM is lower than in SBM.

Regarding AA profile, PBM, like SBM, is rich in lysine, threonine, and isoleucine (Table 2.8). Therefore, PBM can be an excellent AA source to complement cereal grains in swine diets. In addition, methionine, which is inadequate in SBM, is not an issue when including PBM in pig diets. However, the most concerning matter with PBM is the variation in AA concentration among PBM sources. For example, lysine in PBM, the first limiting AA in pigs, can vary from 2.7 to 11.7% CP, while this range in SBM is 5.5-6.6% CP. Thus, accurate information on the AA profile in the PBM when formulating diets for growing-finishing pigs is essential to meet the AA requirements for pig growth.

Table 2.8. Amino acid profile in PBM compared with SBM (g/100g CP)

Amino acids	PBM[a]					SBM[b]				
	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max
Arg	69	6.79	1.831	3.32	15.37	45	7.28	0.164	6.92	7.69
Cys	52	1.29	1.279	0.21	9.40	52	1.44	0.084	1.26	1.65
His	61	2.17	0.989	0.88	8.31	45	2.73	0.119	2.54	3.11
Ile	72	3.71	0.784	1.76	6.79	48	4.54	0.235	3.92	5.73
Leu	72	6.89	1.155	4.45	11.95	45	7.66	0.14	7.21	7.98
Lys	73	5.65	1.196	2.65	11.70	52	6.16	0.186	5.51	6.6
Met	72	1.90	0.549	0.77	4.50	52	1.36	0.056	1.26	1.52
Phe	68	3.90	0.884	2.30	7.20	42	5.09	0.111	4.86	5.41
Thr	72	3.92	0.696	2.55	7.04	52	3.85	0.123	3.31	4.09
Trp	37	0.93	0.373	0.14	2.52	42	1.4	0.138	1.21	1.97
Val	69	4.57	0.859	2.63	7.85	45	4.78	0.172	4.23	5.22

N: Number of extracted studies

[a] *Data calculated by this systematic review.*

[b] *Data extracted from Ibáñez et al. (2020).*

Other essential nutrients in swine feeding are fatty acids which modify the fatty acid composition in pork (Kouba & Mourot, 2011), hence, might influence human nutrition (Calder, 2015). PBM is higher in saturated fatty acids, such as myristic acid (C14:0) and palmitic acid (C16:0), and monounsaturated fatty acids, such as palmitoleic acid (C16:1) and oleic acid (C18:1 n-9), than SBM (Table 2.9), while SBM is superior in polyunsaturated fatty acids to PBM. Saturated fatty acids are linked with the increased plasma cholesterol levels, which raises the risk of cardiovascular disease in humans (Willett, 2012). Polyunsaturated fatty acids reduce the risk of osteoarthritis, cancer, and autoimmune disorders (Kapoor et al., 2021). However, high amounts of unsaturated fatty acids negatively impact pig meat quality and shelf life since unsaturated fats are more likely to be oxidized (Wood et al., 2004).

Therefore, PBM offsets high polyunsaturated fatty acid feedstuffs like DDGS to improve pork quality. The combination of PBM and DDGS in growing-finishing pig diets might result in a well-balanced fatty acid profile in pig meat. Nonetheless, there has been no research on the effect of PBM on fatty acid content in pork and meat quality.

Table 2.9. Fatty acid content in PBM compared with SBM (mg/g of lipid)

Fatty acid	PBM[a]	SBM[b]
C-12:0	0.09	0
C-14:0	0.97	0.08
C-16:0	14.13	7.88
C-16:1	5.36	0.15
C-18:0	9.38	2.85
C-18:1	49.39	16.28
C-18:2	13.83	39.83
C-18:3	1.72	5.55
C-18:4	0.06	0
C-20:0	0.18	0
C-20:1	0.67	0
C-20:4	2.21	0
C-20:5	0.13	0
C-22:0	0.13	0
C-22:1	0.12	0
C-22:5	0.41	0
C-22:6	0.24	0
C-24:0	0	0
SFA	25.9	10.8
MUFAs	56.04	16.43
PUFAs	18	45.38

[a]*Siddik et al. (2019)*; [b]*NRC (2012)*

2.2.4.3. Effect of feeding PBM on growth performance and meat quality of growing-finishing pigs

As mentioned above, studies evaluating PBM on growth performance and meat quality of growing-finishing pigs were mainly conducted before the ban on feeding animal by-products for farmed animals in Europe. The ban was lifted recently. However, there is little research on including PBM in grower-finisher diets for pigs.

Based on the nutritive value of PBM, it is expected to be an excellent protein source for pigs. Some studies proved that PBM is a feasible replacement for other expensive protein sources in nursery pig diets. According to Zier et al. (2004), 20% PBM could replace blood meal and fish meal and a portion of the SBM in weaning pig diets without impacting the overall performance of young pigs through 26 days during the weaning period. Similarly, several previous studies illustrated that PBM could be used in weaner diets in place of spray-dried animal plasma (Keegan et al., 2004). A 2-week experiment by Keegan et al. (2004) showed a linear increase in gain:feed of weaners when including PBM in a maize-SBM-based diet with 10% edible-grade spray-dried whey. PBM and fish meal are valuable sources of essential AA for young pigs in the early growth stage (Frantz et al., 2004; Nemechek et al., 2014).

However, research on incorporating PBM in growing-finishing diets demonstrated the opposite results. Tibbetts et al. (1987) reported inclusion of 30% poultry offal silage (60% ground poultry offal, 30% ground shelled maize, 5% dried molasses and 5% *L. acidophilus* culture) in growing and finishing pig diets resulted in slower growth, poorer feed conversion and smaller longissimus muscle of the pigs. This study claimed that lysine deficiency in the silage diets could be the explanation for the growth impairment since lysine content in the control and 30% offal silage grower diets were 0.77 and 0.57%, respectively. Likewise, Shelton et al. (2001) reported that finishing pigs fed diets using PBM as a sole protein source reduced ADG and ADFI and increased average backfat relative to pigs fed SBM. The author suggested that a high degree of variation in the nutrient digestibility of protein sources derived from animals could affect pig growth performance.

Minor variations in SID AA estimates may explain some of the inconsistencies among studies, which is a limitation of including PBM in pig diets. SID AA for PBM in growing pigs can be 20-30% different across reports (Kerr et al., 2019). The variation in nutrient digestibility might result from the variability in ingredients of raw material and processing methods of poultry by-products. A recent examination of the effect of autoclaving time on PBM in relation to growing pig energy utilisation showed that increasing autoclaving time linearly reduced ATTD of GE and nitrogen, and metabolizability of GE (Sung et al., 2022). Over-heating causes the Maillard reaction, which decreases the biological availability and digestibility of heat-labile AA, especially lysine, the first limiting AA in pig diets (González-Vega et al., 2011). Unutilised AA increase urinary energy, decreasing metabolizability of GE of overheated PBM for pigs (Oliveira et al., 2020; Sung et al., 2022).

In addition, the concentration of bone tissues (Garcia & Phillips, 2009) determines PBM quality. High-bone PBM has high ash, but low GE, and CP (Choi et al., 2021; Kerr et al., 2017; Shirley & Parsons, 2001). The biological value of AA in PBM may be low since collagen, rich in muscle tissue, is deficient in some essential AA (Eastoe & Long, 1960). However, ash content does not affect the digestibility of PBM for dogs or chicks (Johnson et al., 1998; Shirley & Parsons, 2001). Except for one report (Keegan et al., 2004), which showed better feed conversion efficiency in nursery pigs fed diets containing low-ash PBM than high-ash PBM, there has been no research on the effect of either processing method or ash content on pig growth performance.

The quality of PBM needs to be considered when using PBM in pig diets. Inaccurate nutritive value information of PBM leads to inadequate or imbalanced nutrient supply for growth. Precision diet formulation is critical for optimising growth performance, minimising nitrogen excretion, and lowering feed costs.

2.3. Conclusion

Using alternative feedstuffs for pigs is a key strategy for developing a sustainable pig industry. There are various novel feedstuffs available. However, the alternative feedstuffs are often not comparable with the conventional ones due to high anti-nutritional factors and variations in quality. Therefore, substituting alternative feedstuffs in growing-finishing pig diets must be in proper inclusion levels to meet nutrient requirements.

CHAPTER III.

EFFECT OF HIGH INCLUSION CO-PRODUCT INCLUDING DDGS, WHEAT MIDDLINGS AND CANOLA MEAL IN PIG DIET DURING FINISHING STAGE ON PIG GROWTH PERFORMANCE, MEAT QUALITY AND BOAR TAINT

A paper from this chapter has been accepted for publication in Animal Bioscience:

Nguyen, T. T., et al. (2023). Increasing sustainability in pork production by using high inclusion levels of co-products DDGS, wheat middling and canola meal doesn't affect pig growth performance and meat quality but reduce boar taint. Animal bioscience. https://doi.org/10.5713/ab.22.0468

Abstract

The present study is to examine the effect of high inclusion of co-products in pig diets (referred to as an alternative diet) during the finishing stage on pig growth performance, meat quality and boar taint compounds. Growing pigs were fed an alternative diet made with distillers dried grains with solubles (DDGS, 25%), canola meal (CM, 20%), and wheat middling (WM, 15%) or a control diet based on barley and soybean meal (SBM) to investigate the impact of co-products on pig performance and meat quality. Sixteen female and sixteen entire male Duroc × (Large White × Landrace) pigs (22.6 ± 2.07 kg, body weight ± SE) were equally allocated to the diets. The result showed that pigs fed the alternative diet had a lower feed intake; however, growth rate and feed conversion efficiency were unaffected by diet. A diet by sex interaction was found for FCR, whereby males fed the alternative diet had the best feed conversion ($P < 0.01$). Pork from pigs fed the alternative diet had lower a* and Chroma and protein % ($P < 0.05$), while other meat quality characteristics were unaffected. The alternative diet reduced backfat skatole levels ($P < 0.001$). In conclusion, a diet containing a high inclusion of co-products can be fed to pigs during the finishing stage without detrimental effects on pig performance or meat quality and with the potential to enhance pork flavour. This finding suggests a solution to increase the sustainable development of pig production.

Keywords: DDGS, Canola meal, Wheat middling, Indole, Skatole, pig production

3.1. Introduction

Pig meat is the second most commonly consumed meat in the human diet. Pork production is projected to grow to meet the demand of an increasing human population (OECD/FAO, 2022). Nonetheless, feeding pigs with conventional feed stuffs, which are primarily composed of cereal grains and soybean meal (SBM), is unsustainable for the development of the pig industry. Pigs compete directly with human food sources, arable land and agricultural resources (Mottet et al., 2017). Furthermore, the expansion of soybean production is closely linked to deforestation, biodiversity loss, and greenhouse gas emissions (Lathuillière et al., 2017). On the other hand, as feed accounts for approximately 60-70% of the direct cost of pig production, reliance on volatile and competitive commodity markets to supply feed can compromise economic returns.

It is possible to replace conventional feedstuffs in pig diets, given that they are omnivores and are therefore suited to ingest many types of feed. Substituting conventional feed ingredients with co-products in pig diets is a key strategy for making pig production more sustainable (Zijlstra & Beltranena, 2019). Distillers dried grains with solubles (DDGS), canola meal (CM) and wheat middling (WM) are co-products from biofuel and food processing that hold potential as feedstuffs for pigs. They can be included in grower - finisher diets for pigs, however, need a proper risk management as they contain high levels of anti-nutritional factors such as insoluble fibre, which limits their use for non-ruminants (Zijlstra & Beltranena, 2019). The inclusion of DDGS, CM and co-extruded full-fat flax seed and field pea can be up to 50% in grower-finisher diets (Jha et al., 2013). Compared with growing pigs, finishing pigs have greater gut capacity, which possibly removes the physical limitation to digesting high-fibre diets. Therefore, the present study is expected to maximize the inclusion of DDGS, CM, and WM above the previous findings in finishing pig diets with or without negligible depletion in pig growth performance, carcass yield, and meat quality.

3.2. Material and methods

The experiment was conducted at the Massey University Pig Biology Unit, Palmerston North, New Zealand and was approved by the Massey University Animal Ethics Committee (MUAEC 19/125).

3.2.1. Animals

Sixteen female and sixteen entire male Duroc × (Large White × Landrace) pigs from a commercial farm were used for this experiment. The pigs were weighed upon arrival (22.6 ± 2.07 kg, average ± SD) and allocated to 4 pens. Two pens housed female pigs, and the other two pens housed male pigs. Each pig was identified with a numbered tag in the left ear and a radio frequency identification (RFID) tag in the right ear. Pigs had *ad libitum* access to food and water throughout the experiment. One female pig allocated to the alternative finishing group was removed from the trial in week 2 due to diarrhoea. Data from this pig was excluded from the analysis.

3.2.2. Experimental diets

A control diet and an alternative finisher diet (alternative diet) were used in the study (Table 3.1). The main ingredients of the control diet were barley, SBM and soybean oil, while the main ingredients of the alternative diet were co-products: DDGS, CM, and WM. The nutrient composition of both diets was formulated to meet or exceed requirements of growing-finishing pigs according to NRC (2012). The control and alternative diets were equal in digestible energy and apparent ileal digestibility of lysine.

Table 3. 1. Ingredient composition (as-fed basis) of the experimental diets.

Ingredient, g/kg	Dietary *Control*	*Alternative*
Barley	788.3	320.5
Soybean meal	160	0
Canola meal	-	200
Soybean oil	10	-
Wheat middling	-	150
Tallow	-	35
DDGS	-	250
Lysine	2.5	5
Methionine	2	1
Threonine	2	2
Tryptophan	0.2	0.5
Premix pig Grower[1]	2	2
Dicalcium phosphate	30	10
Sodium Hydro-phosphate	2	3
Salt	1	1
Limestone	-	20
Calculated values[2]		
Digestible Energy, MJ/kg)	13.47	13.52
Apparent Ileal Digestible Lysine, g/kg	8.84	8.82

[1] Pig Grower Finisher Premix Low Copper (Nutritech International, Auckland, New Zealand) provided the following (per kg diet, as fed): 7000 IU of vitamin A, 1500 IU of vitamin D3, 35 IU vitamin E, 2 mg of vitamin K, 1.5 mg of vitamin B1, 3 mg of vitamin B2, 2 mg of vitamin B6, 15 µg of vitamin B12, 11 mg of pantothenic acid, 15 mg of niacin, 20 µg of biotin, 0.25 mg of folic acid, 90 mg of choline, 80 mg of iron (sulfate), 30 mg of manganese (sulfate), 1 mg of cobalt (chloride), 0.3 mg of selenium (sodium selenite), 115 mg of zinc (oxide), 20 mg of copper (carbonate), and 1 mg of iodine (potassium iodate)

[2] Morel et al. (1999)

Both diets were pelleted (Figure 3.1). All pigs were fed the control diet for 7 weeks during the growing phase. Subsequently, for the finishing period of 3 weeks, female and male pigs from 2 pens continued with the control diet while the female and male pigs from the other 2 pens were fed the alternative diet.

Figure 3.1. Pelleting feed in the study

3.2.3. Housing

All pigs were housed in one building and grouped in pens measuring 20 m^2 with a solid concrete floor, enabling a space allowance of 2.5 m^2/pig. Each pen was equipped with a nipple water drinker and a single-space electronic feeder (F.I.R.E. feeder, Osborne Industries, Inc., Osborne, KS). Feed and water sources were located in the main pen. Pigs had unlimited access to all areas of their pens (described in Figure 3.2). Temperature and airflow were managed with heat lamps (in the sleeping areas) and mechanical ventilation. The main room temperature was maintained between 18 to 21°C.

Figure 3.2. Pen design

3.2.4. Pig growth performance data

The live weight of each pig was recorded weekly (Figure 3.3)

Figure 3. 3. Weighing pigs

Feed intake (g of feed per visit per pig) was automatically recorded by the F.I.R.E. feeder system. The feeders were calibrated at the start of the study and once each week thereafter, using a 500-g calibration weight. The feeder entrance was covered by an adjustable full-body race that enabled only one pig at a time to eat unmolested. An RIFD ear tag identified each pig to the feeder, which in turn recorded the pig's tag number automatically, the amount of feed consumed per visit, the entry and exit time per visit, and visit duration. If a visit takes place but no tag is identified, then the visit is classified as a "Tag 0" event. No errors about "Tag 0" occurred during this experiment. The data were checked daily for errors and downloaded onto a hard drive until analysis. The criteria detailed in Casey et al. (2005) were applied to eliminate possible erroneous data.

Individual average daily gain, daily feed intake, and FCR were calculated for weekly and each experimental period (weeks 1 to 7 and 8 to 10) and the entire experiment (weeks 1 to 10).

3.2.5. Carcass data

The pigs were transported for approximately two hours to a commercial abattoir (Land Meat Ltd, Wanganui), rested overnight, and slaughtered the next morning. Hot carcass weight without kidneys and leaf fat, and back fat depth (BFD) were recorded within 30 minutes post-slaughter. BFD was measured in the right side of the carcass at the P2 position, about 65 mm from the dorsal mid-line at the level of the last rib, using a Hennessy grading probe (Hennessy Technology, Auckland, New Zealand).

The following day the carcasses were cut, and the bone-in loins were vacuum packaged and transported to Massey University and stored frozen (-20°C) until further meat quality analysis.

3.2.6. Meat quality data

The bone-in loin (*M. longissimus thoracis.)* was defrosted at 4°C over 48 hours and was removed from the bone with the subcutaneous fat left on. The loin was subdivided into 4 portions. A 4 cm section of the cranial portion was used to measure pH and loin chemical composition. A 4 cm section in the mid portion was used to assess drip loss. The next two 2.5 cm wide sections in the mid loin were used for cooking loss and shear force measurements. Meat sample preparation is illustrated in Figure 3.4.

Figure 3.4. Meat samples preparation for meat quality analysis

3.2.6.1. pH

The pH was measured at 45 minutes (pH45) after slaughter in the loin muscle at P2 by a pH spear adjusted by temperature (OAKTON, EUTECH Instruments, Vernon Hills, Il., USA). The ultimate pH was measured after thawing at three points from medial to distal across a transverse, internal cut of the striploin with a pH spear adjusted by temperature (Eutech Instruments, Singapore). The pH spear was calibrated to pH 4.01, 7.00 and 10.01 standard buffers.

3.2.6.2. Colour

The lean meat colour was measured on a fresh cut, transverse surface after 1-hour blooming time using the Minolta Colour Meter calibrated to a standard white tile supplied by the manufacturer (CR-200, Konica Minolta Photo Imaging Inc., Mahwah, NJ, USA). The CIE L* (lightness), a* (redness) and b* (yellowness) values were measured. Chroma C* and hue angle h° were calculated using the below Equations:

$\text{Chroma} = \sqrt{a*^2 + b*^2}$ and Hue = arctan$\frac{b^*}{a^*}$

3.2.6.3. Drip loss

Two cubes of raw meat with 4 cm sides were cut from the 4 cm steak. The 4 cm cube was weighed and then suspended on a net in a plastic bag at 4°C. After 48 h, the suspended cube was blotted dry using tissue paper and reweighed. Drip loss was calculated as the original weight minus the weight at 48 h and the value was expressed as a percentage of the original weight. The value of drip loss of an animal was the mean of the drip loss from two cubes.

3.2.6.4. Cooking loss

Meat was cooked in three batches and samples were allocated randomly with the condition that all treatments were equally represented in each batch. The 2.5 cm steaks were weighed and then suspended in vacuum bag in a water bath and cooked at 70°C for 60 min. Fluid from the bag was poured off and the samples were left to cool at 2°C for 24 h. Steaks were then removed from the bag, blotted dry, and re-weighed. Cooking loss was calculated as the difference in weight of the two 2.5 cm steaks before and after cooking and expressed as a percentage of the weight before cooking. The value of cooking loss of an animal was the mean of the cooking loss from two steaks taken from that animal.

3.2.6.5. Shear force

Round cores (diameter=1.27 cm) were removed parallel to the longitudinal orientation of the muscle fibres from each steak. Shear force measurements were determined using a texture analyzer (Stable Micro System TA.HD Plus texture analyzer, Surry, UK) fitted with a Warner-Bratzler shearing blade with a set crosshead speed at 200 mm/min. The samples were sheared perpendicular to muscle fibre orientation. A maximum of 8 cores were obtained from both steaks per animal and the mean shear force values were reported in Newtons.

3.2.5.6. Loin chemical composition

The portion used for pH then was finely minced (Kenwood MG450, 3 mm hole-plate), vacuum-packed and frozen until assessing chemical composition.

3.2.7. Chemical analyses

Feed samples were pooled by diet and stored at 4 °C during the experiment and meat samples were stored at -20 °C until chemical analyses at the Massey University Nutrition Laboratory, Palmerston North, New Zealand. Gross energy (GE) of the trial diets was determined by combusting the sample completely in a bomb calorimeter (AC-350, LECO Corporation, St. Joseph, MI, USA). Other components were analyzed according to the method of AOAC: dry matter (AOAC 925.10 and 930.16); crude protein (AOAC 968.06, Dumas method); fat (AOAC 922.06, Mojonnier method,); crude fibre (AOAC 962.09/978.10 - modified); NDF (Fibretec, AOAC 2002.04); ADF (Fibretec, AOAC 973.18); lignin (Fibertec, AOAC 973.18); starch (α-amylase Megazyme kit, AOAC 996.11); ash (furnace 550°C, AOAC 942.05); calcium (preparation AOAC 968.08D followed by colorimetric analysis); phosphorus (preparation AOAC 968.08D, ISO6491.1998E, modified in-house method); amino acid profile (acid stable: HCl hydrolysis followed by RP HPLC separation using AccQ Tag derivatization, AOAC 994.12); cysteine/methionine (performic acid oxidation, AOAC 994.12); tryptophan (AOAC 2017.03, sub-contracted, non-accredited).
Loin and backfat samples were stored at -20 ^{0}C until analysis. Chemical composition of meat was analyzed by the methods: AOAC 950.46B for dry matter; furnace 550°C AOAC 920.153, 923.03 for ash; Soxtec, AOAC 991.36 for fat and AOAC 968.06 (Dumas method) for crude protein.
Androstenone, indole and skatole concentrations in back fat samples were determined following the method of Fischer et al. (2011).

3.3. Statistical analysis

All statistical analyses were performed using the SAS software, version 9.4 TS level 1.6 (SAS Institute Inc., Cary, NC, USA).

A linear model (Proc GLM) with pig diet, sex, and their interaction as fixed effects was fitted to the growth performance, carcass characteristics, meat quality attributes and boar taint indicators. In addition, cooking batch was included as a random effect in the model for the analysis of meat cooking loss and shear force variables. Initial live weight was initially added in the model as a covariate but was removed as it was not significant.

3.4. Results

3.4.1. Chemical composition of the diets

The chemical composition differed between the control and alternative finishing diets (Table 3.2). Crude protein, fat, and crude fibre contents were higher in the alternative finishing diet. Lignin and ADF contents in the alternative finishing diet were more than double that of the control diet. Conversely, the alternative finishing diet contained less starch compared to the control diet. Dry matter, GE, and ash concentrations in the alternative finishing diet were slightly higher than in the control diet. In addition, the alternative diet had a higher essential amino acid content than the control diet, except for phenylalanine.

Table 3.2. Proximate composition and amino acid profile of the experimental diets (g/kg, as fed basis, unless noted)

Proximate composition	Dietary	
	Control	*Alternative*
Dry matter	871.8	886.3
Crude protein (Nx6.25)	158.8	185.6
Fat	35.9	77.4
Crude fibre	41.9	59.5
Neutral detergent fibre	144.3	246.2
Acid detergent fibre	45.5	89.6
Lignin	8.2	29.1
Starch	357.2	221.5
Ash	48.9	62.3
Ca	6.6	9.2
P	8.5	8.1
Gross energy, MJ/kg	15.6	16.8
Amino acid profile		
Lysine	8.5	10.5
Threonine	6.6	8.4
Tryptophan	1.9	2.3
Methionine	4	4
Cysteine	2.9	3.8
Isoleucine	5.8	6.2
Histidine	4.7	5.6
Valine	7.5	9.1
Arginine	8.9	10.2
Phenylalanine	8.2	7.9
Tyrosine	5.4	5.7
Aspartic Acid	12.1	11.8
Serine	6.4	7.1
Glutamic Acid	32.1	31.7
Proline	12.6	12.4
Glycine	5.8	8
Alanine	5.9	7.5
Leucine	10.5	11.4

3.4.2. Growth performance and carcass traits

Pig growth performance and carcass yield are presented in Table 3.3. Replacing the control diet with the alternative diet in the finishing stage reduced feed intake ($P < 0.05$) but did not impair growth rate or feed conversion efficiency ($P > 0.05$) of finishing pigs. No differences for these parameters were found between treatment groups for the entire 10 weeks of the experiment. When the initial live weight was included in the model as a covariate, the results did not change.

Sex influenced growing-finishing pig performance. Feed conversion of male pigs was more efficient than in females ($P < 0.05$) in all phases of the experiment. Male pigs also grew faster than females in the finishing stage (1077 vs. 963 g/d for males and females, respectively). However, growth rate in the growing phase and overall experiment was similar between male and female pigs.

The only significant interaction between diet and sex was observed for FCR in the finishing stage ($P < 0.01$). Post-hoc analysis (not presented in Table 3.3) indicated that males fed the alternative finishing diet tended to have the greatest feed conversion ratio (FCR = 2.39) while female pigs fed the same diet tended to have the highest FCR (FCR = 2.93). Equivalent results were obtained if the initial weight of the finishing phase was included as a covariate.

Carcass weight, dressing out percentage, and BFD were not different between treatment groups or sex. However, pigs fed the control diet tended to have a heavier carcass weight ($P = 0.061$) and higher dressing percentage ($P = 0.093$) than pigs fed the alternative finishing diet.

Table 3.3. LSmeans for growth performance of male and female pigs fed two diets (control vs alternative)

Growth performance	Diet (D)		Sex (S)		Pooled	P - value		
	Control (n=16)	Alternative (n=15)	Female (n=15)	Male (n=15)	SE	D	S	D*S
Finishing Phase								
LWf, kg	84.94	79.76	81.14	83.56	2.123	0.105	0.437	0.582
ADG, g/d	1059	981	963	1077	33.7	0.142	0.028	0.083
ADFI, g/d	2.923	2.564	2.712	2.774	109.3	0.029	0.689	0.9
FCR	2.75	2.66	2.84	2.57	0.067	0.283	0.012	0.007
Whole experiment								
ADG, g/d	890	831	841	881	29.1	0.179	0.349	0.582
ADFI, g/d	2023	1905	1968	1961	68.3	0.233	0.944	0.963
FCR	2.27	2.30	2.35	2.23	0.029	0.578	0.006	0.125
Slaughter								
Carcass weight, kg	64.84	59.84	61.91	62.78	1.779	0.061	0.751	0.473
Dressing out, %	76.32	74.97	76.3	74.99	0.558	0.093	0.102	0.494
BFD, mm	8.69	8.52	8.46	8.75	0.26	0.679	0.44	0.649

Abbreviations: ADFI: average daily feed intake; ADG: average daily weight gain; BFD: back fat depth; LWf: live weight finish.

SE: standard error

3.4.3. Meat quality and boar taint

Pork quality characteristics of loins and boar taint of backfat from male and female pigs fed the two diets were displayed in Tables 3.4 and 3.5, respectively.

There were no interactions (*P > 0.05*) between diet and sex for the meat quality variables measured, except for cooking loss (*P < 0.05*). Neither dietary treatment nor sex influenced ultimate pH, drip loss at 48 h, shear force, or hue angle (Table 3.4). However, meat from intact male pigs had a higher pH45 than that of female pigs (*P < 0.05*). Cooking loss of meat from males was higher than females when fed the alternative diet (30.42 vs. 27.81, *P < 0.05*), but no differences (*P > 0.05*) were found in cooking loss due to sex when pigs were fed the control diet. Meat from pigs fed the alternative finishing diet had lower a* and Chroma values than meat from pigs fed the control diet (*P < 0.05*). Intact male pigs had meat that was lighter and more yellow and had a higher Chroma value than that from gilts (*P < 0.05*).

Dietary treatment did not affect the chemical composition of the loin muscle, except for crude protein concentration which was slightly greater in muscle of pigs fed the control diet (*P < 0.05*). There were no differences in dry matter, crude protein, or ash between meat from female or male pigs (*P > 0.05*).

Table 3.4. LSmeans for pork quality characteristics of loins from male and female pigs fed the two diets (control vs alternative)

Meat quality parameters	Diet (D)		Sex (S)		Pooled SE	P- value		
	Control (n=16)	Alternative (n=15)	Female (n=15)	Male (n=16)		D	S	D*S
pH45	6.20	6.32	6.18	6.34	0.053	0.100	0.039	0.869
Ultimate pH	5.46	5.43	5.45	5.44	0.019	0.210	0.582	0.478
Drip loss 48hrs, %	8.66	9.67	8.90	9.43	0.596	0.230	0.538	0.879
Cooking loss, %[1]	28.25	29.12	28.01	29.35	0.558	0.179		0.036
Shear force, N[1]	55.30	53.64	56.52	52.42	2.841	0.610	0.180	0.312
Meat colour								
Lightness (L)*	52.28	52.69	51.60	53.37	0.595	0.588	0.045	0.874
Redness (a)*	6.49	5.51	5.72	6.27	0.279	0.021	0.173	0.970
Yellowness (b)*	7.66	7.29	7.09	7.85	0.213	0.277	0.020	0.419
Chroma	10.07	9.14	9.13	10.09	0.297	0.043	0.031	0.688
Hue	49.99	53.00	51.22	51.76	1.098	0.060	0.742	0.699
Chemical composition, % as fresh meat								
Dry matter	25.84	25.63	25.80	25.66	0.140	0.267	0.516	0.293
Crude protein	23.69	23.23	23.54	23.38	0.153	0.045	0.456	0.321
Fat	1.74	1.60	1.75	1.59	0.144	0.447	0.474	0.242
Ash	1.18	1.17	1.17	1.19	0.015	0.705	0.317	0.670

[1] *Adjusted for cooking batch effect; SE, standard error*

There was no diet x sex interaction (*P > 0.05*) for compound indicators of boar taint in the adipose tissue (Table 3.5). Pigs fed the alternative finishing diet had half the skatole concentration in adipose tissue than those fed the control diet (*P < 0.001*). Concentrations of androstenone, indole and skatole in adipose tissue were all greater in male compared to female pigs (*P < 0.05*).

Table 3.5. Boar taint compounds in backfat of male and female pigs fed two diets (control vs alternative)

Boar taint compounds, ng/g of fat	Diet (D)		Sex (S)		SE	P - value		
	Control (n=12)	Alternative (n=12)	Female (n=12)	Male (n=12)		D	S	D*S
Indole	20.4	22.1	15.3	27.2	2.77	0.356	0.007	0.314
Skatole	35.8	18.2	23.3	30.7	2.48	<0.001	0.048	0.767
Androstenone	871	813	179	1504	110.2	0.303	<0.001	0.706

3.5. Discussion

This paper aimed to examine the effects of high inclusion of co-product in finishing diets on pig growth performance, meat quality, and boar taint. This discussion only focuses on discussing the effect of co-product inclusion and not the impact of sex on these parameters, as previous studies have already revealed the impact of sex on these factors. The main findings of the present study indicate that a three-week feeding of the co-product diet did not have a significant impact on growth performance and meat quality. Moreover, we observed a reduction in skatole levels in the backfat of pork fed with the high inclusion of co-product in their diet. These findings are considered important in the field of pig nutrition and production.

3.5.1. Pig growth performance and carcass yield

The major impact of the alternative diet on pig growth performance in this experiment was for feed intake, though this effect was not unexpected. High fibre and antinutritive factors in the alternative diet could explain the significantly lower feed intake of the pigs fed the alternative diet. Co-products like DDGS, CM and WM are high in fibre content. In the present study, Neutral detergent fibre (NDF), acid detergent fibre (ADF) and lignin in the alternative finishing diet were approximately twice that of the control diet. The greater bulk volume of the alternative finishing diet might cause earlier satiety and then limit feed consumption (Wenk, 2001). On the other hand, a lower feed intake of the co-product diet can be caused by the presence of antinutritional factors like glucosinolates in CM, which are known to inhibit intake (Tripathi & Mishra, 2007).

Nonetheless, a lower feed intake did not negatively influence pig growth rate, feed conversion ratio or carcass yield of pigs fed the alternative diet. This finding is in agreement with many previous studies including those that used DDGS, CM, and WM in growing-finishing pig diets. DDGS could be included up to 30% in growing–finishing pig diets without negatively affecting growth performance or carcass characteristics, providing that the diets were formulated with similar levels of standardized ileal digestible lysine and energy (Xu et al., 2010b). Replacing SBM with CM had no negative impact on pig growth performance. Inclusion of 24% solvent CM or 29.2% expelled CM in growing pig diets did not impair dry matter intake, feed conversion efficiency or weight gain (Brand et al., 2001). WM can be included at up to 30% without impairing weight gain (Erickson et al., 1985).

Co-products can be included together to maximize co-product inclusion in pig diets. Smit, *et al.* (Smit et al., 2014) demonstrated that feeding a diet of up to 240 g CM per kg and 150 g DDGS per kg to growing pigs had small effects on overall growth performance, and no impairment on carcass traits. The inclusion of DDGS, CM and co-extruded full-fat flax seed and field pea can be up to 50% in grower-finisher diets (Jha et al., 2013). Finishing pigs have greater gut capacity than growing pigs, which possibly removes the physical limitation to digesting high-fibre diets. Based on previous studies, it was expected that a diet formulated with a combination of co-products to meet the nutrient recommendations for finishing pigs would have no effect on growth performance and carcass yield. In the present study, despite over half of the barley and all the SBM being replaced by alternative ingredients in the finishing phase, no negative effects on pig growth performance or carcass yield were observed.

In contrast, several studies indicated that DDGS should not be included in pig diets at levels above 20%, and that CM is not an effective replacement for SBM in grower and finisher pig diets (Smit et al., 2018; Whitney et al., 2006). It is important to note that these findings may vary depending on the specific source and processing of the DDGS and CM being used (Zijlstra & Beltranena, 2019). Additionally, the length of the feeding period in a study can also impact the results, as the adaptation of pigs to a high-fibre diet can take several weeks (Bindelle, Leterme, et al., 2008). In the present research, pigs were fed the co-product diet for 3 weeks. The feeding period might not have been long enough for the alternative diet to show the impact of its high fibre content on growth. To my knowledge, there has been no research where over half of the conventional ingredients were substituted with co-products in grower-finisher pig diets. My study results show that the effect of a short-term inclusion of co-products at their maximum inclusion level did improve pork flavour (see the discussion on boar taint) without affecting of growth performance. However, further studies with longer feeding periods are needed to fully understand the effects on pig growth and performance. In addition, for the growth perfromances, a larger number of replicates per treatment group should be used to increase the power of the experiment.

3.5.2. Meat quality

A combination of high fat and low digestible carbohydrate content in an alternative diet may reduce muscle glycogen levels at the time of slaughter, which might increase pH muscle and water-holding capacity of pork (Rosenvold & Andersen, 2003). However, the results in the present study did not show differences in ultimate pH or water-holding capacity (measured as drip loss at 48 hours) between the two diets.

Other studies using similar co-products in pig diets found no compromise in meat quality. For instance, loin muscle harvested from pigs fed diets containing levels of DDGS at 30 or 45% did not differ in marbling, colour lightness (L), redness (a*), drip loss, tenderness, juiciness, or off-flavour characteristics, though the diet leads to softer bellies, higher polyunsaturated fatty acid levels in carcass fat, and higher iodine values (McClelland et al., 2012). Replacing SBM with other plant protein sources did not affect pig meat quality parameters, including loin chemical composition (Zmudzińska et al., 2020). In the present study, the pigs fed the control diet in the finishing stage tended to be heavier than those fed the alternative diet, resulting in a slightly higher percentage of protein in the loin muscle. Loin protein tends to increase when slaughter weight increases (Wiseman et al., 2007). Furthermore, the lower protein content in pork from pigs fed the alternative diet compared to the control diet might be due to slight differences in ideal protein balance. Although the crude protein content of the alternative diet was higher than that of the control diet (186 vs 159 g/kg), the feed intake of the former was lower than the latter. Based on the calculated diet composition, the daily ileal digestible ideal protein balance intake was higher for the control diet than the alternative diet (336 g/d vs 308 g/day, respectively). Therefore, formulating inclusions of co-products in finishing pigs should be adequate in nutrient intake to satisfy growth performance, then the diets would not impact on meat quality.

3.5.3. Boar taint

An additional quality attribute that influences consumer acceptability is flavour, off-odours and off-flavour of pork. Pork sensory attributes like sweaty, musky, urine- or faecal-like odours and flavours are mainly associated with boar taint. It results from the accumulation of androstenone, skatole, and other indoles in fat tissues. While androstenone is produced in the testes, skatole and indole are formed by bacterial breakdown of tryptophan in the large intestine (Claus et al., 1994).

The alternative diet significantly reduced the skatole level in the backfat of male and female pigs. This finding contradicts the hypothesis that high dietary fibre in pig diets leads to less tryptophan being digested in the small intestine (Dégen et al., 2007), hence, more tryptophan is available in the hindgut for bacteria to produce skatole. Based on NRC (2012), the estimated ileal undigested tryptophan reaching the hindgut of the pig fed the control diet and the alternative diet were 0.42 and 0.73 (g/kg feed intake), respectively. Therefore, my research findings support the hypothesis that high dietary fibre decreases skatole concentration in pork due to the availability of fibre for hindgut bacteria digestion. Firstly, dietary fibre encourages carbohydrate-fermenting bacteria population growth in the hindgut, directly and indirectly affecting skatole production. Undigested protein and tryptophan available in hindgut are utilized for the growing biomass of carbohydrate fermenting bacteria, resulting in less tryptophan availability for degradation into indolic compounds (Li et al., 2009). On the other hand, a decreased pH in the hindgut environment caused by an increase in short-chain fatty acids (SCFA) production from carbohydrate-fermentation inhibits skatole-producing bacteria which is optimal at a neutral pH (Diether & Willing, 2019). Secondly, insoluble fibre increases the volume and water-binding capacity of faecal bulk. Therefore, skatole will be diluted in the large intestine (Bach Knudsen, 2001). Consequently, less skatole will be in contact with the intestinal wall and, as a result, skatole absorption is reduced. In the present study, the concentration of NDF, ADF and lignin in the alternative diet was greater than in the control diet.

Several studies have demonstrated the effect of high-fibre diets on the production and absorption of skatole. Hansen et al. (2008) reported that a 25% inclusion of lupins in finisher pig diets significantly reduced skatole in blood and backfat of both males and females after 1 week. Similarly, Pauly et al. (2010) reported that feeding 30% raw potato starch to entire male pigs one week before slaughter reduced skatole levels in loin back fat but had no effect on androstenone levels. However, there are a few studies showing no effect of dietary fibre on boar taint levels in backfat. Studies such as Hawe et al. (1992) showed that feeding 40% sugar beet pulp did not reduce the concentration of skatole in subcutaneous fat. Curry et al. (2019) reported that including DDGS by 10% for pigs from 35-105kg live weight did not reduce skatole but linearly increased the indole concentration in the carcasses of the pigs.

These contradictory results might be explained by the differences in types, amounts and the ratio of dietary fibre in the experimental diets. It is clear that soluble dietary fibre is highly fermentable, providing a substrate for carbohydrate fermenting bacteria. Conversely, insoluble dietary fibre increases the passage rate of digesta and faecal bulk, diluting hindgut contents. Recent investigations also showed the interaction of fibre types and other nutritional dietary factors on hindgut fermentation (Hoogeveen et al., 2021). The present study results might suggest that combining different co-products and conventional feedstuffs in the alternative diet may supply adequate dietary fibre levels to prevent skatole formation in the hindgut. As my estimation, the amount of soluble fibre was similar in the two diets (37.6 vs 39.1 g/kg feed). However, the insoluble fibre in the alternative diet was almost as twice as in the control diet (115.9 vs 211.9 g/kg feed).

Reducing skatole in pig meat is critical to meeting the expectations and preferences of consumers. Leong et al. (2011) reported that the average skatole threshold that Singaporean consumers perceive is 28 ng/g fat. This value is higher than what was measured in pigs fed the alternative finishing diet or female pigs in the current study, but not for pigs fed the control diet or male pigs. It implies that consuming pork from pigs fed the control diet in the finishing phase would result in an unpleasant experience for Singaporean people, while meat from pigs fed the alternative finishing diet may not. Surgical castration of male piglets at a young age is a common method of preventing boar taint, however, is questionable from an animal welfare perspective and is not practiced in some countries. This finding suggests that feeding high-fibre co-products for a short period of three weeks before slaughter may reduce skatole levels in adipose tissue. This application is important for the sustainable production of high-quality pork, particularly for consumers in Far Eastern Asia.

The use of co-products in pig feed not only provides farmers with alternative options to reduce their dependence on traditional feedstuffs, but also offers the potential for improving pork flavour without facing public pressure due to animal welfare concerns. Furthermore, as a recent article has revealed, feeding pigs a diet that includes DDGS is more environmentally efficient than a traditional diet (Haque et al., 2022). The present study's finding implies that incorporating DDGS into the diet of entire male pigs can provide benefits in terms of animal welfare, the environment, and profitability. Using co-products, including DDGS in the diet of entire male pigs for a short period of time might be a solution to achieve greater sustainability in compliance with the United Nations Sustainable Development Goal 12 on responsible consumption and production.

3.6. Conclusion

High inclusion of DDGS (25 %), CM (20%) and WM (15%) can replace 60% of the barley and completely replace the soybean products in finishing pig diets without negatively affecting growth performance, carcass yield, and meat quality. Additionally, the co-product diet significantly reduced skatole levels in subcutaneous fat. Thus, the alternative finisher diet can be utilized on commercial pig farms to reduce the reliance on conventional feedstuffs without negative effects on pig growth performance or meat quality, and with potential benefits in terms of pork flavour. This research adds to a growing body of literature on the use of co-products in finisher diets and underscores the importance of continued research in this area. Furthermore, the present study provides valuable information for pig farmers looking to maximize the efficiency and sustainability of their operations.

CHAPTER IV.

PROVISION OF LUCERNE IN THE DIET OR AS A MANIPULABLE ENRICHMENT MATERIAL ENHANCES FEED EFFICIENCY AND WELFARE STATUS FOR GROWING-FINISHING PIGS

A paper from this chapter has been published in Livestock Science as:

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Abstract

This research investigated the effects of including lucerne in a diet and as manipulable enrichment material on growing-finishing pig growth performance and behaviour. Forty-eight intact male Duroc × (Large White × Landrace) pigs with an initial live weight (LW) of 26.4 ± 2.32 kg (mean ± SD) were blocked by LW and randomly assigned to two dietary treatments (control vs lucerne), and two manipulable material treatments (without and with lucerne chaff for manipulable material). The barley and soybean meal-based control diet was formulated according to a commercial standard, while the lucerne diet replaced 100 g/kg of barley and soybean oil in the control diet with lucerne chaff. The diets were formulated to have the same amount of digestible energy and apparent ileal digestible lysine. Manipulable material (lucerne chaff) was provided daily at 100 g/pig. Pigs had *ad libitum* access to diets via electronic feeders until they reached approximately 90 kg live weight, at which time they were slaughtered. There were no interactions between dietary treatment and provision of manipulable material on pig production and behaviour. Feeding the lucerne diet reduced average daily feed intake, weight gain, feed intake per feeder visit, and feeding rate, but increased feed efficiency ($P < 0.05$). Pig Manipulable material did not affect any growth traits but pig feed ding behaviour. Pigs that had access to lucerne chaff demonstrated a higher frequency of feeder visits per day and shorter visit durations compared to pigs without access to manipulable material ($P < 0.001$). Compared to the other groups, pigs that consumed the lucerne diet or had access to manipulable material rested for a shorter duration but engaged in more social interactions and exploration behaviour. In conclusion, including 10% lucerne in growing-finishing diets improved feed efficiency, and lucerne chaff appears to be an attractive enrichment source for pigs.

Keywords

Pig; Lucerne; Enrichment; Growth; Behaviour

4.1. Introduction

Pig meat is the second most popular meat consumed worldwide. Its production is projected to increase over the next few decades, mainly driven by global population growth and improved standards of living (Henchion et al., 2014; OECD/FAO, 2022). Whilst pig meat consumption is expected to increase, there is increasing concern for food security, the environment and animal welfare. Pig diets mainly rely on grains and soybean meal (SBM), therefore pigs are competing with human food sources, and the production of these feed ingredients raises concerns in terms of environmental emissions, deforestation and biodiversity loss (Mottet et al., 2017; Nguyen et al., 2012). Indoor pig production has benefits for providing for the environmental and health needs of pigs, but often indoor housing is not compatible with providing a substrate or exploratory material due to slatted flooring. The risk of blocked slats and slurry systems limits opportunities to provide some types of enrichment material, therefore limiting the expression of natural behaviour such as exploration and foraging (Studnitz et al., 2007).

Incorporating forage plants into pigs' diets and enriching pig houses with forage roughage may address both of the above concerns. The fibre content in forages has discouraged the feeding of herbage-based diets due to concerns that it will restrict pig growth, although there is evidence of other benefits, such as for pig gut health (Jha & Berrocoso, 2015; B. Kambashi, C. Boudry, et al., 2014; Montagne et al., 2003). In addition, recent studies showed no impact on the digestibility and growth rate of pigs when diets partly replaced conventional feedstuffs with forages (Figueroa et al., 2020; Liu et al., 2012; Rattanasomboon et al., 2019). Forages are recommended as manipulable material to reduce injurious and potentially harmful behaviours in pigs (European Food Safety, 2007). Pigs with access to roughage as enrichment have opportunities to express positive, highly-motivated, species-specific behaviours by imitating their natural environment, therefore, improving their welfare indoors.

Lucerne (Medicago sativa) is a potential feed ingredient and/or manipulable material option for growing pigs. Protein content and apparent ileal digestibilities of essential amino acids in lucerne are close to growing pig requirements (Reverter et al., 1999; Tsikira et al., 2021). Lucerne meal can be included in growing-finishing pig diets at up to 75 g/kg diet during the growing period, and at up to 150 g/kg diet during the finishing period, without adverse effects on growth performance (Thacker & Haq, 2008). However, research on using lucerne as an ingredient in pig diets is scarce or old. Furthermore, studies on using lucerne chaff as a source of manipulable material for growing pigs reared indoors were only once mentioned in a review by Studnitz et al. (2007). The present study aimed to investigate the effect of feeding lucerne together with providing lucerne as manipulable material on growth performance and behaviour of growing pigs.

4.2. Materials and methods

The experiment was carried out at the Massey University Pig Biology Unit, Palmerston North, New Zealand and was approved by the Massey University Animal Ethics Committee (MUAEC 19/131).

4. 2.1. Experimental design, animals and housing

4.2.1.1. Animals

Forty-eight intact, male Duroc × (Large White × Landrace) pigs with an initial live weight (LW) of 26.4 ± 2.32 kg (mean ± SD) were purchased from a commercial pig farm. Pigs were weighed and fitted with a numbered ear tag in the left ear and a radio frequency identification (RFID) tag in the right ear. The pigs were blocked by LW and allocated to eight pens, with 6 pigs per pen. Pigs were acclimated for 5 d before the experiment began. When pigs reached approximately 90 kg LW, they were transported approximately 2 h to a commercial abattoir (Land Meat Ltd, Wanganui, NZ), rested overnight, and then slaughtered the following day.

4.2.1.2. Experimental design

The experiment followed a 2 × 2 factorial design, comprising diet (control vs. lucerne) and provision of manipulable enrichment material (chaff vs. no chaff). Two pens of 6 pigs were allocated randomly to each of the four treatment groups:

1) Control diet without enrichment material available
2) Control diet with enrichment material available
3) Lucerne diet without enrichment material available
4) Lucerne diet with enrichment material available

The control diet was based on barley, SBM, and soybean oil, while the lucerne diet was made by replacing 100 g/kg (as-is basis) of the barley and soybean oil in the control diet with lucerne chaff (Table 4.1). Diets were pelleted and formulated to have the same amount of digestible energy and apparent ileal digestible lysine.

Table 4.1. Ingredient of experimental diets

Ingredient (g/kg, as-fed)	Control	Lucerne
Barley	748.3	618.2
Soybean meal	200	200
Soybean oil	10	40
Lucerne chaff	0	100
Lysine	2.5	2.5
Methionine	2	2
Threonine	2	2
Tryptophan	0.2	0.3
Vitamin + mineral premix[1]	2	2
Dicalcium phosphate	30	30
Sodium phosphate dibasic	2	2
Sodium chloride	1	1
Calculated values[2]		
Digestible energy (MJ/kg)	13.57	13.57
Apparent ileal digestible lysine (g/kg)	9.8	9.83

[1] Provided per kilogram of diet: 7000 IU of vitamin A, 1500 IU of vitamin D3, 35 IU vitamin E, 2 mg of vitamin K, 1.5 mg of vitamin B1, 3 mg of vitamin B2, 2 mg of vitamin B6, 15 μg of vitamin B12, 11 mg of pantothenic acid, 15 mg of niacin, 20 μg of biotin, 0.25 mg of folic acid, 90 mg of choline, 80 mg of iron (sulfate), 30 mg of manganese (sulfate), 1 mg of cobalt (chloride), 0.3 mg of selenium (sodium selenite), 115 mg of zinc (oxide), 20 mg of copper (carbonate), and 1 mg of iodine (potassium iodate).

[2]Morel et al. (1999)

In pens with material offered for enrichment, lucerne chaff was provided in a tray fastened to the floor adjacent to the feeding station. Trays were topped up with 100 g/pig of lucerne chaff each morning at approximately 0900.

4.2.1.3. Housing

The design of the pens is illustrated in Figure 4.1. Pigs were housed in pens measuring 20 m^2 with a solid concrete floor, enabling a space allowance of more than 3 m^2/pig. Pigs had *ad libitum* access to water and feed throughout the experiment.

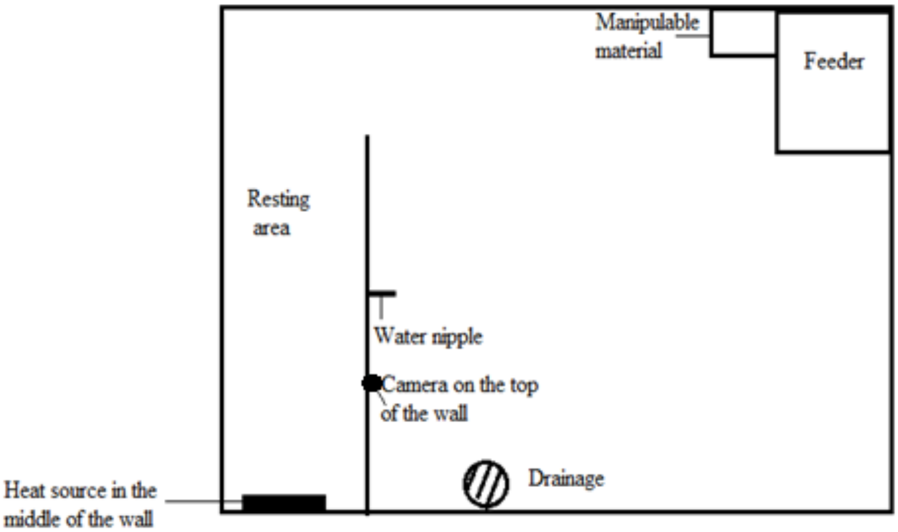

Figure 4.1. Diagram of the pen design

Each pen had an unlit sleeping area separated from where the feeder and drinker were located by a wall and accessed by a doorway. Pigs had free access to all areas of the pen at all times. A thermostatically-controlled heat lamp maintained air temperature inside the lying area at 20 to 25°C when the pigs were under 50 kg LW, and 18 to 22°C when the pigs were over 50 kg LW. Artificial lighting in the feeding area was provided daily from approximately 0700 to 1700.

The automatic electronic feeder was described in **Section 3.2.3**. Feeding areas were under video surveillance to verify errors to improve data accuracy. During this experiment, three of the feeders could not read some of the ear tags properly for two days. In this case, feed consumed from "Tag 0" was allocated to the pigs with an abnormally low feed intake.

4.2.2. Data collection

4.2.2.1. Production trait data

Feed intake per week was calculated for each pig from the downloaded data generated by the automatic feeders. Individual pig LW was recorded weekly by weighing pigs between 0700 and 0800 on the same day each week. Pigs were limited to their lying areas from 0700 on weighing days to prevent unequal feed consumption before weighing.

Hot carcass weight (without kidney and leaf fat) and backfat depth were recorded within 30 minutes post-slaughter. Backfat depth was measured on the right side of the carcass at the P2 position, about 65 mm from the dorsal midline at the level of the last rib, using a Hennessy grading probe (Hennessy Technology, Auckland, New Zealand).

4.2.2.2. Pig behaviour observations

a. Pig feeding behaviour

A total of 468,644 observations were used for analysing feeding behaviour. Mean values for each pig for the number of feeder visits per day, feed intake per visit, feeder occupation duration per visit, feed consumption rate (feed consumption/occupation duration), and total time spent in the feeder per day were calculated.

b. Pig daily behaviour

To record pig daily behaviour, a digital camera (CONCORD AHD CCTV 1080p PIR Bullet Cameras) was placed above each pen to produce a top view image so that all actions of the pigs were observed whilst they were in the feeding and activity area. The only area of the pen that was not visible was the resting area (Figure 4.2).

Figure 4.2. Camera view of the feeding and activity area of the pens

Pig behaviours were recorded on the 3rd, 6th and 9th week of the experiment. In each of these weeks, the behaviour was recorded over three successive days from 0900 to 1700. An instantaneous scan sampling method was used to observe pig behaviour. The interval between scans was 5 minutes, resulting in 12 scans per hour and a total of 96 behavioural observations generated per pen each sampling day. All the videos were scanned by the same trained person. Pig activity and behaviour are described on the defined ethogram (Table 4.2), adapted from Smulders et al. (2006) and Argemí-Armengol et al. (2020).

Table 4.2. Ethogram used in scan sampling recordings

Category	Definition
In lying area	Pigs are in the lying area (assumed to be resting)
In the feeding area	
Resting	Pigs are lying in sternal or lateral recumbency or sitting upright. (N.B. Pigs in the lying area and not visible on the video recording were assumed to be resting.)
Occupying feeder	Pigs are standing with their head in the feeder, assumed to be eating.
Exploring enrichment material	Pigs are chewing, rooting, nosing, digging, or otherwise engaged with material provided for enrichment
Exploring pen	Pigs are licking, biting, nosing or sniffing pen fixtures, e.g., the floor, wall, tray holding enrichment material and feeder
Total exploration	Including pig exploring enrichment material and exploring pen
Positive social interactions	Pig's head or snout in contact with another pig (non-aggressive), e.g., nose-to-nose contact
Negative social interactions	Pigs are chasing, biting or having aggressive contact with other pigs (including those in a feeder)
Other behaviours	Pigs are engaging in other activities, e.g., sexual behaviour, standing or walking.

4.2.3. Feed sample storage and chemical analyses

A feed sample was collected every two weeks from the feeders, pooled and stored at 4°C until chemical analysis at the Massey University Nutrition Laboratory, Palmerston North, New Zealand.

Gross energy (GE) of the trial diets was determined by combusting the sample completely in a bomb calorimeter (AC-350, LECO Corporation, St. Joseph, MI, USA). Other chemicals were analysed according to the method of AOAC (2005): dry matter (AOAC 925.10 and 930.16); crude protein (AOAC 968.06, Dumas method); fat (AOAC 922.06, Mojonnier method,); Neutral Detergent Fibre (NDF, AOAC 2002.04); Acid Detergent Fibre (ADF, AOAC 973.18); lignin (Lignin(sa)AOAC 973.18); starch (α-amylase Megazyme kit, AOAC 996.11); ash (Furnace 550°C, AOAC 942.05); amino acid profile (acid stable: HCl hydrolysis followed by RP HPLC separation using AccQ Tag derivatization, AOAC 994.12); cysteine/methionine (performic acid oxidation, AOAC 994.12); tryptophan (AOAC 2017.03, sub-contracted, non-accredited).

4.3. Statistical analysis

Growth performance and feeding behaviour data were analysed as a two-factorial design with Proc GLM (SAS® software, version 9.4, 2016, SAS Institute Inc., Cary, NC, USA). Dietary treatment, roughage enrichment and their interaction as fixed effects were fitted in the linear model. The experimental unit of the growth performance and feed intake was individual pig.

Behavioural data were analysed as repeated measures with Proc Mixed. The experimental unit of the daily behavioural observations was pen. Effect of dietary treatment, enrichment, day of scanning, and interactions between factors was fitted in the model. Diet and enrichment provision was nested in pen and considered a random effect. For engagement with the manipulable material, only the groups having received lucerne chaff were used to analyse the effect of dietary treatment.

Values are presented as least square means and standard error of the mean (SE). The level of significance was set at 0.05. Differences between least square means were adjusted with the Tukey test.

4.4. Results

4.4.1 Nutritive value of dietary treatments and roughage supplement

The nutritive values of the lucerne roughage, control diet, and the lucerne diet are presented in Table 4.3.

Table 4.3. Nutritive value of roughage, control diet, and lucerne diet

Chemical composition (g/kg DM, unless noted)	**Control**	**Lucerne**
Crude protein	193	177
Fat	43	97
Starch	407	343
Ash	71	69
Neutral detergent fibre	146	164
Acid detergent fibre	51	72
Lignin	11	16
Gross energy (MJ/kg DM)	18	19
Amino acids (g/kg DM)		
Aspartic acid	17.1	17.82
Threonine	7.98	7.8
Serine	7.98	7.8
Glutamic acid	37.63	32.29
Proline	13.68	12.25
Glycine	6.84	6.68
Alanine	7.98	7.8
Valine	9.64	8.93
Isoleucine	7.65	7.12
Leucine	13.45	12.47
Tyrosine	6.96	6.12
Phenylalanine	10.15	9.13
Histidine	4.56	4.34
Lysine	10.49	9.58
Arginine	12.09	11.02
Cysteine	3.31	2.9
Methionine	5.13	4.79
Tryptophan	2.51	2.45

As a portion of the barley and soybean oil in the control diet was replaced by 100 grams of lucerne chaff in the lucerne diet, the nutritive value of the experimental diets was slightly different. Less barley results in a reduced starch level in the lucerne diet (407 g/kg DM vs.

343 g/kg DM for control and lucerne diets, respectively). In addition, the lucerne diets was moderately higher in NDF, ADF, and lignin compared to the control diet. Soybean oil is 4 times higher in the lucerne diet. As such, the fat level of the lucerne diet was double that of the control diet. Therefore, the gross energy of the lucerne diet was relatively higher than the control diet. Digestible energy is expected to be equal in the experimental diets. Crude protein was marginally greater in the control diet than in the lucerne diet. However, the amino acid profile of the two diets was effectively the same. Overall, the control diet had a higher nutrient density than the lucerne diet.

4.4.2. Growth performance

As there was no interaction between diet and enrichment provision, only the results for the main effects are presented in Table 4.4.

The dietary treatment significantly impacted pig growth traits. However, there was no effect of manipulable material provision on pig growth performance. In addition, neither dietary treatment nor manipulable material provision affected carcass weight, dressing out percentage, or backfat thickness.

Pigs fed the control diet ate almost 250 g/d more ($P < 0.001$) and gained nearly 100 g/d more ($P = 0.005$) than those fed the lucerne diet. Nonetheless, pigs fed the lucerne diet had better feed conversion than those fed the control diet. Feed conversion ratio (FCR) of the lucerne diet group and control diet group were 1.93 and 1.99, respectively ($P = 0.014$). When LW was added as covariance in the model, the same significance difference in FCR between the two diets were observed. Growth performance was the same whether pigs were provided with enrichment material or not.

Although no effect of the experimental factors was found for the carcass traits ($P > 0.05$),

there was a tendency for the animals with the enrichment system to have a lower dressing percentage ($P = 0.079$) than their counterparts.

Table 4. 4. Growth performance and carcass traits in pigs fed a barley-soybean meal-based control diet vs. one containing lucerne, with or without access to enrichment material

	Diet (D)		Enrichment provision (E)		SE	*P*-value		
Variable	**Control**	**Lucerne**	**No**	**Yes**		**D**	**E**	**D×E**
Time on experimental diets until slaughter (d)	60.1	61.9	61.3	60.7	0.83	0.143	0.622	0.326
LW (kg)	26.13	26.65	26.67	26.10	0.476	0.443	0.408	0.313
LW finish (kg)	93.00	90.06	92.94	90.13	1.352	0.132	0.148	0.905
ADG (kg/d)	1.12	1.03	1.08	1.06	0.022	0.005	0.440	0.929
ADFI (kg/d)	2.23	1.98	2.12	2.08	0.047	< 0.001	0.519	0.995
FCR	1.99	1.93	1.96	1.96	0.019	0.014	0.769	0.676
Carcass weight (kg)	70.99	68.27	71.00	68.25	1.164	0.105	0.101	0.970
Dressing out percentage (%)	76.3	75.8	76.3	75.7	0.24	0.156	0.079	0.638
Backfat depth (mm)	10.0	9.7	9.9	9.8	0.30	0.364	0.925	1.000

Abbreviation: LW: Live weight; ADG: Average daily gain; ADFI: Average daily feed intake; FCR: Feed conversion ratio. SE: standard error

4.4.3. Feed intake characteristics

As there was no interaction between diet and enrichment provision, only the main effects are presented in Table 4.5

The proportion of each day pigs spent in the feeders was the same (around 4.5% of each 24 h period) regardless of which diet the pigs consumed, or whether they were provided with manipulable material. Feed intake characteristics were significantly influenced by diet and manipulable material, whereas there were no interactions between those factors.

Pigs fed the control diet ate 25 g of feed more in each visit ($P = 0.043$) and consumed 10 g feed more per min ($P < 0.001$) than pigs fed the lucerne diet. Compared with pigs without manipulable material, those with access to chaff spent less time in the feeders per visit (5.1 vs 3.7 min/visit) and ate less each visit (160 vs 115 g/visit) but made more frequent visits each day (13.7 vs 18.3 visits) ($P < 0.001$).

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Table 4. 5. Intake characteristics in pigs fed a barley-soybean meal-based control diet vs. one containing lucerne, with or without access to enrichment material

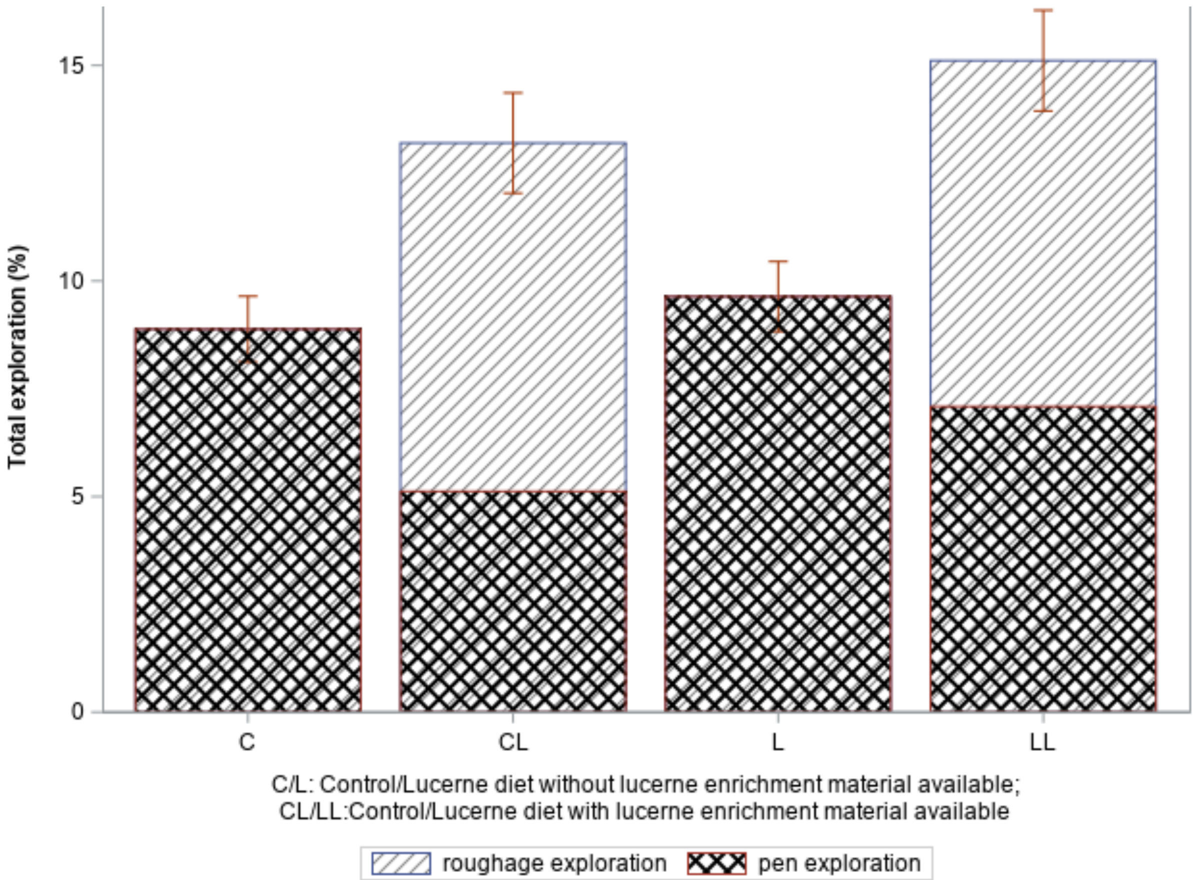
	Diet (D)		Enrichment provision (E)		SE	*P*-value		
Variable	**Control**	**Lucerne**	**No**	**Yes**		**D**	**E**	**D×E**
Number of visits per d	15.4	16.5	13. 7	18.3	0.713	0.269	< 0.001	0.796
Feed intake per visit (g)	151	124	160	115	9.0	0.043	0.001	0.577
Occupation duration per visit (min)	4.4	4.4	5.1	3.7	0.22	0.942	< 0.001	0.709
Feeding rate (g/min)	36	26	32	31	0.8	< 0.001	0.305	0.450
Percentage time spent in feeder per d	4.4	4.7	4.6	4.5	0.12	0.114	0.615	0.357

SE: standard error

4.4.4. Daily behaviour

As there was no interaction between the day of observation, diet and enrichment provision, only the main effects of including lucerne in the grower-finisher diet and providing manipulable lucerne are presented in Table 4.6. The impact of the dietary treatment and enrichment provision on the exploratory activity of the pigs is depicted in Figure 4.3.

Video analysis revealed that daily pig behaviour was different in terms of their time budget for certain activities, which was influenced by either the dietary treatment or the provision of manipulable material (Table 4.6 & Figure 4.3). The only behaviour not influenced by these factors was the time spent occupying a feeder.



Note: P value for the effect of diet on exploring enrichment material = 0.082

Figure 4. 3. Exploratory activity in pigs fed a barley-soybean meal-based control diet vs. one containing lucerne, with or without access to enrichment material

Table 4.6. Behavioural activity in pigs fed a barley-soybean meal-based control diet vs. one containing lucerne, with or without access to enrichment material

	Diet (D)		Enrichment provision (E)			*P*-value		
Variable (%/d)	**Control**	**Lucerne**	**No**	**Yes**	**SE**	**D**	**E**	**D×E**
Resting[1]	72.4	69.1	74.2	67.4	0.44	< 0.001	< 0.001	0.711
Occupying feeder[1]	9.2	9.4	9.1	9.6	0.20	0.445	0.107	0.530
Total exploration[1]	11.5	12.6	9.5	14.7	0.46	0.085	< 0.001	0.434
Positive social interactions	1.5	1.9	1.6	1.8	0.14	0.033	0.223	0.997
Negative social interactions[1]	3.2	4.6	3.6	4.3	0.24	< 0.001	0.038	0.784
Other behaviours	2.1	2.3	2.1	2.3	0.17	0.424	0.621	0.766

SE: standard error

[1] P-value of the day scanning < 0.05

Pigs spent most of their time resting (around 70% of the observation time). The resting time includes the time they were in the lying area. As there was no camera in the lying area, it is not certain that they were actually resting. The remainder of their day was mostly spent eating or exploring their environment, which was more than 20% for both activities. Across all groups, positive and negative social interactions occurred approximately 2 and 4% of the time, respectively, while other activities occupied about 2% of the time budget.

Dietary treatment minimally affected pig behaviour. The total time budget for resting was about 3% lower for pigs fed the lucerne diet than those fed the control diet ($P < 0.001$). However, pigs fed the control diet only tended ($P = 0.082$) to explore enrichment material more than counterparts fed the lucerne diet (Figure 4.3).

However, providing manipulable material obviously caused pig behaviour change by significantly reducing resting time ($P < 0.001$) and increasing exploratory behaviour ($P < 0.001$; Table 4.6 &Figure 4.3). Pigs without manipulable material spent on average 74% of the time resting, while the pigs with access to lucerne chaff spent 67 % of the time resting on average. In addition, pigs with access to lucerne chaff spent less time exploring their pens, but the total exploration time was 5% greater than pigs without chaff, as they interacted with the manipulable material (Figure 4.3).

4.5. Discussion

Growth performance was reduced when lucerne was included in a pelleted diet for growing-finishing pigs, but not when provided as a source of manipulable material. Previous research likewise reported adverse effects on pig growth performance when lucerne was included in growing-finishing pig diets (Bakare et al., 2013; Lindberg & Andersson, 1998; Thacker & Haq, 2008). As expected, supplying lucerne chaff as manipulable material had a significant effect on pig behaviour.

4.5.1. The effect of lucerne on pig production

Decreased growth rate and feed intake of pigs fed the lucerne diet in the current study agrees with previous research. Thacker and Haq (2008) reported a linear decrease in daily weight gain and feed intake of pigs between 36 and 70 kg when fed increasing levels of dehydrated lucerne meal from 75, 150, 225 to 300 g/kg diet. A similar trend was also reported where pigs' average daily weight gain and digestible energy intake declined with increasing lucerne inclusion from 20, 40, to 60% in 50 to 100 kg LW pigs (Powley et al., 1981). Dietary fibre inclusion, especially from forages, increases bulkiness and decreases nutrient density of total mixed rations. Bulkiness can cause an early satiety response in pigs, which likely reduces feed consumption (Wenk, 2001). Additionally, bitter-flavoured saponins present in lucerne may influence diet palatability and reduce feed intake (Cheeke et al., 1977; Szumacher-Strabel et al., 2019). Since feed intake is lowered, pig growth performance is affected.

However, the most striking observation in the present study is that pigs fed the lucerne diet had a more efficient feed conversion ratio than those fed the control diet. This finding suggest that a 10% lucerne inclusion might have a positive impact on the whole tract digestibility of the diet. However, further studies are needed to confirm this finding.. Thacker and Haq (2008) reported that adding 75 g of lucerne meal/kg feed did not affect the apparent total tract digestibility of dry matter, crude protein, and energy of the overall diet when fed to pigs. According to Lindberg and Andersson (1998), the inclusion of 10% lucerne in growing pig diets did not impact the total tract apparent digestibility of nutrients, energy digestibility, or energy excretion in urine. Instead, the digestibility of total fibre, acid detergent fibre and crude fibre improved when lucerne was included. Nonetheless, a 20% or higher inclusion of lucerne in growing-finishing pig diets reduced nutrient digestibility (Kass, Van Soest, Pond, et al., 1980; Lindberg & Andersson, 1998; Thacker & Haq, 2008).

Lucerne may provide a valuable source of dietary fibre to benefit hindgut digestion and health. Although few studies have been performed with lucerne itself, other studies with forage or dietary fibre inclusion reported benefits in young pigs. Ivarsson et al. (2012) found that fibre from chicory forage stimulated hindgut development of weaned piglets. Hindgut fermentation accounts for 7 to 18% of the total available energy absorbed by growing pigs (Anguita et al., 2006a). In general, the concentration of volatile fatty acids increases with an increase in dietary fibre. However, digestibility also depends on the fermentable characteristics of fibre components (Zhao et al., 2020) and pigs' age (Kass, Van Soest, & Pond, 1980). Production of volatile fatty acids in the hindgut from diets with 0, 20, 40 and 60% alfalfa meal inclusion provided up to 6.9, 11.3, 12.5 and 12.0% of the maintenance energy required for a 48 kg pig, and 4.8, 11.4, 14.0 and 12.0% for an 89 kg pig (Kass, Van Soest, & Pond, 1980). These findings suggest that incorporating lucerne in pig diets can supply considerable energy from hindgut fermentation for growing-finishing pigs.

Feed efficiency and carcass yield are crucial economic determinants in the pig industry. While carcass yield defines gross income in pig production, feed efficiency governs total cost of production and is key to sustainability. Previous research showed that pigs adapt to fibrous diets by enlarging their digestive organs, therefore, reducing dressing out percentage. Kass, Van Soest, Pond, et al. (1980) found that empty gastrointestinal tract weight increased with increasing the level of lucerne meal (from 20 to 40 and 60%) in pig diets. Nonetheless, the present result indicates that the inclusion of 10% lucerne does not impair carcass quality or yield, hence, carcass value. Therefore, 10% lucerne chaff in growing-finishing pig diets seems a feasible inclusion level for pig producers to reduce their reliance on conventional diet ingredients based on cereal grains while improving feed efficiency. However, the bulkiness of lucerne chaffs provided as enrichment material could be the reason for the lower dressing percentage tendency. The animal might ingest some chaffs while they were rooting. This finding is in agreement with Presto Åkerfeldt et al. (2019), who found that feeding chicory and red clover silage reduced pig dressing percentage

4.5.2. Feeding intake characteristics

Feeding behaviour of pigs in the current study clearly differed in response to diet composition and provision of manipulable material. The lower feed intake per visit and slower feeding rate of pigs eating the lucerne diet was possibly driven by lower palatability and greater bulkiness of that diet, which affected feeding motivation of pigs. As mentioned earlier, pigs can detect and avoid bitter flavours (Nelson & Sanregret, 1997), such as saponins present in alfalfa (Cheeke et al., 1977; Szumacher-Strabel et al., 2019). Furthermore, meal patterns are controlled by hunger and satiety. Bulky diets can cause early satiety during the meal and prolonged satiety post-meal due to vagal stimulation of fullness signals from stomach distention (Howarth et al., 2001). Pigs in the current study fed the lucerne diet ate slower and a smaller amount of feed each visit, and even though feeding frequency and meal duration were similar to those fed the control diet, resulting total daily feed intake was lower than in previous studies. The present study findings are in accordance with the reports of Ramonet et al. (1999) and Kallabis and Kaufmann (2012), who found that feeding rates significantly reduced in restricted-fed sows or finishing pigs that were fed fibrous diets.

4.5.3. Pig behavioural observations

The advantages of providing manipulable material to pigs housed indoors have been investigated thoroughly (Bench et al., 2013; Bergeron et al., 2000; Brouns et al., 1994; Robert et al., 1993; Stewart et al., 2008). Conversely, few studies exploring the effects of high-fibre diets on growing-finishing pig behaviour have been reported.

Providing lucerne for pigs to manipulate improves pig welfare by encouraging exploratory behaviour. Pigs seek out mental and physical stimulation (i.e., enrichment) by interacting with objects in their environment and provided the opportunity, pigs will express behaviours, such as rooting, nosing, digging and playing (Studnitz et al., 2007). Pigs with access to manipulable material spend less time resting and more time involved in exploration and social interaction than those without enrichment (Beattie et al., 2000; Cornale et al., 2015; van de Weerd & Day, 2009).

The higher percentage of negative social interactions among pigs provided lucerne chaff for enrichment compared to those without enrichment seems contradictory, as it would be expected that pigs housed in enriched pens displayed fewer incidences of aggressive behaviour than pigs that did not have access to enrichment. A similar observation has been reported previously, with the possible explanation being that the material provided could cause competition among pen mates and, therefore, heightened aggression (Bracke & Koene, 2019). Research has shown that increasing the amount of straw provided to pigs daily decreases abnormal behaviour towards pen mates (Day et al., 2002; Fraser et al., 1991; Pedersen et al., 2014). However, an insufficient quantity, or lack of access by all group members, might result in social competition or aggression (Fraser et al., 1991; Studnitz et al., 2007; Zwicker et al., 2015). This limitation in the present study illustrates the importance of adequate access to enrichment materials for them to be effective. In the present study, lucerne chaff was supplied 100 g/pig/day to groups of six pigs in pens with solid flooring, with one access point (a tray) per group. There should be further research to quantify lucerne levels and delivery methods, especially in pens with fully or partially slatted flooring, to satisfy exploratory behaviour in growing pigs.

Our results suggest that a diet containing 10% lucerne might affect pig behaviour as these pigs were apparently resting less and socialising more than those consuming the control diet. However, the actual numerical difference in these behaviours between treatments was very small (1 to 3%), so the significance of these observations must be interpreted cautiously. Bakare et al. (2014) found that growing pigs consuming a fibrous diet spent more time active (standing, walking and fighting) and more time eating and lying down than pigs fed a control diet, but once again, the actual differences in the time budget (measured as second per hour) were very small. The interaction between diet and pig behaviour is not well understood and is likely to be confounded by factors such as sex, breed, age, group composition, housing environment, feeder type, and others. Dietary fibre from lucerne might also influence microbiota-gut-brain axis, with the potential to influence pig social behaviour (Kobek-Kjeldager et al., 2022; Parashar & Udayabanu, 2016). Nonetheless, this complex interaction is still largely unstudied, and the difference in pig behaviour caused by dietary treatment in the present study is minimal and unlikely to be behaviourally significant. Further studies on the effects of diet composition on growing pig behaviour are needed.

4.6. Conclusion

Despite lower daily gain and feed intake, the performance of pigs fed a diet containing 10% lucerne was not significantly different to pigs fed a control diet when considering feed conversion ratio, final slaughter weight, dressing out percentage and backfat thickness. Pigs with access to lucerne roughage used it as an opportunity to engage in more exploratory behaviour. In conclusion, lucerne can be a promising feed ingredient to include in growing-finishing diets, and it appears to be an attractive enrichment source for pigs.

<u>CHAPTER V.</u>

THE EFFECT OF SUBSTITUTION SOYBEAN MEAL WITH POULTRY BY-PRODUCT MEAL IN GROWER-FINISHER DIETS FOR PIGS ON PIG FEEDING BEHAVIOR, GROWTH PERFORMANCE AND MEAT QUALITY

A paper from this chapter is under review for publication in Animal Feed Science and Technology:

Can poultry by-product meal successfully replace soybean meal in grower -finisher diets for pigs?

Authors: Thanh T. Nguyen; K.L. Chidgey; T.J. Wester; N.M. Schreurs; P.C.H. Morel

Abstract

This study investigated the effect of replacing soybean meal (SBM) with poultry by-product meal (PBM) in grower-finisher diets on pig feeding, growth performance, carcass yield and meat quality. The replacement levels were increased from 0% (control) to 33% (P33), 77% (P77) and 100% (P100). All diets met or exceeded nutrient requirements for pigs between 20 – 100 kg live weight (NRC, 2012).

Sixty-four entire males (PIC 337 x PIC Camborough 42), at an average live weight (LW) of 27.60 ± 2.48 kg (mean ±SD), were blocked by LW and randomly assigned to 8 pens, with each diet replicated across 2 pens. Pigs had *ad libitum* access to diets via electronic feeders until they reached approximately 100 kg LW, at which time they were slaughtered.

Results showed no significant effect of replacing SBM with PBM on pig feeding behaviour parameters and the majority of pig growth performance, carcass yield, and meat quality traits, with the exception of higher feed conversion ratio (FCR) in pigs fed the P33 diet. Loin muscles from the group fed the P100 diet had significantly lower ultimate pH and a greater cooking loss than the other treatments ($P < 0.05$). Loin muscles from pigs fed high levels of PBM (P77 and P100) had greater ash content than those fed the P33 and control diets ($P = 0.001$).

Overall, the present research indicated that PBM could be a viable primary protein source in diets for growing-finishing pigs, as it did not appear to have any adverse effects on pig feeding behaviour, growth performance and meat quality. In addition, PBM is potentially a good source of calcium and phosphorus for growing–finishing pigs. However, due to the variation in quality and composition of available PBM, it is essential to measure nutritional composition before including PBM in diets for growing-finishing pigs.

Keywords: slaughter by-products, protein feed, pig production, pork quality, sustainability

5.1. Introduction

Soybean meal (SBM) is the primary protein source in concentrate diets for livestock due to its high protein content, excellent amino acid (AA) availability and palatability (Dei, 2011). The universally high demand for SBM as an ingredient in animal feed drives global soybean production (Goldsmith, 2008; Ritchie and Roser, 2021). Over two-thirds of global soybean production occurs in the USA and Brazil (Ritchie and Roser, 2021).

Dependency on soybean production for farmed animals raises environmental and economic concerns. The expansion of soybean production plays a part in deforestation and biodiversity loss in Amazon countries (Ritchie and Roser, 2021). Furthermore, feed transportation accounts for substantial greenhouse gas emissions (Van der Werf et al., 2005). The high demand for SBM globally, especially in China, inflates SBM prices (OECD/FAO, 2022) and reduces profitability for the livestock industry, as feed is the major cost in livestock production (European Parliament, 2011). The COVID-19 pandemic highlighted the vulnerability of the supply chain to unexpected pressures, including the availability of imported SBM (Schmidhuber et al., 2020), which affected farm production and animal welfare (Hashem et al., 2020; Seleiman et al., 2020). To reduce reliance on imported feed for livestock, locally sourced ingredients and by-products are recommended as alternatives to prevent animal (and human) feed shortages (Zijlstra and Beltranena, 2013; Woyengo et al., 2014; Schader et al., 2015).

The European Parliament expressed concern over potential risks associated with reliance on soy-based feeds, including the possibility of protein-deficient human diets. As a result, they called for research to find alternative protein sources to soy-based feeds (European Parliament, 2011). In addition to the concern of SBM dependency, there is a growing trend in the European Union towards retailer certification schemes that assure animal products using diets free from genetically modified organisms (GMO). This trend could lead to a shift in feed demand towards other protein sources besides SBM. Lifting the ban on the use of processed animal protein (PAP) in feed for farmed non-ruminant animals (Regulation (EU) 2019/6) could partly address concerns relating to protein deficiencies and non-GMO products preference in Europe (Lusk et al., 2018; Dzwonkowski, 2021). The proposed legislation allows poultry processed protein (PPP) to be used in pig feed.

Poultry by-product meal (PBM) is a potential protein source for pigs in terms of availability and quality. Up to 30% of the live weight of broilers is mainly inedible raw materials such as skin, bone, blood, organs, and feathers (Ockerman and Basu, 2014). Global poultry meat production in 2020 was 134 million tons, with an estimated 40 million tons of poultry by-products produced that year. Poultry meat production and its by-products are projected to increase in the next few decades (FAO, 2021). Meanwhile, PBM is a highly concentrated source of protein, minerals and energy for animals (Kerr et al., 2017). Valorizing poultry by-products for feed can also prevent waste contamination and reduce greenhouse gas emissions (Mozhiarasi and Natarajan, 2022). Numerous studies tried substituting fishmeal with poultry by-product meal for aquatic animals, with many being successful (Sabbagh et al., 2019; Galkanda-Arachchige et al., 2020; Fontinha et al., 2021). However, Europe's ban on using PAP in non-ruminant diets lasted many years, therefore there is little recent research investigating the use of poultry by-products in pig diets. Consequently, the lack of information on optimal PBM inclusion levels and the effect on pig performance has hindered farmers from incorporating this ingredient in pig diets.

The present study evaluated the nutritive value of PBM and investigated the effect of replacing SBM with PBM in growing-finishing pig diets on growth performance, carcass yield and meat quality. The aim was to provide more precise information on PBM inclusion in growing-finishing pig diets so that pig farmers have more comprehensive data when considering ingredient substitution.

5.2. Materials and Methods

The experiment was carried out at the Massey University Pig Biology Unit, Palmerston North, New Zealand and was approved by the Massey University Animal Ethics Committee (MUAEC 22/09.).

5.2.1. Animals, experimental design and housing

5.2.1.1. Animals and experimental design

Sixty-four entire males (PIC 337 x PIC Camborough 42), at an average live weight (LW) of 27.60 ± 2.48 kg (mean ± SD), were purchased from a commercial indoor pig farm and transported to the Massey University Pig Biology Unit. They were randomly allocated into 8 pens, with 8 pigs per pen, and had one week of acclimatization before the experiment started.

Partway through the experiment, one pig was removed due to illness and was not included in analyses.

5.2.1.2. Housing and facilities

Pens and electronic feeders were described in **Section 3.2.3**.

During the experiment period, all feeders were working accurately except for one feeder in one pen out of eight pens, which stopped dispensing feed for half a day.

5.2.2. Experimental diets

PBM was sourced from Kakariki Protein (Marton, New Zealand), and diets were mixed and pelleted by Denver Stock Feeds (Palmerston North, New Zealand).

Four dietary treatments were produced by substituting PBM for SBM as the primary protein source: Control (100% SBM), P33 (33% SBM was replaced), P77 (77% SBM was replaced), and P100 (100% was replaced).

All diets met or exceeded nutrient requirements for pigs between 20 – 100 kg LW (NRC, 2012) and were similar in crude protein, digestible energy, and AID Lysine (Table 5.1).

Table 5. 1. Ingredient and proximal composition of experimental diets

Feed ingredients	Dietary treatment[1]			
	Control	P33	P77	P100
	------------------ g/kg, as-fed ------------------			
Barley	744.25	778.42	822.1	846.3
Soybean Meal	200	134	46	0
Soybean oil	20	20	19	18
Poultry by-product meal	0	37	85	111
L-Lysine	1.05	1.78	2.8	3.3
Methionine	1	1	1.1	1.2
Threonine	1.5	1.5	1.5	1.7
Tryptophan	0	0.1	0.4	0.5
Vit + Min Premix[2]	2	2	2	2
Dicalcium Phosphate ($CaHPO_4$)	26	22	18	14
Sodium Phosphate dibasic (Na_2HPO_4)	4	2	2	2
Sodium Chloride (NaCl)	0.2	0.2	0.1	0
Calculated values[3]				
Crude protein	158	158	158	158
Digestible energy (MJ/kg)	13.84	13.84	13.78	13.76
Apparent ileal digestibility Protein	121	122	124	125
Apparent ileal digestibility Lysine	8.66	8.66	8.66	8.66

[1] Control (100% SBM), P33 (33% SBM was replaced), P77 (77% SBM was replaced), and P100 (100% SBM was replaced).

[2] Provided per kilograms of diet: 7000 IU of vitamin A, 1500 IU of vitamin D3, 35 IU vitamin E, 2 mg of vitamin K, 1.5 mg of vitamin B1, 3 mg of vitamin B2, 2 mg of vitamin B6, 15 µg of vitamin B12, 11 mg of pantothenic acid, 15 mg of niacin, 20 µg of biotin, 0.25 mg of folic acid, 90 mg of choline, 80 mg of iron (sulfate), 30 mg of manganese (sulfate), 1 mg of cobalt (chloride), 0.3 mg of selenium (sodium selenite), 115 mg of zinc (oxide), 20 mg of copper (carbonate), and 1 mg of iodine (potassium iodate).

[3]Morel et al. (1999)

5.2.3. Data collection

5.2.3.1. Growth performance data

Feed intake was calculated daily, weekly and for the whole experimental period for each individual pig using the downloaded data generated by the automatic feeders.

All pigs were weighed individually on the same day each week between 0700 and 0800.

Feed conversion ratio (FCR) was calculated weekly for each pig by dividing the total amount of feed consumed in the week by the weekly weight gain.

5.2.3.2. Pig feeding behaviour

Data generated from the feeders were used to analyze pig feeding behaviour. Because the number of pigs per pen was not equal after week 9, feeding behaviour was analyzed only until day 62. Values for each pig for the number of feeder visits per day, feed intake per visit feeder occupation duration per visit), and feed consumption rate were calculated for the 62-day period.

5.2.3.3. Slaughter

The pigs were slaughtered when they reached approximately 100 kg LW. The 25 heaviest pigs were selected for the first cohort to be slaughtered. The following week, the 25 heaviest pigs were selected for the second cohort, with the remainder (n = 13) slaughtered in the third week. The pigs were transported for less than 1 hour to a commercial abattoir (Land Meat Ltd, Wanganui), rested overnight, and were slaughtered the following morning. The pigs at the slaughterhouse were identified by their tattoo ID

Hot carcass weight (without kidneys and leaf fat) and back fat depth (BFD) was recorded within 30 minutes of slaughter. The BFD was measured on the right side of the carcass at the P2 position, about 65 mm from the dorsal mid-line at the level of the last rib, using a Hennessy grading probe (Hennessy Technology, Auckland, New Zealand).

The following day, carcasses were cut, and the deboned loins with fat and skin were transported to Massey University and stored frozen (-20°C) until meat quality analysis was carried out.

5.2.3.4. Meat quality

The loin (m. longissimus thoracis) was defrosted at 4°C over 24 hours. The subcutaneous fat and skin were removed from the loins, and each loin was subdivided into 4 portions. A 4 cm section of the cranial portion was used to measure pH. A 3 cm section in the mid portion was used to assess colour and drip loss. The next two 2.5 cm sections in the mid loin were used for cooking loss, followed by shear force measurements.

The samples were analysed in 6 batches. Within a batch, the samples from all the treatments were present.

5.2.3.4.1. Ultimate pH

The ultimate pH was measured as the average across three points from medial to distal across a transverse, internal cut of the loin with a pH spear (Hanna 99,163 pH meter with a FC232D combined temperature and pH insertion probe, Rhode Island, USA). The pH spear was calibrated to pH 4.01, 7.00 and 10.01 standard buffers.

5.2.3.4.2. Colour

The lean meat colour was measured on a freshly cut, transverse surface after a 30-minute bloom using a Minolta Colour Meter calibrated to a standard white tile supplied by the manufacturer (CR-200, Konica Minolta Photo Imaging Inc., Mahwah, NJ, USA). The CIE L* (lightness), a* (redness) and b* (yellowness) values were measured. Chroma C* and Hue angle h° were calculated using the equations as follows:

$$C = \sqrt{(a^{*2} + b^{*2})}$$

$$H = \arctan \frac{a^*}{b^*}$$

5.2.3.4.3. Drip loss

A 3 × 3 × 3 cm cube of raw meat was weighed and then suspended in a net in a plastic bag at 4°C. After 24 hours and 48 hours, the suspended cube was blotted with tissue paper and reweighed. The water loss was calculated as the original weight minus the weight after 24 hours (drip loss 24 hr) and 48 hours (drip loss 48 hr), with drip loss expressed as a percentage of the original weight.

5.2.3.4.4. Cooking loss

The two 2.5 cm sections were separately weighed, vacuum packed and cooked in a water bath at 70°C for 90 min. Fluid from inside the bag was decanted, and the samples were left to cool at 1-2°C for 4 h. Meat was then removed from the bag, blotted dry, and re-weighed. Cooking loss was calculated as the difference in weight before and after cooking and expressed as a percentage of the weight before cooking.

5.2.3.4.5. Shear force

Cores (diameter = 1.27 cm) from the 2.5 cm portions prepared for cooking loss above were removed parallel to the longitudinal orientation of the muscle fibres. Shear force measurements were determined using a texture analyzer (Stable Micro System TA. HD Plus texture analyzer, Surrey, UK) fitted with a Warner-Bratzler shearing blade with a crosshead speed set at 200 mm/min. The samples were sheared perpendicular to muscle fibre orientation. Values for each pig were an average of 6 cores per sample.

5.2.4. Sample storage and chemical analyses

Samples of feed were pooled by diet and stored at 4°C, while meat samples were stored at -20°C. Chemical analyses of samples were performed at the Massey University Nutrition Laboratory, Palmerston North, New Zealand. Gross energy (GE) of the trial diets was determined by bomb calorimetry (AC-350, LECO Corporation, St. Joseph, MI, USA). Other analyses were according to the respective methods of AOAC (2005) or as follows: dry matter (AOAC 925.10 and 930.16); crude protein (AOAC 968.06, Dumas method); fat (AOAC 922.06, Mojonnier method,); crude fibre (AOAC 962.09/978.10 - modified); NDF (aNDFom, AOAC 2002.04); ADF (ADFom, AOAC 973.18); lignin (Lignin(sa)AOAC 973.18); starch (α-amylase Megazyme kit, AOAC 996.11); ash (Furnace 550°C, AOAC 942.05); minerals (ICP-OES, sub-contracted); amino acid profile (acid stable: HCl hydrolysis followed by RP HPLC separation using AccQ Tag derivatization, AOAC 994.12); cysteine/methionine (performic acid oxidation, AOAC 985.28); tryptophan (AOAC 2017.03, sub-contracted, non-accredited);

Skatole levels in back fat samples were determined using the method of Hansen-Møller (1994).

5.3. Statistical analysis

All statistical analyses were performed using SAS® software, version 9.4 TS level 1.6 version (SAS Institute Inc., Cary, NC, USA). Individual pigs were the experimental unit in all analyses. A linear model (Proc GLM) with diet as a fixed effect was fitted to the feeding behaviour, growth performance, carcass characteristics and skatole concentration. There was no statistically significant effect of pen when it was considered as a random factor in the model used to analyse the growth parameters.

For the meat quality parameters, the batch was added to the model as a random effect.

Statistical significance was at $P < 0.05$, and a trend was expressed when $P < 0.10$. LSD was used for the post hoc test. Results were presented as least square means.

5.4. Results

5.4.1. Chemical composition of PBM and experimental diets

Table 5.2 presents the chemical composition of PBM and the four experimental diets.

Lab analysis results indicate that PBM is an excellent protein source for growing pigs, containing approximately 64% crude protein on an as-fed basis. Furthermore, PBM is rich in essential amino acids, including Lysine, Threonine, and Methionine, which account for 36.3, 22.5, and 12.4 g/kg of PBM, respectively.

However, compared to the control diet, the diets in which SBM was substituted with PBM had slightly lower levels of ash, crude protein, and some essential amino acids, including Isoleucine, Leucine, Phenylalanine, Histidine, and Arginine. Meanwhile, the diets containing PBM were higher in starch, fat, and Methionine. Fibre content and other amino acids were almost similar across the diets, with the exception of lower Lysine in the P33 diet.

Table 5.2. Analysed chemical composition of PBM and the experimental diets (as fed basis)

Chemical composition	Poultry by-product meal	Dietary treatment[1]			
		Control	P33	P77	P100
		------------------- g/kg, as-fed -------------------			
Dry matter	953	878	878	877	877
Gross energy (kJ/g)	-	16	16.1	16.2	16.2
Crude protein	638	165	160	147	153
Starch	-	342	339	385	371
Fat	73	29	33	35	33
Crude fibre	-	45	44	39	47
Neutral detergent fibre[2]	-	138	147	142	153
Acid detergent fibre[2]	-	47	50	44	52
Lignin[4]	-	10	10	11	11
Ash	-	56	52	52	49
Calcium	-	9.1	7.9	9.2	12
Potassium	-	8.1	6.4	5.2	4.4
Sodium	-	1.15	1.24	1.39	1.39
Phosphorus	-	8.4	7.5	8.2	9.1
Chloride	-	1.3	1.58	1.97	2.1
Amino acid profile					
Aspartic Acid	46.7	18.2	14.1	13.1	11.1
Threonine	22.5	7.9	7.2	6.3	6
Serine	24.3	8.7	7.4	7	6.2
Glutamic Acid	77	31.4	34.2	27.2	24
Proline	40.5	11.8	12.3	12	11.2
Glycine	64.2	8.8	8.7	9	9.6
Alanine	40.8	7.6	7.1	7.3	7.3
Valine	25.9	8.7	8	7.7	7.3
Isoleucine	22.1	6.8	6.1	5.6	5.1
Leucine	39.2	12.4	11.3	10.6	9.7
Tyrosine	16.2	6.4	5.8	5.2	4.7
Phenylalanine	21.6	8.6	8.1	7.2	6.4
Histidine	10.1	4	3.5	3.2	2.8
Lysine	36.3	10.6	9.7	10.2	10.1
Arginine	41.6	11.3	9.9	9.1	8.3
Cysteine	6.1	2.8	2.6	2.7	2.6
Methionine	12.4	3	4.6	4.2	4
Tryptophan	4.2	2.2	2.1	2	2.2

[1] Control (100% SBM), P33 (33% SBM was replaced), P77 (77% SBM was replaced), and P100 (100% was replaced)

[2] NDF assayed with a heat stable amylase and expressed exclusive of residual ash; ADF expressed exclusive of residual ash; Lignin determined by solubilization of cellulose with sulphuric acid.

5.4.2. Pig feeding behaviour characteristics.

The effect of replacing SBM with PBM on pig feeding behaviour is presented in Table 5.3.

The result showed no difference in feeding behaviour among pigs fed a control diet and those fed diets substituting 33%, 77%, or 100% of SBM with PBM. Specifically, the number of feeder visits per day, feed intake per visit, occupation duration per visit, and feeding rate were similar across the different dietary treatments (*P > 0.05*).

Table 5. 3. Least square means for feeding characteristics of pigs fed the control diet with SBM and the diets substituting SBM with PBM

Feeding behaviour characteristics	Treatment[1]				SE[2]	P value
	Control	P33	P77	P100		
Number of visits feeder per day (N)	13.37	14.30	15.61	14.19	0.963	0.433
Feed intake per visit (g/visit)	186	179	157	171	13.9	0.487
Occupation duration per visit (min/visit)	5.81	5.61	4.77	5.38	0.434	0.364
Feeding rate (g/min)	31.84	32.75	32.64	31.88	1.204	0.922

[1]*Control (100% SBM), P33 (33% PBM was replaced), P77 (33% 77% SBM was reolaced), and P100 (100% SBM was replaced).*

[2]*SE: standard error*

5.4.3. Pig growth performance and carcass yield

Table 5.4 displays the impact of substituting SBM with PBM on both pig growth performance and carcass yield. The results revealed that there were no significant differences observed between the control diets and the experimental diets with regard to pig growth performance and carcass yield. However, a significant difference was found in the feed conversion ratio (FCR) across the diets containing PBM, where pigs fed the P33 diet had a higher FCR compared to those fed the P77 and P100 diets (FCR = 2.28 vs. 2.13; P < 0.05). Furthermore, there was a tendency towards slightly higher dressing percentages in pigs fed the PBM-containing diets compared to those fed the control diet (P = 0.088).

Table 5.4. Least square means for growth performance and carcass traits for pigs fed the control diet and the diets substituting SBM with PBM

Growth performance and carcass traits[3]	Treatment[1]				SE[2]	P value
	Control	P33	P77	P100		
Day on trial (day)	69	69	69	68	1.3	0.953
Live weight start (kg)	27.72	27.19	27.81	27.67	0.636	0.899
Live weight finish (kg)	103.72	101.91	101.98	103.66	1.286	0.609
ADG (kg/d)	1.11	1.09	1.09	1.12	0.029	0.832
ADFI (kg/d)	2.44	2.47	2.31	2.39	0.063	0.331
FCR (kg/kg)	2.21[ab]	2.28[a]	2.13[b]	2.13[b]	0.039	0.014
Carcass weight (kg)	77.20	77.32	76.51	78.07	1.002	0.754
Dressing percentage (%)	74.45	75.85	75.02	75.33	0.390	0.088
Backfat thickness (mm)	10.56	11.06	10.06	10.47	0.499	0.563

[1]*Control (100% SBM), P33 (33% SBM was replaced), P77 (77% PBM was replaced), and P100 (100% SBM was replaced);* [2]*SE: standard error.*

[3]*Abbreviations: ADG: average daily weight gain; ADFI: average daily feed intake; FCR: Feed*

5.4.5. Physicochemical characteristics of meat

Overall, replacing SBM with PBM did not significantly impact the majority of examined meat quality traits (Table 5.5). No effects of dietary treatment were found regarding shear force, water holding capacity (expressed as drip loss), colour of loin muscles (**L*, a*, b***) and skatole concentration (*P > 0.05*). However, the variation of this trait was large. Dry matter, protein and fat content of loin were similar across the treatments.

Nevertheless, there were slight differences in some traits. For instance, the ultimate pH of pork in the P77 and P100 groups was lower than that of pork in the control diet and P33 group (*P < 0.05*). Additionally, the ash content of loin muscles from pigs fed diets with greater SBM substitution (P77 and P100) was higher than those fed P33 and the control diet (*P = 0.001*). Finally, while the cooking loss of pork in the P100 diet was slightly higher than that in the other diets with lower levels of SBM substitution with PBM, it was still comparable to that in the control diet.

Table 5.5. Least square means for pork quality parameters of pigs fed a control diet and diets substituting SBM with PBM

Pork quality parameters	Treatment[1]				SE[2]	P value
	Control	P33	P77	P100		
Ultimate pH	5.44[ab]	5.46[a]	5.37[b]	5.35[b]	0.028	0.011
Drip loss 24 hr (%)	7.04	5.69	8.38	7.19	0.976	0.27
Drip loss 48 hr (%)	8.40	7.35	10.39	9.00	1.005	0.179
Cooking loss (%)	30.0[ab]	29.4[b]	29.5[b]	30.5[a]	0.33	0.041
Shear force (kgF)	6.31	6.68	6.06	6.56	0.318	0.508
Lightness (L*)	45.50	44.57	44.43	45.93	0.736	0.513
Redness (a*)	5.95	5.88	5.29	6.26	0.354	0.513
Yellowness (b*)	4.24	3.99	3.42	4.55	0.278	0.104
Chroma	7.33	7.16	6.31	7.77	0.419	1.662
Hue	34.79	33.25	33.2	34.98	1.336	0.618
Skatole (ng/ml of fat)	7.52	4.68	3.95	10.78	2.786	0.311
Chemical composition, % as fresh meat						
Dry matter	25.88	25.71	25.69	25.82	0.189	0.883
Crude protein	23.53	23.65	23.70	23.59	0.161	0.888
Fat	1.36	1.14	1.10	1.21	0.121	0.458
Ash	1.19[a]	1.19[a]	1.22[b]	1.23[b]	0.008	0.001

[1]*Control (100% SBM), P33 (33% SBM was replaced), P77 (77% was replace), and P100 (100% SBM was replaced).*

[2]*SE: standard error*

[a, b] *Values in the same row with different superscripts are different (P < 0.05).*

5.5. Discussion

Poultry byproduct meal (PBM) is a nutrient-rich feed ingredient derived from rendered poultry byproducts such as heads, feet, and internal organs. With its high levels of protein, ash, and other essential nutrients, PBM has shown promise as a replacement for fish meal in aquaculture and as a protein supplement in young pig diets (Galkanda-Arachchige et al., 2020; Zier et al., 2004). Yet, despite these encouraging findings, there remains a dearth of research into the effects of feeding PBM for growing–finishing pigs on growth performance pork quality. Previous studies on PBM in growing-finishing pigs have yielded conflicting results compared with young pig research. The recent lifting of the ban presents an opportunity to revisit this issue. There is much to learn about the implications of using PBM for pigs in terms of growth performance and pork quality.

5.5.1. Feeding value of PBM

PBM is widely acknowledged as a valuable protein source for farmed animals owing to its high protein content, which is over 60%, and abundance of essential AAs. Nonetheless, the precise contents of PBM may differ between studies owing to the varied characteristics of raw materials and processing conditions used in each study.

The laboratory analysis conducted in this study revealed that the levels of crude protein and AAs in PBM were similar to values reported by NRC (2012) and the other recent publications (Kerr et al., 2019; Lewis et al., 2019; Yoo et al., 2019). However, crude protein and AA profile of PBM revealed in the present study were lower than those in other studies, such as Keegan et al. (2004) and Sung et al. (2022). In contrast, several studies have reported much lower values of crude protein and AA profiles than those observed in the present study (Ye et al., 2011; Mahmood et al., 2018). Within 16 PBM samples representing different geographical locations and animal rendering facilities, Kerr et al. (2019) observed a range from 55 to 71% for CP, 3.1 to 4.6% for Leucine, 2.7 to 4.0 for Lysine, 1.8 to 2.6% for Methionine. Similarly, a meta-analysis conducted by Galkanda-Arachchige et al. (2020) reported protein content ranging from 51 to 72% for PBM across 47 studies. The composition of PBM, which is made from inedible materials from poultry slaughter, including bones, offal, and undeveloped eggs, can vary across facilities resulting in the high variation of the chemical composition of PBM.

Meanwhile, nutritional values of SBM are relatively constant due to uniform processing conditions and homogeneous soybean varieties used in the process (Ferket et al., 2002).

Furthermore, research has shown that the digestibility of amino acids (AA) in processed animal proteins (PAPs) is not equivalent to that of soybean meal (SBM) (Rojas and Stein, 2013). Animal proteins, in general, often contain a high proportion of collagen (around 80%), which is derived from connective tissue, skin, tendon, and cartilage (Chiba, 2000). Collagen is a source of low biological value AAs that can reduce the overall digestibility of AAs in the protein (Eastoe and Long, 1960). Furthermore, the use of high temperatures during the processing of processed PBM to eliminate excess moisture and neutralize potentially harmful microorganisms may trigger the Maillard reaction and racemization, which could result in reduced amino acid digestibility and lower energy utilization (Oliveira et al., 2020; Sung et al., 2022). For example, Sung et al. (2022) reported that autoclaving time during PBM processing linearly reduced apparent total tract digestibility (ATTD) of gross energy (GE) and nitrogen and metabolizability of GE (Sung et al., 2022). The quality of AAs in PBM affects the estimation of standardized ileal digestibility AAs, which differs by 20-30% across peer reports (Kerr et al., 2019).

Inaccurate nutritive value information of PBM leads to inadequate or imbalanced nutrient supply for growth. The wide range of nutritive quality and digestibility of PBM makes it challenging to formulate diets for pigs, however, it is better to balance diets regarding the nutrient digestibility rather than the chemical composition of PBM diets. In the present study, the digestibility of PBM for growing-finishing pigs was not determined. Instead, assuming that the digestibility of PBM in this study, like chemical composition, is the same as reported by NRC (2012), the information on ileal digestibility AA from NRC (2012) was used to formulate diets that exceeded nutrient requirements for growing pigs. The objective of this study is to investigate the impact of replacing SBM with PBM in grower-finisher diet on pig growth performance, while ensuring that the diets fulfil the necessary nutrient requirements. Given the considerable variability in the nutritive value and digestibility of PBM, formulating a diet that can meet the optimal growth performance of pigs can be challenging for farmers who lack the resources to conduct laboratory analysis of feed ingredients. Therefore, this study aims to provide a reference for the formulation of diets for growing-finishing pigs, particularly in light of the observed variability in PBM quality in previous research.

5.5.2. Effect of replacing SBM with PBM on growing-finishing pig production

Based on the nutritive value of PBM, it is expected to be an excellent protein source for pigs. However, previous research on using PBM for weaning and growing pigs yielded conflicting results. This inconsistency underscores the need for further investigation and careful consideration of the specific growth stage when making dietary recommendations.

Studies on young pigs showed no effects on growth performance with diets that substituted other expensive protein supplements with PBM. A study by Zier et al. (2004) found that 20% PBM could replace blood meal and fish meal, as well as a portion of SBM in weaner pig diets, without affecting the overall performance of young pigs during 26 days post-weaning period. Additionally, Keegan et al. (2004) demonstrated that PBM could be used in weaner diets in place of spray-dried animal plasma. That study also showed a linear increase in gain:feed of weaners when PBM was included in the corn-soybean diet with 10% spray-dried whey. In contrast, the two studies that fed diets with PBM to growing-finishing pigs reported a negative impact on pig growth performance. As reported by Tibbetts et al. (1987), pigs fed a diet containing 30% poultry offal silage (60% ground poultry offal, 30% ground shelled corn, 5% dried molasses, and 5% *L. acidophilus* culture) had a slower growth rate, poorer feed conversion, and smaller longissimus muscle size compared to those fed a commercial diet. Similarly, Shelton et al. (2001) reported that finishing pigs fed diets using PBM as the sole protein source had a lower average daily gain and average daily feed intake and increased average backfat relative to pigs fed a SBM-based diet.

The failure to effectively use poultry PBM in pig diets may be due to inaccurate diet formulation that failed to meet requirements for growing pigs. As mentioned above, PBM poses a challenge to feed formulation due to variations in its nutritive value. For example, Tibbetts et al. (1987) explained that the lower level of lysine in poultry offal silage diet resulted in the negative impact of the diet on pig growth performance. In the present study, all the diets were formulated to meet or exceed the nutrient requirements and were equal in digestible energy and lysine. Unfortunately, the lower lysine content in the P33 diet, which was not expected, could have resulted in the higher FCR of the pigs fed that diet compared to the other groups. Due to the high degree of variability in the nutrient profile and digestibility of PBM, precise diet formulation posed a challenge.

However, overall, the present research demonstrated that PBM could effectively substitute SBM without detrimental effects on pig growth performance during the grower-finisher stage. Furthermore, I found that pig feeding behaviour was not adversely affected when PBM was included in their diets. Given that pig voluntary feed intake is affected in case the diet less appetite, or bulkiness or imbalance in nutrients (Nyachoti et al., 2004), the present research confirms that PBM is similar to SBM in terms of appetite.

5.5.3. Effect of replacing SBM with PBM on meat quality

It was hypothesized that the difference in fatty acid composition of PBM and SBM might modify the fatty acid composition and concentration in pork, possibly affecting pork quality. Previous literature indicated that PBM is higher in saturated fatty acids compared to SBM (Siddik et al., 2019), while SBM is superior in polyunsaturated fatty acids in comparison to PBM (NRC, 2012). Meat with a high polyunsaturated fatty acids content may be of inferior quality (known as "soft" meat) with an increased susceptibility for oxidation, reducing the shelf life of the product (Rosenvold and Andersen, 2003; Wood et al., 2004). However, my research showed no effect of partly or completely replacing SBM with PBM on any of the evaluated traits of meat quality or skatole concentration. As far as I know, this is the first study to examine the effect of incorporating PBM in the diets of pigs during their growth and finishing stage on meat quality. Further study needs to evaluate the effect of feeding PBM on fat characteristics.

The results of the present study align with other findings where SBM was substituted for alternative dietary protein sources. Altmann et al. (2019) reported that meat from pigs fed Spirulina or *Hermetia illucens* larval meal was comparable in quality to meat from soy-fed animals, according to sensory and physico-chemical meat quality analyses, although this study found an effect on fat characteristics of backfat. Alternative plant-based protein sources, such as local oilseed meals or legume plants, can possibly replace SBM in pig diets without compromising meat quality. Qin et al. (2015) noted a decrease in muscle-specific AAs when substituting 100% SBM with cottonseed meal but found no impact on meat quality traits. Similarly, Zmudzińska et al. (2020) found that neither pork meat quality parameters determining the technological suitability of the meat nor proximal composition of loin muscles were affected by feeding pigs with the diet based on legume seeds and rapeseed meal instead of the conventional diet based on SBM. These findings suggest that while the type of protein source used in pig diets may affect fat characteristics or AA profile of loin muscles, it may not have a significant impact on overall meat quality. Consequently, when considering the integration of alternative protein sources, such as plant-based meals, in pig diets, it is vital to evaluate their impact on pig performance and fat characteristics while not requiring a thorough examination of their impact on meat quality.

In addition, compared with plant protein sources, PBM can be a better source of phosphorus for growing-finishing pigs due to its higher biological availability of phosphorus from bones included in PBM (Woyengo and Nyachoti, 2013; Woyengo et al., 2022). In my calculation to balance mineral contents across diets, less dicalcium phosphate (CaHPO4) and sodium phosphate dibasic (Na2HPO4) were used in diets containing high inclusion of PBM. However, ash content of pork samples from groups fed high levels of PBM was greater than the control and P33 diets, indicating that digestibility of ash, specifically calcium and phosphorous, in those pigs was greater than the estimate I used when formulating diets. There is a lack of information on digestibility of phosphorus and calcium in protein sources derived from slaughter by-products for pigs. Pig producers cannot formulate optimal diets based on these products without knowledge of their available phosphorus and calcium contents. Futher research needs to evaluate biological availability of phosphorus and calcium in PBM for growing-finishing pigs.

5.6. Implications

The success of using PBM in diets formulated for growing-finishing pigs expands the opportunities to select alternative protein sources. Global PBM production is estimated at around 40 million tons per year, which can be tapped to reduce reliance on SBM as a protein source, particularly in countries that do not produce much or any SBM. Using PBM has two key benefits. Firstly, it can address supply chain disruptions because PBM is widely available and can be produced locally in countries with high poultry production. Secondly, using PBM instead of SBM can help achieve environmental sustainability goals by reducing waste and lowering the carbon footprint of pig diets that rely on soybean production and transportation. Thirdly, in terms of economics, PBM based diet was shown to be less expensive than SMB based diet in the present study (1.19NZD vs 1.26NZD/kg diet). Therefore, PBM can also be a cost-effective alternative feed for SBM. Given that pigs are already efficient at converting feed into animal protein, incorporating more PBM in pig feed can make pork more sustainable, leading to a more efficient, profitable, and sustainable livestock industry. The research findings offer valuable insights into how the quest for alternative feedstuffs can avoid compromising pig growth performance and meat quality.

5.7. Conclusion

Our study suggests that poultry by-product meals (PBM) can serve as a viable primary protein source in growing-finishing pig diets without compromising pig production. The inclusion of PBM in pig feed can contribute to a more efficient and sustainable livestock industry while also providing a rich source of calcium and phosphorus for growing-finishing pigs. However, given the significant variation in the quality and composition of PBM, it is crucial to ensure that this by-product is added in a manner that meets the nutrient requirements for optimal pig growth. The present research findings can serve as a useful reference for farmers who are unable to conduct lab analyses for feed ingredients, particularly given the observed variability in PBM quality in previous research.

CHAPTER VI.

THE EFFECT OF SUBSTITUTING SOYBEAN MEAL WITH THE ALTERNATIVE OILSEED MEAL IN GROWER-FINISHER DIETS FOR PIGS ON PIG GROWTH PERFORMANCE, CARCASS YIELD AND MEAT QUALITY: A META-ANALYSIS

A paper from this chapter is under review for publication in Animal Feed Science and Technology:

Can alternative oilseed meals successfully substitute soybean meal in grower-finisher pig diets? An insight from a meta-analysis

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Abstract

The universal use of soybean meal in animal feed raises issues regarding deforestation in soybean-producing countries and the world's dependency on soybean exportation. Therefore, replacing soybean meal with other oil-processing co-products in grower-finisher pig diets has been attempted in many studies, with varying degrees of success and failure. The various outcomes across studies might be due to the replacement level of soybean meal with the alternative oilseed meal and the growing stage of the pigs. Therefore, a meta-analysis is necessary to quantify the effect of substituting soybean meal with alternative oilseed meal at low- and high-level during grower – finisher period. Twenty-eight studies were included in this meta-analysis. The meta-analysis was conducted according to the guideline of Harrer et al. (2021). Overall, the result showed that replacing soybean meal with the alternative oilseed meal impaired pig daily weight gain while remained daily feed intake, therefore, increased the feed conversion ratio (FCR) for both growers and finishers. In addition, feeding the diets that replaced soybean meal with the alternative oilseed meal reduced carcass and loin yield but did not impact meat quality. These negative impacts of the alternative oilseed meal on pig growth performance might be due to high fibre concentration and other antinutritional factors. However, the effect of subgroup for low and high level of replacement was not clearly found. The heterogeneities of the analysis for most parameters of pig growth performance were substantial. It might be due to the high variation in the quality of the alternative oilseed meal used across studies. Therefore, improving the quality of the alternative oilseed meal by removing the hull during the oil extraction process or eliminating antinutritive factors by breed technology is essential.

Keywords: Alternative protein source; Oil processing co-products; Growing – finishing pigs; Growth performance; Meat quality; Pig production.

6.1. Introduction

Soybean meal (SBM) is the principal protein source for farmed animals worldwide. However, the wide use of SBM raises many economic and environmental problems. Deforestation and biodiversity loss in Amazon countries is attributed to the expansion of soybean production in these areas, which produces most of the world's soybean supply (Ritchie & Roser, 2021). At the same time, many countries heavily depend on exporting soybean for protein feed for farmed animals. SBM price volatility, trade distortions and the accessibility of the feed source impact livestock production in these countries. Covid-19 is a learned lesson of logistic disruption and increasing feed prices, which affected whole farm production (Hashem et al., 2020). The European Parliament calls for research on substituting soy-based feeds with local protein sources to resolve the protein deficit in Europe (European Parliament, 2011).

Given the comparable protein content and amino acids profile with SBM, the other by-products from the oil processing industry are hypothesized to be feasible to replace SBM in pig diets. Therefore, many studies investigated the effect of replacing SBM with alternative oilseed meal on pig growth performance, carcass yield and meat quality. Unfortunately, some studies have failed to include alternative oilseed meals in growing-finishing pig diets (Shelton et al., 2001; Smit & Beltranena, 2017; Thacker, 2001). In contrast, several studies showed no negative impact on pig growth traits when replacing SBM with alternative oilseed meals (Castell & Cliplef, 1993; Dora A. Roth-Maier et al., 2004). Those different outcomes across studies might be due to the variation in the quality of oilseed meals, the replacement level and the growing stage of pigs. Furthermore, the various results from previous publications confuse farmers about applying alternative oilseed meals for pigs.

The current paper presents a meta-analysis that quantifies the impact of substituting SBM with alternative oilseed meals, including canola, camelina, cottonseed, sunflower, and rapeseed meal, on pig production at different growth stages and replacement levels. While a previous meta-analysis by Hansen et al. (2020) investigated the effects of incorporating canola/double low rapeseed meal on pig growth performance among weanling and growing-finishing pigs, no meta-analysis has been conducted regarding the impact of other alternative oilseed meals on carcass yield and meat quality in grower-finisher diets. Moreover, this meta-analysis aims to assess the efficiency of substituting SBM with various alternative oilseed meals, including but not limited to canola/double low rapeseed meal, on pig growth performance, carcass yield, and meat quality.

6.2. Methodology

6.2.1. Data collection

This data collection was conducted in February 2022. Sources of search studies included PubMed (https://pubmed.ncbi.nlm.nih.gov/) and Web of Science (https://www.webofscience.com/).

6.2.1.1. Searching strategy

The search strategy is shown in Table 6.1.

Table 6.1. Searching strategy

Search	Query	Items found
PubMed Search Strategy		
#1	pig or gilt OR boar OR swine OR hog	281682
#2	soybean meal	17467
#3	oilseed meal OR canola meal OR camelia meal OR rapeseed meal OR sunflower meal or cottonseed meal	2444
#4	growth performance OR ADG OR ADFI OR FCR OR G: F OR carcass OR backfat or lean	32963
#5	piglet or weaned pig or weanling pig or nursery pig or sow OR broiler OR chicken OR poultry	253637
(#1 AND #2 AND #3 AND #4) NOT #5		50
Web of Science Search Strategy		
#1	"pig" OR "swine" OR "gilt" OR "barrow" OR "Grower" OR "finisher"	400552
#2	“Soybean meal” OR “soybean cake”	15476
#3	"Oilseed meal" OR "canola meal" OR "rapeseed meal" OR "sunflower meal" OR "cottonseed meal" OR "camelina meal" OR "oilseed meal" OR "canola cake" OR "rapeseed cake" OR "sunflower cake" OR "cottonseed cake" OR "camelina cake"	6178
#4	"grow" OR "weight gain" OR "feed conversion" OR “ADG" OR "ADWG" OR "AFI" OR "ADFI " OR "FCR" OR "G: F "	308479
#5	“Piglet” OR “weaned pig” OR “weanling pig” OR “nursery pig” OR “sow” OR “broiler” OR “chicken” OR “poultry”	278468
#1 AND #2 AND #3 AND #4 NOT #5		107

6.2.1.2. Data inclusion

After checking duplicates across the two searching sources, 107 articles were used for scanning abstracts. Studies were considered eligible if they met the following inclusion criteria:

- ✓ The studies were randomized controlled trials;
- ✓ Growers range from 20 kg to 65 kg live weight;
- ✓ Finisher live weight was greater than 50 kg.

6.2.1.3. Data exclusion

The exclusion criteria were:

- ✓ Studies do not meet the Inclusion criteria;
- ✓ Studies on native pure pig breeds or crossbred pigs with local breeds;
- ✓ Studies with cannulated pigs;
- ✓ Studies not equal in initial weight of experimental pigs;
- ✓ Studies mixing the replacement of SBM with oilseed meals and other protein sources;
- ✓ Studies are not equal in the intensity of energy and protein across treatments;
- ✓ Studies were not in English.

After scanning abstracts for inclusion and exclusion criteria, 28 publications were included in this meta-analysis (Supplementary Table 1 of the appendix). The mean beginning and ending body weight of pigs during the growing phase was 27.00 and 65.79 kg, while beginning and ending body weight of pigs in the finishing phase was 59.45 and 102.53 kg.

6.2.2. Information extraction

Relevant data were extracted from all selected studies into a database in Microsoft Excel. The database included study characteristics, research design, outcome comparison of growth performance, carcass, and meat quality traits. Outcome data for each comparison were presented with a mean value and a standard deviation (SD).

The study characteristics included: author information (first author, year); SBM and alternative oilseed meal component of the control diet and the experimental diets, following by diet nutritive value gross energy (GE), crude protein (CP), crude fibre (CF), neutral detergent fibre (NDF), acid detergent fibre (ADF) of each treatment; type of oilseed meal; level of replacement; growth stage (grower, finisher); breed; initial body weight (kg) and final body weight (kg); the number of replications (number of replications are the experimental unit of the studies, they can be number of individual pigs or number of pens).

The outcome data is means and variances for average daily weight gain (ADG), average daily feed intake (ADFI), feed conversion ratio (FCR), dressing percentage (%), lean meat (%), loin eye muscle (cm^2), pH, drip loss, cooking loss, lightness (L), redness (a^*), yellowness (b^*). Each trait must have at least 10 comparisons between the control diet and experimental diets, otherwise will b To investigate the impact of SBM replacement at different growth stages, the replacements were classified as either low (equal to or less than 50%) or high (greater than 50%) levels at both grower and finisher stage.

6.2.3. Data conversion

In all the studies included in the present meta-analysis, the corresponding variances were reported as standard error of mean (SEM), or coefficient of variation (CV). Standard deviation (SD) was calculated using the formulas:

$SD = SEM \times \sqrt{n}$

$SD = (CV \times \bar{x}) \div 100$

where n, $\bar{x}$ refers to the number of replications and mean of each treatment.

In the study that feed conversion efficiency was expressed as gain:feed, the mean FCR and variance of FCR were estimated according to Vanrolleghem et al. (2019)

$FCR = \frac{1}{(gain:feed)}$ and $Var\ FCR = \frac{1}{(gain:feed)^4} \times Var\ (gain:feed)$

6.3. Data analysis

The meta-analysis was conducted using Rstudio, followed the guideline of Harrer et al. (2021). A random-effect model was applied to analyze the effects of replacement SBM with the alternative oilseed on pig growth performance, carcass and meat quality traits.

Mean differences (MD) ($MD = M_{treatment} - M_{control}$)

The standard error of mean difference was obtained using this formula:

$SD_{MD} = Spooled \sqrt{(\frac{1}{n1} + \frac{1}{n2})}$, while $Spooled = \sqrt{(\frac{(n1-1)S1^2 + (n2-1)S2^2}{(n1-2)+(n2-1)})}$

Heterogeneity: The inconsistency index (I^2 statistic) used to quantify between-study heterogeneity. $I^2 < 25\%$: no heterogeneity; I^2 = 25%-50%: low heterogeneity; I^2 = 50% -75%: moderate heterogeneity; $I^2 > 75\%$: substantial heterogeneity (Higgins & Thompson, 2002).

Forest plots were produced to demonstrate MD with 95% confidence intervals (95% CI) and weight of the studies, placed in the appendix.

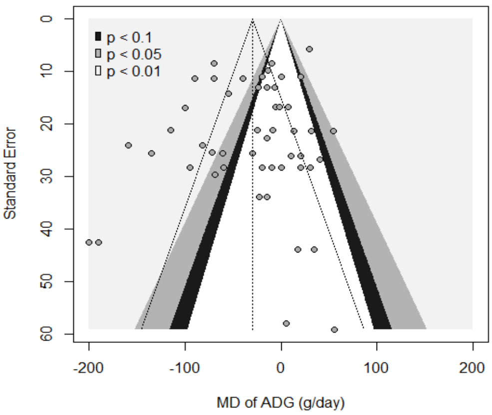
Publication bias: Egger's test was used to assess potential publication bias. The Eggers's test was regarded as significant at $P \leq 0.05$ (Egger et al., 1997). Publication bias was also inspected by contour-enhanced funnel plots (Peters et al., 2008).

6.4. Result

6.4.1. Publication bias

Publication bias for growth performance traits was illustrated in Figure 6.1, Figure 6.2, and Figure 6.3 for growth performance. Figure 6.4 and Figure 6.5 demonstrated publication bias for carcass yield and meat quality traits. There was no evidence of publication bias across studies in this meta-analysis. P values for Egger's test were greater than 0.05 for all given parameters.

a) Grower



b) Finisher

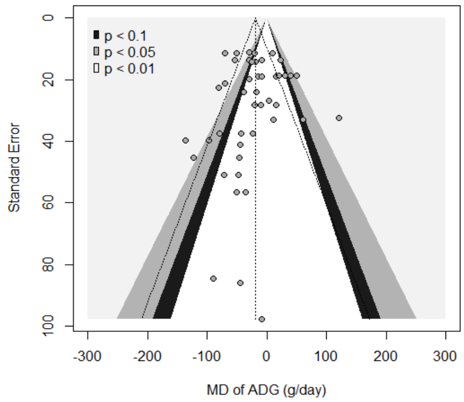


Figure 6.1. Funnel plots of the meta-analysis for average daily gain (ADG)

a) Grower b) Finisher

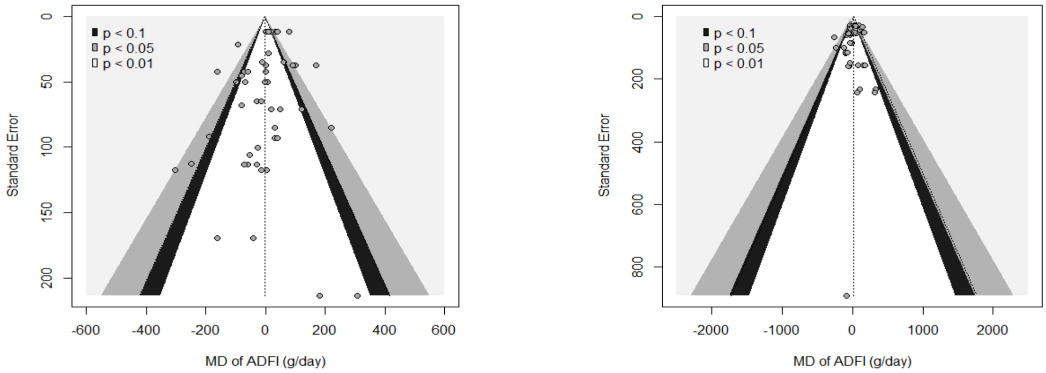


Figure 6.2. Funnel plots of the meta-analysis for average daily feed intake (ADFI)

a) Grower

b) Finisher

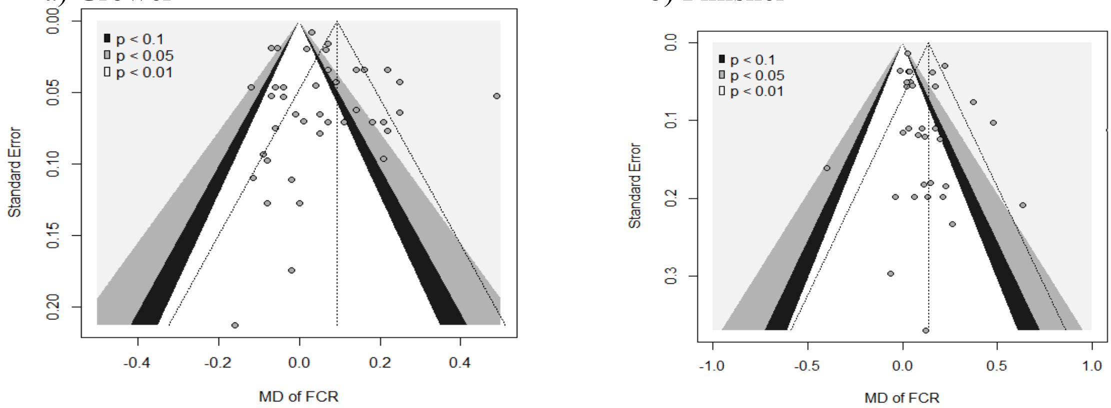
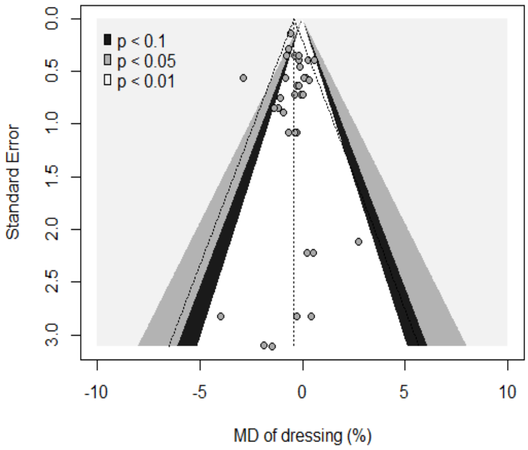
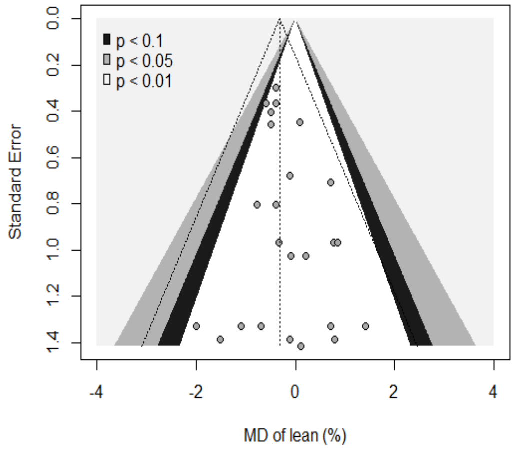


Figure 6.3. Funnel plots of the meta-analysis for feed conversion ratio (FCR)

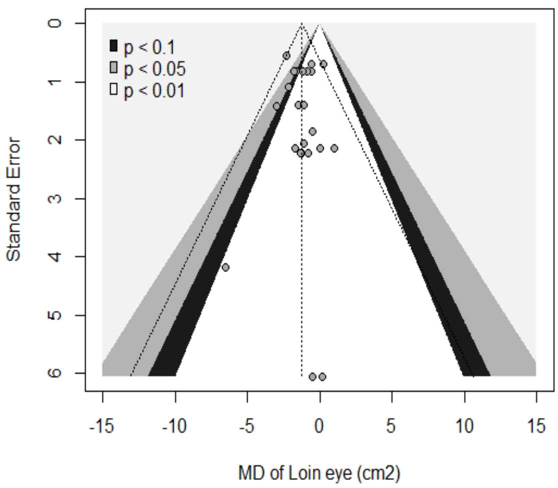
a) Dressing yield

b) Lean yield





c) Loin eye area



d) Backfat thickness

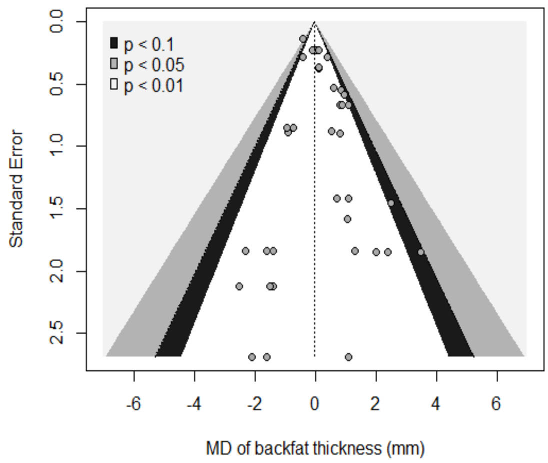


Figure 6.4. Funnel plots of the meta-analysis for carcass yield traits

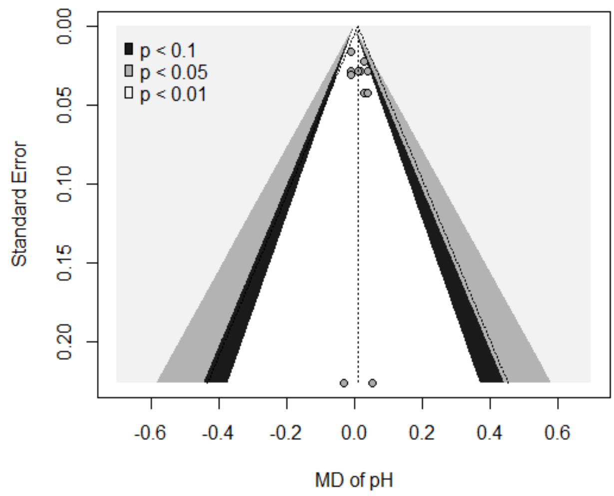
a) . Funnel plots of the meta-analysis for dressing yield;

b) . Funnel plots of the meta-analysis for lean yield;

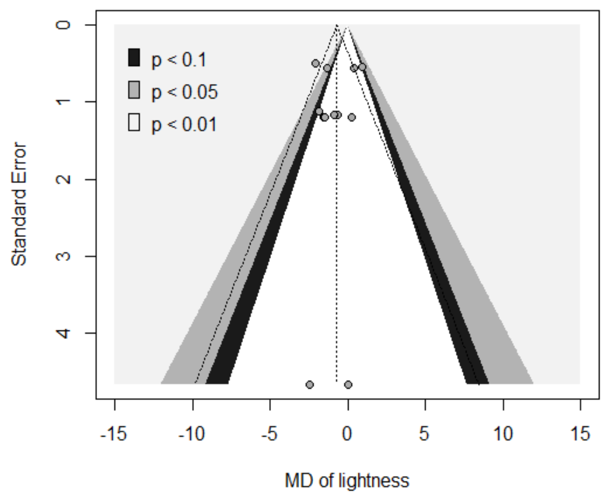
c): . Funnel plots of the meta-analysis for loin eye area;

d): . Funnel plots of the meta-analysis for backfat thickness.

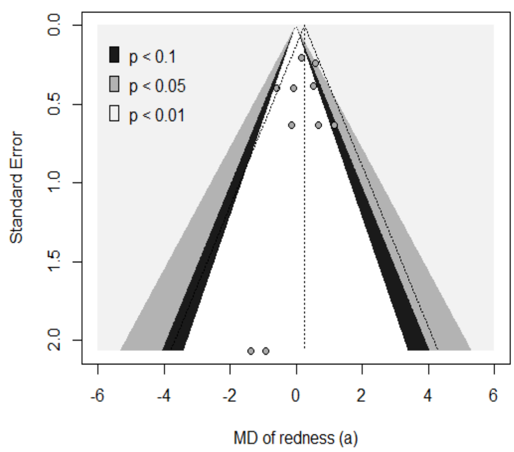
a) pH



b) Lightness



c) Redness



d) Yellowness

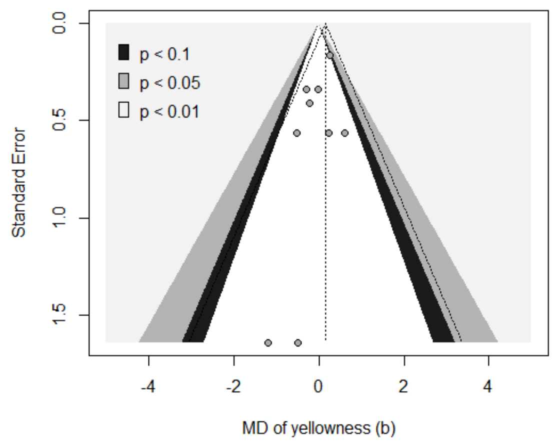


Figure 6.5. Funnel plots of the meta-analysis for meat quality traits

a) . Funnel plots of the meta-analysis for pH;

b) . Funnel plots of the meta-analysis for lightness (L*);

c): . Funnel plots of the meta-analysis for redness (a*);

d): . Funnel plots of the meta-analysis for yellowness (b*).

6.4.2. Effect of SBM replacement by alternative oilseed meals on pig growth performance

The effects of replacing SBM with the alternative oilseed meals at low level (<50%) and high-level (>50%) on pig growth performance traits are summarized in Table 6.2.

Table 6.2. The effect of replacing SBM with alternative oilseed meals in grower – finisher diet on pig growth performance

Variables[1]	Replacement level	N	WMD	P_value	95% CI	I^2 (%)
	ADG, g/d					
Grower	Low	21	-21.16	0.037	[-40.922; -1.391]	74.7
	High	28	-21.93	0.010	[-38.059; -5.806]	90.3
	Overall	49	-21.64	0.001	[-33.677; -9.608]	88.3
Finisher	Low	12	0.43	0.679	[-16.261; 17.119]	47.3
	High	27	-20.42	0.005	[-37.121; -3.722]	73.7
	Overall	39	-13.83	0.034	[-26.562; -1.108]	71.8
	ADFI, g/d					
Grower	Low	19	22.46	0.038	[1.408; 43.508]	48.5
	High	26	-3.68	0.784	[-31.018; 23.659]	77.7
	Overall	45	9.37	0.335	[-10.024; 28.767]	70.1
Finisher	Low	11	16.48	0.460	[-31.315; 64.277]	63.7
	High	24	28.73	0.119	[-7.936; 65.388]	63.5
	Overall	35	23.75	0.088	[-3.681; 51.179]	62.7
	FCR					
Grower	Low	17	0.07	0.015	[0.015; 0.119]	69.9
	High	19	0.05	0.248	[-0.035; 0.127]	89.5
	Overall	36	0.05	0.026	[0.007; 0.101]	85.0
Finisher	Low	10	0.07	0.007	[0.024; 0.113]	0
	High	24	0.16	0.006	[0.049; 0.264]	87.6
	Overall	34	0.13	0.002	[0.053; 0.205]	82.8

CI: confidence interval; N: Number of comparisons; ***I_2****: heterogeneity; WMD: weighted mean difference*

[1] *ADFI: average daily feed intake; ADG: average daily weight gain: FCR: feed conversion ratio*

Overall, the replacement of SBM with the alternative oilseed meals did not impact feed intake, but reduced growth rate and increased FCR. However, the variation between study outcomes in this meta-analysis was considerable. The heterogeneities of the analysis for most parameters were substantial (I^2 > 50). There was no significant difference between low level and high level of replacing SMM with the alternative oilseed meal. P value for subgroup was greater than 0.05. The corresponding forest plots were presented from Supplementary Figure 1 to Supplementary Figure 6 of the appendix.

Regarding pig growth rate, replacing SBM with an alternative oilseed meal, either at a low or high level in grower diets, significantly reduced weight gain of growing pigs. Weighted mean difference (WMD) of ADG in the grower phase across both inclusion levels was around -21 g/d ($P < 0.05$). At finisher stage, the overall impact of replacing SBM with the alternative oilseed meal was less severe than in grower stage, where WMD of ADG across both inclusion levels was -13 g/d. However, the reduction of the WMD in this stage is mainly driven by the impairment of ADG at high replacement level. The meta-analysis did not show an effect of replacing SBM with the alternative oilseed meal on ADG of finishers at the low replacement level ($P > 0.05$).

Only the replacement at low level also significantly increased feed consumption of growers ($P < 0.05$). However, overall, replacing SBM with an alternative oilseed pig diets did not change feed consumption during grower - finisher stage ($P > 0.05$). Given a lower growth rate while maintaining or increasing feed intake, pigs fed an alternative oilseed meal generally had a higher FCR, except the situation for growing pigs fed high level replacement. There was no difference in FCR between growers fed control diets and the diets containing high level of SBM replacement.

6.4.3. Effect of soybean replacement by alternative oilseed meals on carcass yield and meat quality

The effects of replacing SBM with an alternative oilseed meal on carcass and meat quality traits are summarised in Table 6.3. Due to the few numbers of studies included and no significant difference in low and high replacement on pig growth performance, there was no classification for the level of SBM replacement.

Overall, replacement with an alternative oilseed meal resulted in lower dressing percentage, lean meat percentage and loin eyes muscle area, with WMD decreased by -0.42%, -0.36%, and -1.21 cm^2, respectively. However, backfat thickness and meat quality traits were not affected by replacing SBM with an alternative oilseed meal. In addition, between-study heterogeneities were low for most carcass yield and meat quality traits ($I^2 < 25\%$), except for

Lightness (L). The corresponding forest plots were presented from Supplementary Figure 7 to Supplementary Figure 15 of the appendix.

Table 6.3. The effect of replacing SBM with the alternative oilseed meals in grower – finisher pig diets on carcass yield and meat quality

Variables	N	WMD	P_value	95% CI	I^2 (%)
Dressing (%)	33	-0.42	< 0.001	[-0.616; -0.224]	26.1
Lean (%)	21	-0.36	0.001	[-0.560; -0.156]	0
Loin (cm^2)	21	-1.21	< 0.001	[-1.612; -0.807]	0
Backfat thickness (mm)	33	-0.02	0.806	[-0.193; 0.151]	26.4
pH	12	0.01	0.186	[-0.004; 0.019]	0
Driploss (%)	9	-0.011	0.952	[-0.439; 0.417]	0
Lightness (L)	11	-0.571	0.172	[-1.443; 0.294]	56.7
Redness (a)	10	0.251	0.105	[-0.0633; 0.557]	22
Yellowness	10	0.15	0.098	[-0.034; 0.342]	0

CI: confidence interval; N: Number of comparisons; I_2*: heterogeneity; WMD: weighted mean difference*

6.4.4. Fibre content in the control diet compared with the alternative oilseed meal diets

Fibre contents in the control diet compared with the alternative oilseed meal diets are shown in Table 6.4. The mean value of CF, NDF and ADF across control diets and experimental diets are much higher than the control diets. In addition, increasing the level of replacement of SBM with oilseed meals leads to a greater concentration of fibre in diets.

Table 6.4. Mean fibre content across studies (as fed basic).

Fibre[1]		CF (g/kg)		NDF (g/kg)		ADF (g/kg)	
Period	Level of replacement	Control	Treatment	Control	Treatment	Control	Treatment
Grower	Low	38.23	44.07	110.08	143.86	45.70	73.25
	High	39.39	47.98	122.71	149.21	58.08	77.40
Finisher	Low	37.56	44.52	90.06	107.80	35.3	50.45
	High	40.04	48.29	135.35	155.64	54.42	77.11

[1] *ADF: acid detergent fibre; CF: crude fibre; NDF: Neutral detergent fibre*

6.5. Discussion

Our meta-analysis corroborates the findings of Hansen et al. (2020) that the incorporation of alternative oilseed meal in grower-finisher diets reduced average daily gain (ADG) while did not impact average daily feed intake (ADFI), hence, increased feed conversion ratio (FCR). However, the impact of the level of substitution of SBM with alternative oilseed meal was not clear. Furthermore, the present study results demonstrate that replacing SBM with alternative oilseed meal negatively affects carcass yield but has no significant effect on meat quality.

Higher fibre content in alternative oilseed meals compared with SBM could be the reason for the impairment of pig growth rate and feed conversion efficiency. Fibre reduces digestibility and utilization of all nutrients in growing pigs. Insoluble fibre may decrease nutrient digestibility by hydrophobic binding of amino acids and minerals, and increasing feed passage rate in the digestive tract. For example, Thacker (2001) reported that 5-10% reduction of total tract digestibility coefficients for DM, CP and GE when replacing SBM with canola meal. Similarly, Smit et al. (2014) observed a significant reduction of the apparent total tract digestibility of GE, CP, DM, organic matter and ash when SBM was replaced by canola meal. The ileal digestibility of amino acids in the diets replacing 100% SBM by rapeseed meal and cottonseed meal was considerably lower than the SBM-based diet (Shim et al., 2003). Since digestible dietary energy is low, pigs on alternative oilseed diets attempt to increase feed consumption to compensate for the low energy intake. However, feed intake capacity depends on gut volume, which increases as the body weight increases and the capacity to digest energy and nutrients of fibrous diets improves (Dierick et al., 1989; Goff et al., 2002; Noblet & van Milgen, 2004a). In finishing pigs, the larger size of the hindgut and a lower relative feeding level allows microbial flora to better digest fibre, and the digestibility of the dietary fibre fraction of diets improves. Therefore, finishing pigs seems less affected by the replacement SBM by alternative oilseed meal as they tend to consume more feed to meet their energy requirement.

Nonetheless, despite an increased ability of finishing pigs to digest fibre and can eat more on oilseed meal diets, this does not offset overall reduced energy intake, which results in slower weight gain, lighter weight and less lean at slaughter. In addition, the presence of antinutritional factors (ANFs) in alternative oilseed meals possibly impacts pig production. They are chemical compounds containing secondary plant metabolites produced by oilseed plants. These compounds, such as phenolic in sunflower meal, bind with amino acids, vitamins, and minerals, resulting in the impairment of nutrient absorption in the gastrointestinal tract (Lomascolo et al., 2012). High consumption of free gossypol (over 146 ppm) causes feed intake and weight depletion in growing pigs (Fombad & Bryant, 2004). Similarly, the glucosinolates present in canola varieties impact animals' appetizing and growth mechanisms. Glucosinolate metabolites interfere with the synthesis of thyroid hormones by impairing the uptake of iodine by the gland to synthesize the thyroid hormones. The consequence of thyroid hormone reduction is slowing down the growth rate of animals (Schöne et al., 1997). The slower growth rate leads to the lighter carcass weight of the pigs fed the experimental diets. Moreover, the negative impact of dressing percentage might link to the increase in visceral organ weight and size from long-term feeding of diets with greater fibre concentration (Wenk, 2001). In terms of pork quality, many studies show that glucosinolate or dietary fibre does not reduce meat quality (Andersen et al., 2005; Dransfield et al., 1985; Rosenvold & Andersen, 2003).

The substantial heterogeneities for growth performance in the current meta-analysis reflect the high variation in nutritional characteristics among oilseed meal sources used in different studies. Nutritive value and anti-nutritional factors of the alternative oilseed meals vary considerably depending on the varieties and processing methods (Bernard, 2011; Maison & Stein, 2014; Mejicanos & Nyachoti, 2018). The recently developed yellow-seeded varieties of canola, with a thinner seed coat, higher protein concentration, and 7% less NDF and ADF compared to conventional CM, result in the improvement of standardized ileal digestible amino acid (Berrocoso et al., 2015; Liu et al., 2016). Furthermore, the degree of dehulling determines the concentration of fibre in oilseed meals. Fibre content in oilseed meals can be reduced by 40% by dehulling, resulting in increased CP and ileal digestibility of amino acids (Mejicanos & Nyachoti, 2018). Since meal from dehulled sunflowers is comparable with SBM in nutritive value (González-Vega & Stein, 2012), it can completely replace SBM without any impact on pig growth performance and carcass yield (Cortamira et al., 2000). In the present meta-analysis, there are some studies reporting superior growth performance of pigs fed on the alternative oilseed meal.

The variation in the quality of oilseed meals can lead to inaccuracies in formulation, hence, have negative consequences on animal growth, health, and productivity. To overcome this challenge, researchers have recommended more precise methods for formulating diets using oilseed meals. Maison and Stein (2014) suggested not to formulate canola and rapeseed co-product diets based on the concentration of CP and essential amino acids because it may reduce the accuracy of estimation for the standardized ileal digestibility of essential amino acids. Little et al. (2015) found no impairment of pig weight gain and feed conversion efficiency when SBM was replaced with either high-protein or conventional CM, providing diets are formulated to contain equal quantities of digestible P and digestible amino acids. Another possible solution is to provide feed additives that can enhance the nutrient utilization of alternative oilseed meals. This can be achieved through the degradation of anti-nutritional factors (ANFs) such as phytate, α-galactosides, galactomannans, and non-starch polysaccharides. These additives can help improve the digestibility of the meal, leading to better growth performance (Shim et al., 2003).

6.6. Conclusion

The meta-analysis showed that SBM is superior to the alternative oilseed meals in the pig growth performance and carcass yield. Replacing SBM with the alternative oilseed meals reduced pig growth rate and increased feed conversation ratio. These negative impacts of the alternative oilseed meals might be due to the high concentration of fibre and other ANFs. Therefore, improving the quality of the alternative oilseed meal by removing hulls during oil extraction or eliminating ANFs by selective breeding is important. Furthermore, having an accurate estimate of AA digestibility and digestible energy is essential when formulating diets containing alternative oilseed meals to ensure sufficient nutrients so that pig growth performance is not impaired.

CHAPTER VII.

GENERAL DISCUSSION

7.1. Justification for alternative feedstuffs in pig production

The pig industry plays a vital role in the global food supply, as pork is a widely consumed meat in many cultures worldwide (OECD/FAO, 2022). According to OECD/FAO (2022), the rising demand for pork is expected to continue, driven by growing incomes and urbanization in developing countries. To meet the rising demand for pork, the pig industry continues to grow in both the number of pigs produced and through improved production efficiency via genetic selection and feeding technology (Babinszky et al., 2019).

Feed plays a crucial role in pig production in determining productivity and profitability. It provides the necessary nutrients and energy for the pigs to grow and perform to their full potential. The combination of soybean meal (SBM) and cereal grains has been a standard formulation to maximize pig growth since the 1950s (Stein et al., 2016). Cereal grains, high in starch and highly digestible, provide primary energy for growth, maintenance, and fat deposition and makeup 60-80% of growing-finishing pig diets. SBM, comprising around 20% of pig diets, is used as a protein source due to its high protein level and amino acid profile that is suitable for growing pigs. Increasing pig production will likely increase the demand for feed resources for the pig industry. However, a rise in pork production also exacerbates "feed-food" competition between humans and animals and generates concerns about the utilization of agricultural resources and environmental impacts (Van Zanten et al., 2018).

Cropping of cereal grains and SBM for pigs uses a considerable amount of arable land (Mottet et al., 2017), water (de Miguel et al., 2015; Mekonnen et al., 2019) and drives deforestation (Lathuillière et al., 2017). Meanwhile, conventional feed production is a significant source of greenhouse gas emissions (Van der Werf et al., 2005). In addition, reliance on imported feed ingredients contributes to eutrophication, acidification, and energy use (Van der Werf et al., 2005). Last but not least, with feed making up 60-70% of the direct cost of pig production (Woyengo et al., 2014), pig farmers are at risk of fluctuations in the price of the limited feed sources on the market. The conventional diets used in the swine production sector often rely on large amounts of SBM and cereal grains, contrary to sustainable development goals.

As a result, there is a growing need to explore alternative feedstuffs for pigs that are inedible to humans, cheap for producers and with or no little impact on the environment. As omnivores, pigs are ideal for converting many types of feed into meat (Zijlstra & Beltranena, 2019). These alternative feedstuffs can be by-products/co-products from other industries or locally sourced ingredients. Besides reducing reliance on limited feed sources, alternative feedstuffs might benefit pig health, well-being, and the environment. For example, dietary fibre in alternative feedstuffs may improve pigs' gut health (Jarrett & Ashworth, 2018; Jha & Berrocoso, 2015; Bienvenu Kambashi et al., 2014; Montagne et al., 2003) and reduce boar taint in pork (Hansen et al., 2008). Research and development in alternative feedstuffs have been ongoing, and farmers are encouraged to explore these options to improve their operations' sustainability. However, including alternative feedstuffs in grower–finisher pig diets need proper risk management as they can contain high levels of insoluble fibre and anti-nutritional factors (ANFs), which might impact pig growth performance and pork quality.

Numerous innovative feedstuffs for pigs have been suggested, and in the context of this thesis, representative alternative feedstuffs were chosen for investigation. Therefore, the four research chapters are as follows:

Chapter 3 examined the impact of high levels of co-products, such as distiller's dried grains with soluble (DDGS), wheat middling, and canola meal, on finishing pigs' growth performance, meat quality, and skatole levels.

Chapter 4 evaluated the effects of feeding lucerne and/or supplying lucerne as enrichment material to growing-finishing pigs on their performance and behaviour.

Chapter 5 analysed the effects of substituting SBM for poultry by-product meal (PBM) at increasing levels in growing-finishing pig diets on the animals' growth performance, carcass yield, and meat quality.

Chapter 6 conducted a meta-analysis of previous studies to assess the effects of replacing SBM with different types of alternative oilseed meals in the diets of growing-finishing pigs.

This research aimed to address the future of sustainable pork production by investigating the effects of alternative feedstuffs on pig performance, meat quality, and behavior. This research will provide guidance for farmers looking to adopt more sustainable dietary options for pigs.

7.2. Research findings and implications

This research demonstrates the feasibility and inherent potential for enhancing pork quality and ensuring the welfare of pigs. The findings derived from the evaluation of representative alternative feedstuffs for pigs achieved deeper insights in relation to their potential contribution to meeting the nutritional requirements of pigs. In addition, the findings offer practical solutions to address the challenges facing the pig industry, including animal welfare and customer acceptability toward sustainable pork production.

The overarching objective of the present research was to discern sustainable dietary alternatives that effectively mitigate the dynamic challenges related to conventional diet formulation in the pig industry. Ultimately, the current research has the potential to contribute to the broader field of animal nutrition and agricultural sustainability while also benefiting farmers and consumers. More details will be discussed in the subsequent sections.

7.2.1. Mixed co-products can be included in finisher diets up to 60%

The objective of Chapter 3 was to investigate the effect of a diet formulated with a high inclusion of a combination of co-products in finisher diets on pig growth performance, carcass yield and meat quality. A general limitation with diets based on co-products is that they may contain a high level of insoluble fibre, which limits nutrient utilization for non-ruminants. However, the hypothesis was that a diet meeting nutrient recommendations for finishing pigs would not impair performance or yield due to the gut's greater capacity to digest fibre. The results of the study confirmed this hypothesis, showing that pig growth, carcass yield, and meat quality were not significantly affected by the experimental diets.

While previous studies have focused on individual co-products, the potential of diets containing mixed co-products has been largely unexplored. Recent research has suggested that co-products should not exceed 50% in pig diets (Jha et al., 2013). In addition, some studies have indicated that DDGS should not be included in pig diets at levels above 20%, and that canola meal is not a suitable substitute for SBM in grower- finisher pig diets (Smit et al., 2018; Whitney et al., 2006). However, the present study revealed that mixed co-products could be included in finisher diets up to 60% without any negative impacts on weight gain, feed conversion, carcass yield, or meat quality. The experimental diet included 25% DDGS, 20% canola meal, and 15% wheat middling, replacing the total SBM and half of the barley in a conventional diet. The variation in outcomes from studies on co-product inclusion for pigs might result from variations in the quality of DDGS and canola meal used for diet formulation (Stein & Shurson, 2009; Zijlstra & Beltranena, 2019) or the length of the feeding period.

My findings demonstrate the potential for pig producers to incorporate mixed co-products into finisher diets at higher levels than previously recommended without compromising performance or carcass quality.

7.2.2. High inclusion of a fibrous co-product in finisher diets can reduce skatole, hence, improve pork flavour.

Skatole is a compound that causes boar taint, an unappealing odour and flavour that can develop in pork from uncastrated male pigs. The presence of boar taint in pork can lead to a decline in demand for pork products, ultimately affecting the profitability of the industry. Castrating male piglets to prevent the development of boar taint is a solution. However, surgical castration of pigs is not practised in the pork industry in many countries and is regulated as a veterinary-only procedure. Whilst there is a non-surgical option available (immune castration), it comes at a cost that is not currently recovered via a market premium or other incentive.

The outcome of Chapter 3 indicates that incorporating fibrous co-products into pig diets by up to 60% can lower the incidence of skatole. The finding suggested that fibrous co-product/by-products can play a significant role in decreasing skatole levels in pork from entire male pigs. This discovery has significant applications for the pig farming sector, as it offers the potential to address boar taint without surgical or immuno-castration whilst also utilizing co-products. This practice is particularly crucial for producing high-quality pork sustainably, especially for consumers in Far Eastern Asia who are sensitive to the skatole level in pork. In addition, raising entire male pigs can enhance productivity and reduce greenhouse gas emissions and carbon footprint since they grow faster and have better feed efficiency compared with castrated male pigs (Bonneau & Weiler, 2019; Squires et al., 2020).

7.2.3. Inclusion of 10% lucerne in grower–finisher diets can improve feed conversion efficiency.

Previous research revealed that the apparent ileal digestibility of crude protein and most essential amino acids in a diet including 10% lucerne was comparable to that of a conventional diet for growing pigs (Tsikira et al., 2021). Based on this finding, I investigated the effect of including 10% lucerne in a pig diet during the growing-finishing period on growth performance, carcass yield, meat quality, and behaviour (Chapter 4). Unfortunately, due to COVID-19 disruptions when the pigs were slaughtered, meat samples could not be collected to analyse meat quality. Nevertheless, a noteworthy point of this study is that including 10% lucerne in grower-finisher diets improved feed conversion efficiency.

Feed efficiency and carcass yield are crucial economic determinants in the pig industry. While carcass yield defines gross income in pig production, feed efficiency governs the total cost of production and is key to sustainability. Previous research has suggested that feeding forages to pigs can lead to slow growth and carcass yield reduction (Kass, Van Soest, Pond, et al., 1980; Ngoc et al., 2013). However, my findings indicate that including 10% lucerne in growing-finishing pig diets did not negatively impact carcass quality or yield, thus, could maintain the overall value of the carcass. Therefore, using 10% lucerne chaff in pig diets may be a practical option for producers seeking to reduce reliance on conventional feed ingredients based on cereal grains while improving feed efficiency.

7.2.4. Supplying lucerne both as a feed ingredient and as manipulable material for growing – finishing pigs encouraged exploration and social interaction

Chapter 4 also highlighted the potential benefits of using lucerne in pig diets for manipulable material, which allows pigs to engage in natural exploratory behaviour and improve their welfare by reducing boredom and frustration. Better welfare is not only beneficial for the animals but can also have economic benefits for producers, including lower rates of illness and mortality, better growth rates, and improved feed conversion efficiency (Jääskeläinen et al., 2014). However, more research is needed to gain a more comprehensive understanding of the potential effects of using lucerne in pig farming.

Furthermore, Chapter 4 provides insights into the potential effects of feeding lucerne on pig behaviour, possibly linked to the hypothesis of the impact of the microbiota-gut-brain axis on social behaviour (Kobek-Kjeldager et al., 2022; Parashar & Udayabanu, 2016). However, this complex interaction is not well understood, and the difference in pig behaviour caused by the dietary treatment in Chapter 4 is minimal and unlikely to be behaviourally significant. If lucerne has any impact on the microbiota-gut-brain axis interaction, it needs to be clarified as to whether the effect comes from fibre content or other bioactive compounds. Further studies on the effects of lucerne in the diet of growing pig behaviour are needed.

7.2.5. Poultry meal and other types of oilseed meal are potential protein sources for growing - finishing pigs.

The results of Chapters 5 and 6 illustrated that PBM and other types of oilseed meals could replace SBM in grower-finisher diets without affecting pig production and pork quality, providing the diets meet nutrient requirements for growing pigs. This discovery is significant because it aligns with the United Nations Sustainable Development Goal 12 on responsible consumption and production by promoting sustainability in pig diets. In addition, one of the advantages of using alternative protein sources is the potential to reduce the industry's dependence on SBM.

Using PBM or other oilseed meals as the alternative protein source in pig diets can address human protein deficits in many countries and decrease reliance on imported soybeans from soybean-producing nations (European Parliament, 2011). This reduction, in turn, can lead to a more resilient pig industry that can withstand the effects of wars, pandemics, and economic crises (Hashem et al., 2020). Additionally, the use of alternative protein sources can reduce the environmental impact of soybean production and transport (Lathuillière et al., 2017; Ritchie & Roser, 2021; Van der Werf et al., 2005). Furthermore, pig farmers can reduce their dependence on genetically modified (GM) SBM by utilizing alternative protein sources. This approach enables them to provide feed that caters to the preferences of certain consumers, where shifting to organic and non-GM products (OECD/FAO, 2022) could open new markets for their products. Altering the protein source can increase profitability and sustainability in the pig industry.

The findings of Chapters 5 and 6 highlight the potential benefits of utilizing alternative protein sources in pig diets. By doing so, the industry can promote sustainability, reduce reliance on soybean imports, and minimize environmental impact while meeting consumer preferences.

7.2.6. The variation in the quality of co-products/by-products might be a challenge for diet formulation.

In Chapter 6, a meta-analysis was conducted using studies where SBM was replaced with different oilseed meals. The findings revealed substantial heterogeneity in growth performance among the studies, indicating that the nutritional characteristics of the oilseed meal sources varied greatly. While some studies showed a decrease in average daily gain and an increase in feed conversion ratio when SBM was replaced at low levels, others found that replacing over 50% of SBM with alternative oilseed meal had no effect on pig performance. These conflicting results may be due to the variation in the quality of co-products/by-products. This finding highlights the challenge of formulating diets for pigs with co-products and by-products of variable quality. Since the effects of replacing SBM with alternative ingredients can be unpredictable, it is important to carefully evaluate these alternatives when incorporating them into pig diets to optimize pig production.

7.3. Future research

7.3.1. Research on effects of alternative feedstuffs on gut microbiota.

The result obtained in Chapter 3 and 4 implied that fermentation by gut microbes contributes considerable energy and skatole production for the hosts. Previous studies have shown that fibre inclusion in pig diets can promote gut health by increasing the abundance of beneficial bacteria, improving gut microbial diversity and producing substantial energy for the host (Bindelle, Buldgen, et al., 2008; den Besten et al., 2013; Ivarsson et al., 2012; Rérat, 1978). However, more research is needed to determine the optimal level and type of fibre for inclusion in pig diets. Additionally, evidence suggests that fibre can modulate gut immune function and inflammatory responses in pigs, but further research is necessary to understand the underlying mechanisms and potential implications for pig health and productivity (Shang et al., 2021). Future research needs to investigate the impact of varying levels of insoluble and soluble fibre on gut microbiota composition and activity and the role of fibre in modulating gut immune function and inflammatory responses. These investigations are critical for optimizing pig gut health and enhancing pig productivity.

7.3.2. Research on feeding period of fibrous diets for growing-finishing pigs on pig performance and skatole.

The results within this thesis indicate that a high inclusion of fibrous co-products in finisher diets for pigs can improve pork flavour through reducing skatole in pork fat without adversely affecting pig growth. However, previous research on the effect of fibrous diets on skatole in pork is inconsistent, likely due to variations in fibre types, amounts, and ratios. Soluble fibre promotes fermentation, while insoluble fibre increases faecal bulk, which dilutes hindgut contents. Furthermore, recent investigations also showed the interaction of fibre types and other nutritional dietary factors on hindgut fermentation (Hoogeveen et al., 2021). It is important to understand the extent to which different fibre sources impact skatole production in the hindgut and its accumulation in pork fat.

On the other hand, the present study was conducted over a short feeding period (3 weeks), which may not be long enough for the adaptation of pigs to high-fibre diets (Bindelle, Leterme, et al., 2008). It is necessary to investigate the optimal duration of feeding a fibrous diet to achieve a significant reduction of skatole accumulation in pork fat. It is also worth exploring the effects of feeding highly fibrous feed ingredients during the grower phase and withdrawing them a short time before slaughter on overall pig growth performance, carcass yield, and meat quality. Compared to finishing pigs, growing pigs have a smaller gut capacity which may impair their ability to digest high-fibre diets. However, the compensatory effect gained when pigs are fed highly nutritious diets before slaughter can benefit overall growth performance and meat quality (Lebret, 2008). To further advance the knowledge in this field, future research should focus on examining the effects of different feeding regimes of fibrous diets on pig growth performance, carcass weight, and meat quality while avoiding high concentrations of skatole accumulation in the carcass.

7.3.3. Research on the quantity and method to supply manipulable material for pigs.

Chapter 4 revealed that pigs provided with lucerne chaff as enrichment exhibited a higher percentage of negative social interactions than those without enrichment. This finding appears to contradict the expected outcome, as the provision of enrichment is typically associated with a reduction in aggressive behaviours among pigs (Day et al., 2002; Fraser et al., 1991; Pedersen et al., 2014). However, some research suggests that providing insufficient enrichment materials increases competition and aggression among pen mates (Fraser et al., 1991; Studnitz et al., 2007; Zwicker et al., 2015). To be effective, enrichment materials need to be adequate and accessible for all group members. In my study, lucerne chaff might not have been assessable to all pigs or provided in sufficient quantity, which resulted in competition among the pigs. Further research is needed to determine the appropriate levels, replenishment frequency and delivery methods of enrichment material to satisfy the exploratory behaviour of growing pigs.

7.3.4. The evaluation of environmental impacts Life Cycle Assessment (LCA) on using co-products/by-products fed for pigs.

My studies indicated that there was no or just a minor impact on pig production and meat quality of pigs fed co-product/by-product diets. The amount of feed required to produce a kilogram of pork for different diets can be estimated based on this study. However, the environmental impact of using these co-products and by-products as feed has not been evaluated. To gain a more comprehensive perspective on feeding pigs with co-products/by-products in terms of sustainability, Life Cycle Assessment is necessary. Life cycle assessment would allow for the evaluation of environmental impacts associated with using co-products/by-products as feed for pigs, such as greenhouse gas emissions, water use, land use, and energy use, and compare them to the standard diet's impact. The entire life cycle of the feed, including the production, transportation, and processing of co-products and by-products, as well as their use as pig feed instead of other end uses, would be considered. The results of the life cycle assessment would assist in identifying areas that could be made to decrease the environmental impact while maintaining pig production.

7.3.5. Research on the inclusion of PBM and fibrous alternative feedstuffs for growing-finishing pigs.

Chapter 5 demonstrated that PBM is an effective protein source for growing-finishing pigs. Additionally, PBM has lower fibre content and higher calcium and phosphorus levels compared to SBM, as described in the chapter Literature Review. The ash in PBM may also have high biological availability (discussed in Chapter 5). Thus, incorporating PBM into fibrous diets may offset the disadvantages of fibrous feedstuffs, resulting in better utilization of the alternative diet.

Unfortunately, fatty acids in the PBM used were not evaluated in my research. However, the fatty acid composition in PBM is high in saturated and monounsaturated fatty acids, which have been linked to an increased risk of cardiovascular disease in humans (Willett, 2012). Conversely, some fibrous alternative feedstuffs, such as DDGS, are high in polyunsaturated fatty acids that have been associated with a reduced risk of osteoarthritis, cancer, and autoimmune disorders in humans (Kapoor et al., 2021). However, high polyunsaturated fatty acids content can negatively affect pig meat quality and shelf life (Wood et al., 2004). Therefore, the high polyunsaturated fatty acids content of fibrous feedstuffs may offset the inclusion of PBM and combining PBM and DDGS in pig diets may result in a well-balanced fatty acid profile in pig meat.

Further research is needed to determine the optimal inclusion levels of PBM and fibrous feed ingredients in grower-finisher diets to maximize pig production and pork quality.

7.3.6. Research on improving the utilization of alternative feedstuffs for growing finishing pigs

The high fibre content in many alternative feedstuffs presents a significant challenge for pig nutrition since fibre cannot be broken down by endogenous digestive enzymes, which in turn reduces nutrient digestibility and pig growth performance. Furthermore, diets that are high in bulk can cause early satiety during a meal and prolonged satiety post-meal due to vagal stimulation of fullness signals from stomach distention (Howarth et al., 2001). As a result, feed intake per visit and overall feed intake are reduced (Nguyen et al., 2022; Olumodeji, 2021). Such reductions in feed intake and digestibility can impair pig growth (results shown in Chapter 2 and 3).

One effective strategy to improve nutrient digestibility and pig growth performance is with use of exogenous enzymes, which can also modify microbial communities in the hindgut of pigs (Chen et al., 2020; Recharla et al., 2019). Feed additives for use in pig diets can be produced from fermenting high-fibre agro-industrial by-products. Fan et al. (2023) demonstrated that fermenting agro-industrial by-products using *Aspergillus niger (A. niger), Trichoderma reesei (T. reesei), Candida utilis (C. utilis), Bacillus subtilis (B. subtilis), and Bacillus coagulans (B. coagulans)* resulted in a product with greater nutrition, improved flavoured, and decreased fibre compared to the unfermented by-product. Therefore, feed additives used in diets with high inclusion of co-products (e.g., Chapter 3) and in forage-based diets (e.g., Chapter 4) can improve diet utilization diets of growing–finishing pigs. However, this suggestion needs to be fully investigated with the many possible additives.

7.3.7. Research other novel alternative feedstuffs for pig

Within the context of my PhD research, I studied several alternative feedstuffs for pigs. However, I am aware that there is still much to be explored in the field of pig nutrition, and a vast number of novel feedstuffs are yet to be explored. These feedstuffs could include other high-nutritive value forage plants, such as legumes, brassicas, and chicory, which have the potential to provide a range of beneficial nutrients and secondary metabolites to support pig health and growth (Rattanasomboon et al., 2019). Additionally, insects, like black soldier flies and mealworms, and microalgae, like spirulina and chlorella, have been shown to be rich sources of protein and other essential nutrients that can be incorporated into pig diets (Benemann, 2013; Sánchez-Muros et al., 2014). These alternative feedstuffs have the potential to provide a range of benefits, including improved nutrient utilization, reduced environmental impact, and lower production costs. However, there are challenges associated with using alternative feedstuffs, which need to be addressed.

The greatest challenge to feeding alternative feedstuffs for pigs is the high variation in nutritive value and the presence of anti-nutritional factors (Zijlstra & Beltranena, 2019). Variations in nutrient levels could affect the performance and health of the pigs. In addition, some feedstuffs might contain a high level of fibre or anti-nutritional factors that can reduce nutrient absorption and affect pig growth. Therefore, it is essential to understand the nutritional characteristics and bioavailability of the nutrients in feedstuffs to ensure that they meet the pigs' requirements. Proper evaluation of the nutritional quality of novel feedstuffs helps ensure that pigs receive adequate nutrition and avoid the negative impacts of anti-nutritional factors. In addition, research on appropriate feed processing for alternative feedstuffs to improve pig ultilization is needed. Furthermore, it is necessary to investigate the impact of incorporating novel feedstuffs into pig diets on pork quality that comply with customer preference and food safety regulations (Hong & Kim, 2022). Consumer preferences are a key driver of pork product sales, so ensuring that novel feedstuffs do not negatively affect the sensory quality of pork products is important for maintaining consumer demand.

7.4. Conclusion

Switching from conventional feed ingredients to alternative ones is crucial for achieving sustainable development in the livestock sector. The present research has shown that alternative feedstuffs for growing-finishing pigs can improve meat quality and well-being without negatively affecting production. However, it is essential to conduct further research to identify alternative feedstuffs that can be effectively integrated into pig diets while contributing to sustainable development.

In this regard, evaluating their effect on pig growth performance, meat quality, economic, and environmental implications of these alternative feedstuffs is crucial. Proper evaluation of these factors will help identify the most promising alternatives and develop strategies to optimize their use in pig production systems. With careful consideration of these factors, researchers and producers can work together to develop sustainable and cost-effective alternatives to conventional pig feed ingredients. By doing so, a sustainable existence for future generations can be worked towards by ensuring that the increasing demand for pork is met.

REFERENCES

Aarnink, A. J. A., & Verstegen, M. W. A. (2007). Nutrition, key factor to reduce environmental load from pig production. *Livestock science*, *109*(1), 194-203. https://doi.org/10.1016/j.livsci.2007.01.112

An, L. V., Hong, T. T. T., & Lindberg, J. E. (2004). Ileal and total tract digestibility in growing pigs fed cassava root meal diets with inclusion of fresh, dry and ensiled sweet potato (Ipomoea batatas L. (Lam.)) leaves. *Animal Feed Science and Technology*, *114*(1), 127-139. https://doi.org/10.1016/j.anifeedsci.2003.12.007

Andersen, H. J., Oksbjerg, N., Young, J. F., & Therkildsen, M. (2005). Feeding and meat quality – a future approach. *Meat science*, *70*(3), 543-554. https://doi.org/10.1016/j.meatsci.2004.07.015

Anderson, R. L., & Wolf, W. J. (1995). Compositional changes in trypsin inhibitors, phytic acid, saponins and isoflavones related to soybean processing. *The Journal of Nutrition*, *125*(suppl_3), 581S-588S. https://doi.org/10.1093/jn/125.suppl_3.581S

Anguita, M., Canibe, N., Pérez, J. F., & Jensen, B. B. (2006a). Influence of the amount of dietary fiber on the available energy from hindgut fermentation in growing pigs: Use of cannulated pigs and in vitro fermentation. *Journal of Animal Science*, *84*(10), 2766-2778. https://doi.org/10.2527/jas.2005-212

Anguita, M., Canibe, N., Pérez, J. F., & Jensen, B. B. (2006b). Influence of the amount of dietary fiber on the available energy from hindgut fermentation in growing pigs: Use of cannulated pigs and in vitro fermentation1. *Journal of Animal Science*, *84*(10), 2766-2778. https://doi.org/http://doi.org/10.2527/jas.2005-212

Anyanwu, G. A., Okoro, V. M. O., & Mbajiorgu, C. A. (2021). Optimum inclusion levels of Leucaena leucocephala pasture leaf-meal on growth, haematology and physiological performance of growing pigs. *Tropical Animal Health and Production*, *53*(1), 116. https://doi.org/10.1007/s11250-021-02565-x

AOAC. (2005). Official methods of analysis of AOAC International. In *Official methods of analysis of AOAC International* (18th ed.). AOAC International.

Argemí-Armengol, I., Villalba, D., Tor, M., Bertolin, J. R., Latorre, M. A., & Alvarez-Rodriguez, J. (2020). Effects of dietary roughage on organic pig performance, behaviour and antioxidants accretion in perirenal adipose tissue. *Livestock science*, *241*, Article 104255. https://doi.org/10.1016/j.livsci.2020.104255

Arrutia, F., Binner, E., Williams, P., & Waldron, K. W. (2020). Oilseeds beyond oil: Press cakes and meals supplying global protein requirements. *Trends in Food Science & Technology*, *100*, 88-102. https://doi.org/10.1016/j.tifs.2020.03.044

Asche, F., Oglend, A., & Tveteras, S. (2013). Regime shifts in the fish meal/Soybean meal price ratio. *Journal of Agricultural Economics*, *64*(1), 97-111. https://doi.org/10.1111/j.1477-9552.2012.00357.x

Attene-Ramos, M. S., Nava, G. M., Muellner, M. G., Wagner, E. D., Plewa, M. J., & Gaskins, H. R. (2010). DNA damage and toxicogenomic analyses of hydrogen sulfide in human intestinal epithelial FHs 74 Int cells. *Environmental and Molecular Mutagenesis*, *51*(4), 304-314. https://doi.org/10.1002/em.20546

Babinszky, L., Verstegen, M. W. A., & Hendriks, W. H. (2019). Challenges in the 21 st century in pig and poultry nutrition and the future of animal nutrition. In W. H. Hendriks, M. W. A. Verstegen, & L. Babinszky (Eds.), *Poultry and pig nutrition : challenges of the 21st century* (1 ed., pp. 17-37). Wageningen Academic Publishers. https://doi.org/10.3920/978-90-8686-884-1_1

Bach Knudsen, K. E. (2001). The nutritional significance of "dietary fibre" analysis. *Animal Feed Science and Technology*, *90*(1), 3-20. https://doi.org/10.1016/S0377-8401(01)00193-6

Bai, Z., Zhao, J., Wei, Z., Jin, X., & Ma, L. (2019). Socio-economic drivers of pig production and their effects on achieving sustainable development goals in China. *Journal of Integrative Environmental Sciences*, *16*(1), 141-155. https://doi.org/10.1080/1943815X.2019.1671463

Bai, Z. H., Ma, L., Qin, W., Chen, Q., Oenema, O., & Zhang, F. S. (2014). Changes in pig production in China and their effects on nitrogen and phosphorus use and losses. *Environmental Science & Technology*, *48*(21), 12742-12749. https://doi.org/10.1021/es502160v

Bakare, A. G., Madzimure, J., Ndou, S. P., & Chimonyo, M. (2014). Growth performance and behaviour in grouped pigs fed fibrous diet. *Asian-Australasian Journal of Animal Sciences*, *27*(8), 1204-1210. https://doi.org/10.5713/ajas.2013.13774

Bakare, A. G., Ndou, S. P., & Chimonyo, M. (2013). Influence of physicochemical properties of fibrous diets on behavioural reactions of individually housed pigs. *Livestock science*, *157*(2), 527-534. https://doi.org/10.1016/j.livsci.2013.08.021

Baker, D. H., Becker, D. E., Norton, H. W., Jensen, A. H., & Harmon, B. G. (1969). Lysine imbalance of corn protein in the growing pig. *Journal of Animal Science*, *28*(1), 23-26. https://doi.org/10.2527/jas1969.28123x

Basset-Mens, C., & Van Der Werf, H. M. G. (2005). Scenario-based environmental assessment of farming systems: The case of pig production in France. *Agriculture, Ecosystems and Environment*, *105*(1-2), 127-144. https://doi.org/10.1016/j.agee.2004.05.007

Beattie, V. E., O'Connell, N. E., & Moss, B. W. (2000). Influence of environmental enrichment on the behaviour, performance and meat quality of domestic pigs. *Livestock Production Science*, *65*(1), 71-79. https://doi.org/10.1016/S0301-6226(99)00179-7

Bee, G., Guex, G., & Herzog, W. (2004). Free-range rearing of pigs during the winter: Adaptations in muscle fiber characteristics and effects on adipose tissue composition and meat quality traits. *Journal of Animal Science*, *82*(4), 1206-1218. https://doi.org/10.1093/ansci/82.4.1206

Belyea, R. L., Rausch, K. D., & Tumbleson, M. E. (2004). Composition of corn and distillers dried grains with solubles from dry grind ethanol processing. *Bioresource Technology*, *94*(3), 293-298. https://doi.org/10.1016/j.biortech.2004.01.001

Bench, C. J., Rioja-Lang, F. C., Hayne, S. M., & Gonyou, H. W. (2013). Group gestation sow housing with individual feeding—II: How space allowance, group size and composition, and flooring affect sow welfare. *Livestock science*, *152*(2), 218-227. https://doi.org/10.1016/j.livsci.2012.12.020

Benemann, J. (2013). Microalgae for biofuels and animal feeds. *Energies*, *6*(11), 5869-5886. https://www.mdpi.com/1996-1073/6/11/5869

Bennett, G., & Richard, J. (1996). Influence of processing on Fusarium mycotoxins in contaminated grains.

Bergeron, R., Bolduc, J., Ramonet, Y., Meunier-Salaün, M. C., & Robert, S. (2000). Feeding motivation and stereotypies in pregnant sows fed increasing levels of fibre and/or food. *Applied Animal Behaviour Science*, *70*(1), 27-40. https://doi.org/10.1016/S0168-1591(00)00142-8

Bernard, J. K. (2011). Feed concentrates: Oilseed and Oilseed meals. In J. W. Fuquay (Ed.), *Encyclopedia of Dairy Sciences* (Second Edition ed., pp. 349-355). Academic Press. https://doi.org/10.1016/B978-0-12-374407-4.00165-5

Berrocoso, J. D., Rojas, O. J., Liu, Y., Shoulders, J., González-Vega, J. C., & Stein, H. H. (2015). Energy concentration and amino acid digestibility in high-protein canola meal, conventional canola meal, and soybean meal fed to growing pigs. *Journal of Animal Science*, *93*(5), 2208-2217. https://doi.org/10.2527/jas.2014-8528

Bindelle, J., Buldgen, A., & Leterme, P. (2008). Nutritional and environmental consequences of dietary fibre in pig nutrition: A review. *Biotechnology, Agronomy and Society and Environment*, *12*(1), 3247-3256. https://doi.org/http://hdl.handle.net/2268/19202

Bindelle, J., Leterme, P., & Buldgen, A. (2008). Nutritional and environmental consequences of dietary fibre in pig nutrition: A review [Conséquences nutritionnelles et environnementales des fibres alimentaires dans la nutrition du porc : une revue.]. *Biotechnologie, Agronomie, Société et Environnement*, *12*, 69. http://www.bib.fsagx.ac.be/base/text/v12n4/405.pdf

Boland, M. J., Rae, A. N., Vereijken, J. M., Meuwissen, M. P. M., Fischer, A. R. H., van Boekel, M. A. J. S., Rutherfurd, S. M., Gruppen, H., Moughan, P. J., & Hendriks, W. H. (2013). The future supply of animal-derived protein for human consumption. *Trends in Food Science and Technology*, *29*(1), 62-73. https://doi.org/10.1016/j.tifs.2012.07.002

Boler, D. D., Fernández-Dueñas, D. M., Kutzler, L. W., Zhao, J., Harrell, R. J., Campion, D. R., McKeith, F. K., Killefer, J., & Dilger, A. C. (2012). Effects of oxidized corn oil and a synthetic antioxidant blend on performance, oxidative status of tissues, and fresh meat quality in finishing barrows. *Journal of Animal Science*, *90*(13), 5159-5169. https://doi.org/10.2527/jas.2012-5266

Bonneau, M., & Weiler, U. (2019). Pros and cons of alternatives to piglet castration: welfare, boar taint, and other meat quality traits. *Animals*, *9*(11), 884. https://www.mdpi.com/2076-2615/9/11/884

Borin, K., Lindberg, J. E., & Ogle, R. B. (2005). Effect of variety and preservation method of cassava leaves on diet digestibility by indigenous and improved pigs. *Animal Science*, *80*(3), 319-324. https://doi.org/10.1079/ASC41560319

Boro, P., Patel, B., Sahoo, N., Naha, B., Madkar, A., Dutt, T., Gaur, G., Singh, M., & Singh, A. K. (2018). Managemental practices of Bareilly Desi pigs. *Journal of Entomology and Zoology Studies*, *6*(5), 2265-2269. https://www.entomoljournal.com/archives/2018/vol6issue5/PartZ/6-5-148-274.pdf

Böttger, C., & Südekum, K. H. (2018). Review: protein value of distillers dried grains with solubles (DDGS) in animal nutrition as affected by the ethanol production process. *Animal Feed Science and Technology*, *244*, 11-17. https://doi.org/10.1016/j.anifeedsci.2018.07.018

Bracke, M. B. M., & Koene, P. (2019). Expert opinion on metal chains and other indestructible objects as proper enrichment for intensively-farmed pigs. *PLoS ONE*, *14*(2), e0212610. https://doi.org/10.1371/journal.pone.0212610

Brand, T. S., Brandt, D. A., & Cruywagen, C. W. (2001). Utilisation of growing-finishing pig diets containing high levels of solvent or expeller oil extracted canola meal. *New Zealand Journal of Agricultural Research*, *44*(1), 31-35. https://doi.org/10.1080/00288233.2001.9513459

Brouns, F., Edwards, S. A., & English, P. R. (1994). Effect of dietary fibre and feeding system on activity and oral behaviour of group housed gilts. *Applied Animal Behaviour Science*, *39*(3), 215-223. https://doi.org/10.1016/0168-1591(94)90157-0

Calder, P. C. (2015). Functional roles of fatty acids and their effects on human health. *Journal of Parenteral and Enteral Nutrition*, *39*(1S), 18S-32S. https://doi.org/10.1177/0148607115595980

Canh, T. T., Aarnink, A. J. A., Mroz, Z., Jongbloed, A. W., Schrama, J. W., & Verstegen, M. W. A. (1998). Influence of electrolyte balance and acidifying calcium salts in the diet of growing-finishing pigs on urinary pH, slurry pH and ammonia volatilisation from slurry. *Livestock Production Science*, *56*(1), 1-13. https://doi.org/10.1016/S0301-6226(98)00148-1

Carr, S. N., Rincker, P. J., Killefer, J., Baker, D. H., Ellis, M., & McKeith, F. K. (2005). Effects of different cereal grains and ractopamine hydrochloride on performance, carcass characteristics, and fat quality in late-finishing pigs. *Journal of Animal Science*, *83*(1), 223-230. https://doi.org/10.2527/2005.831223x

Casey, D. S., Stern, H. S., & Dekkers, J. C. M. (2005). Identification of errors and factors associated with errors in data from electronic swine feeders. *Journal of Animal Science*, *83*(5), 969-982. https://doi.org/10102527/2005.835969x
Castell, A. G., & Cliplef, R. L. (1993). Evaluation of pea screenings and canola meal as a supplementary protein source in barley-based diets fed to growing-finishing pigs. *Canadian Journal of Animal Science*, *73*(1), 129-139. https://doi.org/10.4141/cjas93-012
Chakraborty, S., & Newton, A. C. (2011). Climate change, plant diseases and food security: an overview. *Plant Pathology*, *60*(1), 2-14. https://doi.org/10.1111/j.1365-3059.2010.02411.x

Chauhan, A., Patel, B., Maurya, R., Kumar, S., Shukla, S., Kumar, S., Agustina, K. K., Wirata, I. W., , A. A. G. O. D., Kardena, I. M., & Dharmawan4, N. S. (2016). Pig production system as a source of livelihood in Indian scenario: An overview. *Buletin Veteriner Udayana*, *8*(2), 122-127.
Cheeke, P. R., Kinzell, J. H., & Pedersen, M. W. (1977). Influence of saponins on Alfalfa utilization by rats, rabbits and swine. *Journal of Animal Science*, *45*(3), 476-481. https://doi.org/10.2527/jas1977.453476x
Chen, H., Zhang, S., & Kim, S. W. (2020). Effects of supplemental xylanase on health of the small intestine in nursery pigs fed diets with corn distillers' dried grains with solubles. *Journal of Animal Science*, *98*(6). https://doi.org/10.1093/jas/skaa185
Cho, J. H., & Kim, I. H. (2011). Fish meal – nutritive value. *Journal of Animal Physiology and Animal Nutrition*, *95*(6), 685-692. https://doi.org/10.1111/j.1439-0396.2010.01109.x
Choi, H., Won, C. S., & Kim, B. G. (2021). Protein and energy concentrations of meat meal and meat and bone meal fed to pigs based on in vitro assays. *Animal Nutrition*, *7*(1), 252-257. https://doi.org/10.1016/j.aninu.2020.07.007
Claus, R., Weiler, U., & Herzog, A. (1994). Physiological aspects of androstenone and skatole formation in the boar—A review with experimental data. *Meat science*, *38*(2), 289-305. https://doi.org/10.1016/0309-1740(94)90118-X
Cooper, G., & Weber, J. A. (2012). An outlook on world biofuel production and its implications for the animal feed industry. In H. P. S. Makkar (Ed.), *Biofuel co-products as livestock feed - Opportunities and challenges* (pp. 13). FAO.
Cornale, P., Macchi, E., Miretti, S., Renna, M., Lussiana, C., Perona, G., & Mimosi, A. (2015). Effects of stocking density and environmental enrichment on behavior and fecal corticosteroid levels of pigs under commercial farm conditions. *Journal of veterinary behavior*, *10*(6), 569-576. https://doi.org/10.1016/j.jveb.2015.05.002
Cortamira, O., Gallego, A., & Kim, S. W. (2000). Evaluation of twice decorticated sunflower meal as a protein source compared with soybean meal in pig diets. *Asian-Australasian Journal of Animal Sciences*, *13*(9), 1296-1303. https://doi.org/10.5713/ajas.2000.1296
Cromwell, G., Herkelman, K., & Stahly, T. (1993). Physical, chemical, and nutritional characteristics of distillers dried grains with solubles for chicks and pigs. *Journal of Animal science*, *71*(3), 679-686. https://doi.org/10.2527/1993.713679x
Curry, S. M., Blavi, L., Wiseman, J., & Stein, H. H. (2019). Effects of distillers dried grains with solubles on amino acid digestibility, growth performance, and carcass characteristics of growing pigs. *Translational Animal Science*, *3*(2), 641-653. https://doi.org/10.1093/tas/txz005
Dadalt, J. C., E. Velayudhan, D., Neto, M. A. T., Slominski, B. A., & Nyachoti, C. M. (2016). Ileal amino acid digestibility in high protein sunflower meal and pea protein isolate fed to growing pigs with or without multi-carbohydrase supplementation. *Animal Feed Science and Technology*, *221*, 62-69. https://doi.org/10.1016/j.anifeedsci.2016.08.015
Dahlen, R. B. A., Baidoo, S. K., Shurson, G. C., Anderson, J. E., Dahlen, C. R., & Johnston, L. J. (2011). Assessment of energy content of low-solubles corn distillers dried grains and effects

on growth performance, carcass characteristics, and pork fat quality in growing-finishing pigs. *Journal of Animal Science*, *89*(10), 3140-3152. https://doi.org/10.2527/jas.2010-3342
Dang, D. X., Kim, Y. M., & Kim, I. H. (2020). Effects of a root extract from Achyranthes Japonica Nakai on the growth performance, blood profile, fecal microbial community, fecal gas emission, and meat quality of finishing pigs. *Livestock science*, *239*, Article 104160. https://doi.org/10.1016/j.livsci.2020.104160
Day, J. E. L., Burfoot, A., Docking, C. M., Whittaker, X., Spoolder, H. A. M., & Edwards, S. A. (2002). The effects of prior experience of straw and the level of straw provision on the behaviour of growing pigs. *Applied Animal Behaviour Science*, *76*(3), 189-202. https://doi.org/10.1016/S0168-1591(02)00017-5
de Miguel, Á., Hoekstra, A. Y., & García-Calvo, E. (2015). Sustainability of the water footprint of the Spanish pork industry. *Ecological Indicators*, *57*, 465-474. https://doi.org/10.1016/j.ecolind.2015.05.023
Dégen, L., Halas, V., & Babinszky, L. (2007). Effect of dietary fibre on protein and fat digestibility and its consequences on diet formulation for growing and fattening pigs: A review. *Acta Agriculturae Scandinavica, Section A — Animal Science*, *57*(1), 1-9. https://doi.org/10.1080/09064700701372038
Dei, H. (2011). Soybean as a feed ingredient for livestock and poultry. In D. Krezhova (Ed.), *Recent trends for enhancing the diversity and quality of soybean products* (pp. 215-226). IntechOpen. https://doi.org/10105772/17601
den Besten, G., van Eunen, K., Groen, A. K., Venema, K., Reijngoud, D.-J., & Bakker, B. M. (2013). The role of short-chain fatty acids in the interplay between diet, gut microbiota, and host energy metabolism. *Journal of Lipid Research*, *54*(9), 2325-2340. https://doi.org/10.1194/jlr.R036012
Dibner, J. J., Atwell, C. A., Kitchell, M. L., Shermer, W. D., & Ivey, F. J. (1996). Feeding of oxidized fats to broilers and swine: effects on enterocyte turnover, hepatocyte proliferation and the gut associated lymphoid tissue. *Animal Feed Science and Technology*, *62*(1), 1-13. https://doi.org/10.1016/S0377-8401(96)01000-0
Dierick, N. A., Vervaeke, I. J., Demeyer, D. I., & Decuypere, J. A. (1989). Approach to the energetic importance of fibre digestion in pigs. I. Importance of fermentation in the overall energy supply. *Animal Feed Science and Technology*, *23*(1), 141-167. https://doi.org/10.1016/0377-8401(89)90095-3
Diether, N. E., & Willing, B. P. (2019). Microbial fermentation of dietary protein: An important factor in diet‑microbe‑host interaction. *Microorganisms*, *7*(1), 19. https://doi.org/10.3390/microorganisms7010019
Ding, H. X., Cao, A. Z., Li, H. Y., Zhao, Y., & Feng, J. (2020). Effects of Eucommia ulmoides leaf extracts on growth performance, antioxidant capacity and intestinal function in weaned piglets. *Journal of Animal Physiology and Animal Nutrition*, *104*(4), 1169-1177. https://doi.org/10.1111/jpn.13333
Dorea, J. G. (2006). Fish meal in animal feed and human exposure to persistent bioaccumulative and toxic substances. *Journal of Food Protection*, *69*(11), 2777-2785. https://doi.org/10.4315/0362-028x-69.11.2777
Dransfield, E., Nute, G. R., Mottram, D. S., Rowan, T. G., & Lawrence, T. L. J. (1985). Pork quality from pigs fed on low glucosinate rapeseed meal: Influence of level in the diet, sex and ultimate pH. *Journal of the Science of Food and Agriculture*, *36*(7), 546-556. https://doi.org/10.1002/jsfa.2740360705
Dunford, N. (2016). *Oil and Oilseed Processing II*. https://extension.okstate.edu/fact-sheets/oil-and-oilseed-processing-ii.html

Dzuman, Z., Stranska-Zachariasova, M., Vaclavikova, M., Tomaniova, M., Veprikova, Z., Slavikova, P., & Hajslova, J. (2016). Fate of free and conjugated Mycotoxins within the production of Distiller's Dried Grains with Solubles (DDGS). *Journal of Agricultural and Food Chemistry*, *64*(24), 5085-5092. https://doi.org/10.1021/acs.jafc.6b00304

Eastoe, J. E., & Long, J. E. (1960). The amino-acid composition of processed bones and meat. *Journal of the Science of Food and Agriculture*, *11*(2), 87-92. https://doi.org/10101002/jsfa.2740110204

Ebata, A., MacGregor, H., Loevinsohn, M., & Win, K. S. (2020). Why behaviours do not change: structural constraints that influence household decisions to control pig diseases in Myanmar. *Preventive Veterinary Medicine*, *183*, 105138. https://doi.org/10.1016/j.prevetmed.2020.105138

EC. (2007). Attitudes of EU citizens towards Animal Welfare. In: Special Eurobarometer 270 / Wave 66.1.

Edwards, S. A. (2003). Intake of nutrients from pasture by pigs. *Proceedings of the Nutrition Society*, *62*(2), 257-265. https://doi.org/10.1079/PNS2002199

Egger, M., Davey Smith, G., Schneider, M., & Minder, C. (1997). Bias in meta-analysis detected by a simple, graphical test. *Bmj*, *315*(7109), 629-634. https://doi.org/10.1136/bmj.315.7109.629

Elgersma, A., Søegaard, K., & Jensen, S. K. (2013). Fatty acids, α-Tocopherol, β-Carotene, and lutein contents in forage legumes, forbs, and a grass–clover mixture. *Journal of Agricultural and Food Chemistry*, *61*(49), 11913-11920. https://doi.org/10.1021/jf403195v

Erickson, J. P., Miller, E. R., Ku, P. K., Collings, G. F., & Black, J. R. (1985). Wheat middlings as a source of energy, amino acids, phosphorus and pellet binding quality for swine diets. *Journal of Animal Science*, *60*(4), 1012-1020. https://doi.org/10.2527/jas1985.6041012x

Espinosa, C. D., & Stein, H. H. (2018). High-protein distillers dried grains with solubles produced using a novel front-end–back-end fractionation technology has greater nutritional value than conventional distillers dried grains with solubles when fed to growing pigs. *Journal of Animal Science*, *96*(5), 1869-1876. https://doi.org/10.1093/jas/sky052

European Parliament. (2011). *The EU protein deficit: what solution for a long-standing problem? (2010/2111(INI))*.

Fan, W., Huang, X., Liu, K., Xu, Y., & Chi, Z. (2023). Advanced upcycling of agro-industrial co-products of corn via different microorganisms. *Biomass and Bioenergy*, *168*, 106669. https://doi.org/10.1016/j.biombioe.2022.106669

FAO. (2019). *The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction*. FAO Retrieved from http://www.fao.org/3/ca6030en/ca6030en.pdf

FAO. (2022a). *Hunger and food insecurity*.

FAO. (2022b). *World food situation*. Retrieved 28/11/2022 from

Farzad Taheripour, T. W. H., Wallace E. Tyner. (2011). Implications of biofuels mandates for the global livestock industry: a computable general equilibrium analysis. *Agricultural Economics*, *42*, 18. https://doi.org/10.1111/j.1574-0862.2010.00517.x

Ferket, P. R., van Heugten, E., van Kempen, T. A. T. G., & Angel, R. (2002). Nutritional strategies to reduce environmental emissions from nonruminants. *Journal of Animal Science*, *80*(E-suppl_2), E168-E182. https://doi.org/10102527/animalsci2002.80E-Suppl_2E168x

Figueroa, J., del Rio, K., Romero, F., Keim, J. P., & Gandarillas, M. (2020). Acceptability, preferences, and palatability of diets containing Summer and Winter Brassica forage in growing pigs: A pilot study. *Animals*, *10*(6), Article 1080. https://doi.org/10.3390/ani10061080

Fischer, J., Elsinghorst, P. W., Bücking, M., Tholen, E., Petersen, B., & Wüst, M. (2011). Development of a candidate feference method for the simultaneous quantitation of the boar taint compounds Androstenone, 3α-Androstenol, 3β-Androstenol, Skatole, and Indole in pig

fat by means of stable isotope dilution analysis (SIDA) and headspace solid-phase microextraction–gas chromatography/mass spectrometry. *Analytical Chemistry*, *83*(17), 6785-6791. https://doi.org/10.1021/ac201465q
Florou-Paneri, P., Christaki, E., Giannenas, I., Bonos, E., Skoufos, I., Tsinas, A., Tzora, A., & Peng, J. (2014). Alternative protein sources to soybean meal in pig diets. *Journal of Food, Agriculture and Environment*, *12*, 655-660.
Fombad, R. B., & Bryant, M. J. (2004). An evaluation of the use of cottonseed cake in the diet of growing pigs. *Tropical Animal Health and Production*, *36*(3), 295-305. https://doi.org/10.1023/b:trop.0000016828.48326.59
Frantz, N., Tokach, M. D., Nelssen, J. L., DeRouchey, J. M., Goodband, R. D., & Dritz, S. S. (2004). The effect of replacing specialty protein sources with synthetic amino acids in phase 2 nursery-pig diets. https://krex.k-state.edu/dspace/handle/2097/1901
Fraser, D., Phillips, P. A., Thompson, B. K., & Tennessen, T. (1991). Effect of straw on the behaviour of growing pigs. *Applied Animal Behaviour Science*, *30*(3), 307-318. https://doi.org/10.1016/0168-1591(91)90135-K
Friend, D. W., Nicholson, J. W. G., & Cunningham, H. M. (1964). Volatile fatty acid and lactic acid content of pig blood. *Canadian Journal of Animal Science*, *44*(3), 303-308. https://doi.org/10.4141/cjas64-044
Früh, B., Bochicchio, D., Edwards, S., Hegelund, L., Leeb, C., Sundrum, A., Werne, S., Wiberg, S., & Prunier, A. (2014). Description of organic pig production in Europe. *Organic Agriculture*, *4*(2), 83-92. https://doi.org/10.1007/s13165-013-0056-9
Galkanda-Arachchige, H. S. C., Wilson, A. E., & Davis, D. A. (2020). Success of fishmeal replacement through poultry by-product meal in aquaculture feed formulations: a meta-analysis. *Reviews in Aquaculture*, *12*(3), 1624-1636. https://doi.org/10101111/raq.12401
Garcia, R. A., & Phillips, J. G. (2009). Physical distribution and characteristics of meat and bone meal protein. *Journal of the Science of Food and Agriculture*, *89*(2), 329-336. https://doi.org/10.1002/jsfa.3453
Gemede, H. F., & Ratta, N. (2014). Antinutritional factors in plant foods: Potential health benefits and adverse effects. *International Journal of Nutrition and Food Sciences*, *3*(4), 284-289. https://doi.org/10.11648/j.ijnfs.20140304.18
Gentry, J. G., McGlone, J. J., Blanton, J. R., Jr., & Miller, M. F. (2002). Alternative housing systems for pigs: Influences on growth, composition, and pork quality. *Journal of Animal Science*, *80*(7), 1781-1790. https://doi.org/10.2527/2002.8071781x
Gentry, J. G., McGlone, J. J., Miller, M. F., & Blanton, J. R., Jr. (2004). Environmental effects on pig performance, meat quality, and muscle characteristics. *Journal of Animal Science*, *82*(1), 209-217. https://doi.org/10.2527/2004.821209x
Gerbens-Leenes, P. W., Mekonnen, M. M., & Hoekstra, A. Y. (2013). The water footprint of poultry, pork and beef: A comparative study in different countries and production systems. *Water Resources and Industry*, *1-2*, 25-36. https://doi.org/10.1016/j.wri.2013.03.001
Goff, G. L., Milgen, J. v., & Noblet, J. (2002). Influence of dietary fibre on digestive utilization and rate of passage in growing pigs, finishing pigs and adult sows. *Animal Science*, *74*(3), 503-515. https://doi.org/10.1017/S1357729800052668
González-Vega, J. C., Kim, B. G., Htoo, J. K., Lemme, A., & Stein, H. H. (2011). Amino acid digestibility in heated soybean meal fed to growing pigs. *Journal of Animal Science*, *89*(11), 3617-3625. https://doi.org/10.2527/jas.2010-3465
González-Vega, J. C., & Stein, H. H. (2012). Amino acid digestibility in canola, cottonseed, and sunflower products fed to finishing pigs. *Journal of Animal Science*, *90*(12), 4391-4400. https://doi.org/10.2527/jas.2011-4631
Graham, A. B., Goodband, R. D., Tokach, M. D., Dritz, S. S., DeRouchey, J. M., Nitikanchana, S., & Updike, J. J. (2014). The effects of low-, medium-, and high-oil distillers dried grains with

solubles on growth performance, nutrient digestibility, and fat quality in finishing pigs. *Journal of Animal Science*, *92*(8), 3610-3623. https://doi.org/10.2527/jas.2014-7678

Guy, J., Cain, P., Seddon, Y., Baxter, E., & Edwards, S. (2012). Economic evaluation of high welfare indoor farrowing systems for pigs. *Animal Welfare*, *21*(1), 19. https://doi.org/10.7120/096272812X13345905673520

Halimani, T. E., Ndlovu, L. R., Dzama, K., Chimonyo, M., & Miller, B. G. (2005). Metabolic response of pigs supplemented with incremental levels of leguminous Acacia karroo, Acacia nilotica and Colophospermum mopane leaf meals. *Animal Science*, *81*(1), 39-45. https://doi.org/10.1079/ASC41360045

Hamer, G. (2003). Solid waste treatment and disposal: effects on public health and environmental safety. *Biotechnology Advances*, *22*(1), 71-79. https://doi.org/10.1016/j.biotechadv.2003.08.007

Han, J., & Liu, K. (2010). Changes in composition and amino acid profile during dry grind ethanol processing from corn and estimation of yeast contribution toward DDGS proteins. *Journal of Agricultural and Food Chemistry*, *58*(6), 3430-3437. https://doi.org/10.1021/jf9034833

Han, Y. K., Soita, H. W., & Thacker, P. A. (2005). Performance and carcass composition of growing-finishing pigs fed wheat or corn-based diets. *Asian-Australasian Journal of Animal Sciences*, *18*(5), 704-710. https://doi.org/10.5713/ajas.2005.704

Hansen, A. (2018). Meat consumption and capitalist development: The meatification of food provision and practice in Vietnam. *Geoforum*, *93*, 57-68. https://doi.org/10.1016/j.geoforum.2018.05.008

Hansen, C. F., Sørensen, G., & Lyngbye, M. (2007). Reduced diet crude protein level, benzoic acid and inulin reduced ammonia, but failed to influence odour emission from finishing pigs. *Livestock science*, *109*(1), 228-231. https://doi.org/10.1016/j.livsci.2007.01.133

Hansen, J. Ø., Øverland, M., Skrede, A., Anderson, D. M., & Collins, S. A. (2020). A meta-analysis of the effects of dietary canola / double low rapeseed meal on growth performance of weanling and growing-finishing pigs. *Animal Feed Science and Technology*, *259*, 114302. https://doi.org/10.1016/j.anifeedsci.2019.114302

Hansen, L. L., Claudi-Magnussen, C., Jensen, S. K., & Andersen, H. J. (2006). Effect of organic pig production systems on performance and meat quality. *Meat science*, *74*(4), 605-615. https://doi.org/10.1016/j.meatsci.2006.02.014

Hansen, L. L., Stolzenbach, S., Jensen, J. A., Henckel, P., Hansen-Møller, J., Syriopoulos, K., & Byrne, D. V. (2008). Effect of feeding fermentable fibre-rich feedstuffs on meat quality with emphasis on chemical and sensory boar taint in entire male and female pigs. *Meat science*, *80*(4), 1165-1173. https://doi.org/10.1016/j.meatsci.2008.05.010

Haque, M. A., Liu, Z., Demilade, A., & Kumar, N. M. (2022). Assessing the environmental footprint of distiller-dried grains with soluble diet as a substitute for standard corn-soybean for swine production in the United States of America. *Sustainability*, *14*(3), 1161. https://doi.org/doi:10.3390/su14031161

Harrer, M., Cuijpers, P., Furukawa, T. A., & Ebert, D. D. (2021). *Doing meta-analysis with R: A hands-on guide*. Chapman and Hall/CRC. https://doi.org/10.1201/9781003107347

Harris, J., Nguyen, P. H., Tran, L. M., & Huynh, P. N. (2020). Nutrition transition in Vietnam: changing food supply, food prices, household expenditure, diet and nutrition outcomes. *Food Security*, *12*(5), 1141-1155. https://doi.org/10.1007/s12571-020-01096-x

Hart, K. B., Ribeiro, F. A., Henriott, M. L., Herrera, N. J., & Calkins, C. R. (2019). Quality effects on beef strip steaks from cattle fed high-protein corn distillers grains and other ethanol by-products. *Journal of Animal Science*, *97*(5), 2087-2098. https://doi.org/10.1093/jas/skz086

Hashem, N. M., González-Bulnes, A., & Rodriguez-Morales, A. J. (2020). Animal welfare and livestock supply chain sustainability under the COVID-19 Outbreak: An overview [Review]. *Frontiers in Veterinary Science*, *7*. https://doi.org/10103389/fvets.2020.582528
Hatlen, B., Jakobsen, J.-V., Crampton, V., Alm, M., Langmyhr, E., Espe, M., Hevrøy, E. M., Torstensen, B. E., Liland, N., & Waagbø, R. (2015). Growth, feed utilization and endocrine responses in Atlantic salmon (Salmo salar) fed diets added poultry by-product meal and blood meal in combination with poultry oil. *Aquaculture Nutrition*, *21*(5), 714-725. https://doi.org/10.1111/anu.12194
Hawe, S. M., Walker, N., & Moss, B. W. (1992). The effects of dietary fibre, lactose and antibiotic on the levels of skatole and indole in faeces and subcutaneous fat in growing pigs. *Animal Science*, *54*(3), 413-419. https://doi.org/10.1017/S0003356100020870
Heda, R., & Tombazzi, C. R. (2020). *Physiology, Pepsin*. StatPearls Publishing, Treasure Island (FL). https://www.ncbi.nlm.nih.gov/books/NBK537005/
Henchion, M., McCarthy, M., Resconi, V. C., & Troy, D. (2014). Meat consumption: Trends and quality matters. *Meat science*, *98*(3), 561-568. https://doi.org/10.1016/j.meatsci.2014.06.007

Hendriks, W. H., Verstegen, M. W. A., & Babinszky, L. (2019). *Poultry and pig nutrition : challenges of the 21st century*. Wageningen Academic Publishers. https://doi.org/10.3920/978-90-8686-884-1
Higgins, J. P., & Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine*, *21*(11), 1539-1558. https://doi.org/10.1002/sim.1186
Honeyman, M. S. (2005). Extensive bedded indoor and outdoor pig production systems in USA: current trends and effects on animal care and product quality. *Livestock Production Science*, *94*(1), 15-24. https://doi.org/10.1016/j.livprodsci.2004.11.029
Hong, J., & Kim, Y. Y. (2022). Insect as feed ingredients for pigs. *Animal bioscience*, *35*(2), 347-355. https://doi.org/10.5713/ab.21.0475
Hong, Y.-C., Chu, J.-H., Kirby, R., Sheen, S.-S., & Chien, A. (2021). The effects of replacing fish meal protein with a mixture of poultry by-product meal and fermented soybean meal on the growth performance and tissue nutritional composition of Asian seabass (Lates calcarifer) [https://doi.org/10.1111/are.15249]. *Aquaculture Research*, *52*(9), 4105-4115. https://doi.org/10.1111/are.15249
Hoogeveen, A. M. E., Moughan, P. J., Henare, S. J., Schulze, P., McNabb, W. C., & Montoya, C. A. (2021). Type of dietary fiber is associated with changes in ileal and hindgut microbial communities in growing pigs and influences in vitro ileal and hindgut fermentation. *The Journal of Nutrition*, *151*(10), 2976-2985. https://doi.org/10.1093/jn/nxab228
Howarth, N. C., Saltzman, E., & Roberts, S. B. (2001). Dietary fiber and weight regulation. *Nutrition Reviews*, *59*(5), 129-139. https://doi.org/10.1111/j.1753-4887.2001.tb07001.x
Ibáñez, M. A., de Blas, C., Cámara, L., & Mateos, G. G. (2020). Chemical composition, protein quality and nutritive value of commercial soybean meals produced from beans from different countries: A meta-analytical study. *Animal Feed Science and Technology*, *267*, 114531. https://doi.org/10.1016/j.anifeedsci.2020.114531
Ivarsson, E. (2012). *Chicory (Cichorium intybus L) as fibre source in pig diets effects on digestibility , gut microbiota and ferformance* [publication, Swedish University].
Ivarsson, E., Frankow-Lindberg, B. E., Andersson, H. K., & Lindberg, J. E. (2011). Growth performance, digestibility and faecal coliform bacteria in weaned piglets fed a cereal-based diet including either chicory (Cichorium intybus L) or ribwort (Plantago lanceolata L) forage. *Animal*, *5*(4), 558-564. https://doi.org/http://doi.org/10.1017/s1751731110002193
Ivarsson, E., Liu, H. Y., Dicksved, J., Roos, S., & Lindberg, J. E. (2012). Impact of chicory inclusion in a cereal-based diet on digestibility, organ size and faecal microbiota in growing pigs. *animal*, *6*(7), 1077-1085. https://doi.org/10.1017/S1751731111002709

Jääskeläinen, T., Kauppinen, T., Vesala, K. M., & Valros, A. (2014). Relationships between pig welfare, productivity and farmer disposition. *Animal Welfare*, *23*(4), 435-443. https://doi.org/10.7120/09627286.23.4.435

Jacela, J. Y., DeRouchey, J. M., Dritz, S. S., Tokach, M. D., Goodband, R. D., Nelssen, J. L., Sulabo, R. C., Thaler, R. C., Brandts, L., Little, D. E., & Prusa, K. J. (2011). Amino acid digestibility and energy content of deoiled (solvent-extracted) corn distillers dried grains with solubles for swine and effects on growth performance and carcass characteristics. *Journal of Animal Science*, *89*(6), 1817-1829. https://doi.org/10.2527/jas.2010-3097

Jakobsen, M., Kongsted, A. G., & Hermansen, J. E. (2015). Foraging behaviour, nutrient intake from pasture and performance of free-range growing pigs in relation to feed CP level in two organic cropping systems. *animal*, *9*(12), 2006-2016. https://doi.org/10.1017/S1751731115001585

Jarrett, S., & Ashworth, C. J. (2018). The role of dietary fibre in pig production, with a particular emphasis on reproduction. *Journal of Animal Science and Biotechnology*, *9*(1), 59. https://doi.org/10.1186/s40104-018-0270-0

Jayathilakan, K., Sultana, K., Radhakrishna, K., & Bawa, A. S. (2012). Utilization of byproducts and waste materials from meat, poultry and fish processing industries: a review. *Journal of Food Science and Technology*, *49*(3), 278-293. https://doi.org/10.1007/s13197-011-0290-7

Jha, R., & Berrocoso, J. D. (2015). Review: Dietary fiber utilization and its effects on physiological functions and gut health of swine. *animal*, *9*(9), 1441-1452. https://doi.org/10.1017/S1751731115000919

Jha, R., & Berrocoso, J. F. D. (2016). Dietary fiber and protein fermentation in the intestine of swine and their interactive effects on gut health and on the environment: A review. *Animal Feed Science and Technology*, *212*, 18-26. https://doi.org/10.1016/j.anifeedsci.2015.12.002

Jha, R., Htoo, J. K., Young, M. G., Beltranena, E., & Zijlstra, R. T. (2013). Effects of increasing co-product inclusion and reducing dietary protein on growth performance, carcass characteristics, and jowl fatty acid profile of growing–finishing pigs. *Journal of Animal Science*, *91*(5), 2178-2191. https://doi.org/10.2527/jas.2011-5065

Johnson, M. L., Parsons, C. M., Fahey, G. C., Jr., Merchen, N. R., & Aldrich, C. G. (1998). Effects of species raw material source, ash content, and processing temperature on amino acid digestibility of animal by-product meals by cecectomized roosters and ileally cannulated dogs. *Journal of Animal Science*, *76*(4), 1112-1122. https://doi.org/10.2527/1998.7641112x

Jónsdóttir, R., Valdimarsdottir, T., Baldursdottir, B., & Thorkelsson, G. (2003). Influence of low fat fishmeal on fatty acid composition and sensory quality of pork. *Journal of Muscle Foods*, *14*(1), 51-65. https://doi.org/10.1111/j.1745-4573.2003.tb00345.x

Kaensombath, L., & Lindberg, J. E. (2012). Effect of replacing soybean protein by taro leaf (Colocasia esculenta (L.) Schott) protein on growth performance of exotic (Landrace × Yorkshire) and native (Moo Lath) Lao pigs. *Tropical Animal Health and Production*, *45*(1), 45-51. https://doi.org/https://doi.org/10.1007/s11250-012-0172-7

Kaensombath, L., Neil, M., & Lindberg, J. E. (2013). Effect of replacing soybean protein with protein from ensiled stylo (Stylosanthes guianensis (Aubl.) Sw. var. guianensis) on growth performance, carcass traits and organ weights of exotic (Landrace x Yorkshire) and native (Moo Lath) Lao pigs. *Tropical Animal Health and Production*, *45*(3), 865-871. https://doi.org/10.1007/s11250-012-0299-6

Kallabis, K. E., & Kaufmann, O. (2012). Effect of a high-fibre diet on the feeding behaviour of fattening pigs. *Archives of Animal Breeding*, *55*(3), 272-284.

Kalscheur, K. F., Garcia, A. D., Schingoethe, D. J., Royón, F. D., & Hippen, A. R. (2012). Feeding biofuel co-products to dairy cattle. In H. P. S. Makkar (Ed.), *Biofuel co-products as livestock feed: Opportunities and challenges*. Food & Agriculture Organization.

Kambashi, B., Boudry, C., Picron, P., & Bindelle, J. (2014). Forage plants as an alternative feed resource for sustainable pig production in the tropics: A review. *animal*, *8*(8), 1298-1311. https://doi.org/10.1017/S1751731114000561

Kambashi, B., Boudry, C., Picron, P., Kiatoko, H., & Bindelle, J. (2014). Feeding value of hays of tropical forage legumes in pigs: Vigna unguiculata, Psophocarpus scandens, Pueraria phaseoloides and Stylosanthes guianensis. *Tropical Animal Health and Production*, *46*(8), 1497-1502. https://doi.org/10.1007/s11250-014-0647-9

Kambashi, B., Kalala, G., Dochain, D., Mafwila, J., Rollin, X., Boudry, C., Picron, P., & Bindelle, J. (2016). Nutritive value of three tropical forage legumes and their influence on growth performance, carcass traits and organ weights of pigs. *Tropical Animal Health and Production*, *48*(6), 1165-1173. https://doi.org/10.1007/s11250-016-1070-1

Kambashi, B., Picron, P., Boudry, C., Théwis, A., Kiatoko, H., & Bindelle, J. (2014). Nutritive value of tropical forage plants fed to pigs in the Western provinces of the Democratic Republic of the Congo. *Animal Feed Science and Technology*, *191*, 47-56. https://doi.org/10.1016/j.anifeedsci.2014.01.012

Kapoor, B., Kapoor, D., Gautam, S., Singh, R., & Bhardwaj, S. (2021). Dietary polyunsaturated fatty acids (PUFAs): Uses and potential health benefits. *Current Nutrition Reports*, *10*(3), 232-242. https://doi.org/10.1007/s13668-021-00363-3

Kass, M. L., Van Soest, P. J., & Pond, W. G. (1980). Utilization of dietary fiber from Alfalfa by growing Swine. II. Volatile fatty acid concentrations in and disappearance from the gastrointestinal tract. *Journal of Animal Science*, *50*(1), 192-197. https://doi.org/10.2527/jas1980.501192x

Kass, M. L., Van Soest, P. J., Pond, W. G., Lewis, B., & McDowell, R. E. (1980). Utilization of dietary fiber from alfalfa by growing sine. I. Apparent digestibility of det components in secific sgments of the gastrointestinal tact. *Journal of Animal Science*, *50*(1), 175-191. https://doi.org/10.2527/jas1980.501175x

Keegan, T. P., DeRouchey, J. M., Nelssen, J. L., Tokach, M. D., Goodband, R. D., & Dritz, S. S. (2004). The effects of poultry meal source and ash level on nursery pig performance. *Journal of Animal Science*, *82*(9), 2750-2756. https://doi.org/10102527/2004.8292750x

Kelly, H. R. C., Browning, H. M., Day, J. E. L., Martins, A., Pearce, G. P., Stopes, C., & Edwards, S. A. (2007). Effect of breed type, housing and feeding system on performance of growing pigs managed under organic conditions. *Journal of the Science of Food and Agriculture*, *87*(15), 2794-2800. https://doi.org/10.1002/jsfa.3060

Kerr, B. J., Jha, R., Urriola, P. E., & Shurson, G. C. (2017). Nutrient composition, digestible and metabolizable energy content, and prediction of energy for animal protein byproducts in finishing pig diets. *Journal of Animal Science*, *95*(6), 2614-2626. https://doi.org/10102527/jas.2016.1165

Kerr, B. J., Urriola, P. E., Jha, R., Thomson, J. E., Curry, S. M., & Shurson, G. C. (2019). Amino acid composition and digestible amino acid content in animal protein by-product meals fed to growing pigs. *Journal of Animal Science*, *97*(11), 4540-4547. https://doi.org/10101093/jas/skz294

Kim, B. G., Zhang, Y., & Stein, H. H. (2012). Sulfur concentration in diets containing corn, soybean meal, and distillers dried grains with solubles does not affect feed preference or growth performance of weanling or growing-finishing pigs. *Journal of Animal Science*, *90*(1), 272-281. https://doi.org/10.2527/jas.2010-3777

Kim, G.-D., Kim, B.-W., Jeong, J.-Y., Hur, S.-J., Cho, I.-C., Lim, H.-T., & Joo, S.-T. (2013). Relationship of Carcass Weight to Muscle Fiber Characteristics and Pork Quality of Crossbred (Korean Native Black Pig × Landrace) F2 Pigs. *Food and Bioprocess Technology*, *6*(2), 522-529. https://doi.org/10.1007/s11947-011-0724-2

Kingsly, A. R. P., Ileleji, K. E., Clementson, C. L., Garcia, A., Maier, D. E., Stroshine, R. L., & Radcliff, S. (2010). The effect of process variables during drying on the physical and chemical characteristics of corn dried distillers grains with solubles (DDGS) – Plant scale experiments. *Bioresource Technology*, *101*(1), 193-199. https://doi.org/10.1016/j.biortech.2009.07.070

Kjos, N. P., Øverland, M., Fauske, A. K., & Sørum, H. (2010). Feeding chicory inulin to entire male pigs during the last period before slaughter reduces skatole in digesta and backfat. *Livestock science*, *134*(1), 143-145. https://doi.org/10.1016/j.livsci.2010.06.120

Kleinbeck, S. N., & McGlone, J. J. (1999). Intensive indoor versus outdoor swine production systems: genotype and supplemental iron effects on blood hemoglobin and selected immune measures in young pigs1. *Journal of Animal Science*, *77*(9), 2384-2390. https://doi.org/10.2527/1999.7792384x

Kobek-Kjeldager, C., Schönherz, A. A., Canibe, N., & Pedersen, L. J. (2022). Diet and microbiota-gut-brain axis in relation to tail biting in pigs: A review. *Applied Animal Behaviour Science*, *246*, 105514. https://doi.org/10.1016/j.applanim.2021.105514

Kongsted, A. G., Norgaard, J. V., Jensen, S. K., Lauridsen, C., Juul-Madsen, H. R., Norup, L. R., Engberg, R. M., Horsted, K., & Hermansen, J. E. (2015). Influence of genotype and feeding strategy on pig performance, plasma concentrations of micro nutrients, immune responses and faecal microbiota composition of growing-finishing pigs in a forage-based system. *Livestock science*, *178*, 263-271. https://doi.org/10.1016/j.livsci.2015.06.010

Kouba, M., & Mourot, J. (2011). A review of nutritional effects on fat composition of animal products with special emphasis on n-3 polyunsaturated fatty acids. *Biochimie*, *93*(1), 13-17. https://doi.org/10.1016/j.biochi.2010.02.027

Krimpen, M. M. v., Bikker, P., Meer, I. M. v. d., Peet-Schwering, C. M. C. v. d., & Vereijken, J. M. (2013). *Cultivation, processing and nutritional aspects for pigs and poultry of European protein sources as alternatives for imported soybean products* (1570-8616). https://edepot.wur.nl/250643

Kumar, A., Sharma, A., & Upadhyaya, K. C. (2016). Vegetable oil: Nutritional and industrial perspective. *Current Genomics*, *17*(3), 230-240. https://doi.org/10.2174/1389202917666160202220107

Kumar, R. (1992). Anti-nutritional factors, the potential risks of toxicity and methods to alleviate them. Legume trees and other fodder trees as protein source for livestock. FAO Animal Production and Health Paper, Kuala Lumpur, Malaysia.

Kumaresan, A., Bujarbaruah, K. M., Pathak, K. A., Chhetri, B., Das, S. K., Das, A., & Ahmed, S. K. (2007). Performance of pigs reared under traditional tribal low input production system and chemical composition of non-conventional tropical plants used as pig feed. *Livestock science*, *107*(2), 294-298. https://doi.org/10.1016/j.livsci.2006.12.007

Lathuillière, M. J., Miranda, E. J., Bulle, C., Couto, E. G., & Johnson, M. S. (2017). Land occupation and transformation impacts of soybean production in Southern Amazonia, Brazil. *Journal of Cleaner Production*, *149*, 680-689. https://doi.org/10.1016/j.jclepro.2017.02.120

Lebret, B. (2008). Effects of feeding and rearing systems on growth, carcass composition and meat quality in pigs. *animal*, *2*(10), 1548-1558. https://doi.org/10.1017/S1751731108002796

Lebret, B., & Guillard, A.-S. (2005). Outdoor rearing of cull sows: Effects on carcass, tissue composition and meat quality. *Meat science*, *70*(2), 247-257. https://doi.org/10.1016/j.meatsci.2005.01.007

Lebret, B., Meunier-Salaün, M. C., Foury, A., Mormède, P., Dransfield, E., & Dourmad, J. Y. (2006). Influence of rearing conditions on performance, behavioral, and physiological responses of

pigs to preslaughter handling, carcass traits, and meat quality. *Journal of Animal Science*, *84*(9), 2436-2447. https://doi.org/10.2527/jas.2005-689
Lei, X. G., Ku, P. K., Miller, E. R., & Yokoyama, M. T. (1993). Supplementing corn-soybean meal diets with microbial phytase linearly improves phytate phosphorus utilization by weanling pigs. *Journal of Animal Science*, *71*(12), 3359-3367. https://doi.org/10.2527/1993.71123359x

Lekule, F. P., & Kyvsgaard, N. C. (2003). Improving pig husbandry in tropical resource-poor communities and its potential to reduce risk of porcine cysticercosis. *Acta Tropica*, *87*(1), 111-117. https://doi.org/10.1016/S0001-706X(03)00026-3
Len, N. T., Hong, T. T. T., Ogle, B., & Lindberg, J. E. (2009). Comparison of total tract digestibility, development of visceral organs and digestive tract of Mong cai and Yorkshire × Landrace piglets fed diets with different fibre sources. *Journal of Animal Physiology and Animal Nutrition*, *93*(2), 181-191. https://doi.org/10.1111/j.1439-0396.2007.00804.x
Leong, J., Morel, P. C. H., Purchas, R. W., & Wilkinson, B. H. P. (2011). Effects of dietary components including garlic on concentrations of skatole and indole in subcutaneous fat of female pigs. *Meat science*, *88*(1), 45-50. https://doi.org/10.1016/j.meatsci.2010.12.001
Leterme, P., Londoño, A. M., Muñoz, J. E., Súarez, J., Bedoya, C. A., Souffrant, W. B., & Buldgen, A. (2009). Nutritional value of aquatic ferns (Azolla filiculoides Lam. and Salvinia molesta Mitchell) in pigs. *Animal Feed Science and Technology*, *149*(1), 135-148. https://doi.org/10.1016/j.anifeedsci.2008.04.013
Lewis, A. J., Southern, L. L., Lewis, A. J., & Southern, L. L. (2000). *Swine Nutrition*. Taylor & Francis Group. http://ebookcentral.proquest.com/lib/massey/detail.action?docID=264554
Li, C. Y., Liu, J. X., Wang, Y. Z., Wu, Y. M., Wang, J. K., & Zhou, Y. Y. (2009). Influence of differing carbohydrate sources on l-tryptophan metabolism by porcine fecal microbiota studied in vitro. *Livestock science*, *120*(1), 43-50. https://doi.org/10.1016/j.livsci.2008.04.014

Li, X., Zhao, L., Fan, Y., Jia, Y., Sun, L., Ma, S., Ji, C., Ma, Q., & Zhang, J. (2014). Occurrence of mycotoxins in feed ingredients and complete feeds obtained from the Beijing region of China. *Journal of Animal Science and Biotechnology*, *5*(1), 37. https://doi.org/10.1186/2049-1891-5-37
Lindberg, J. E., & Andersson, C. (1998). The nutritive value of barley-based diets with forage meal inclusion for growing pigs based on total tract digestibility and nitrogen utilization. *Livestock Production Science*, *56*(1), 43-52. https://doi.org/10.1016/S0301-6226(98)00146-8
Linneen, S. K., DeRouchey, J. M., Dritz, S. S., Goodband, R. D., Tokach, M. D., & Nelssen, J. L. (2008). Effects of dried distillers grains with solubles on growing and finishing pig performance in a commercial environment. *Journal of Animal Science*, *86*(7), 1579-1587. https://doi.org/10.2527/jas.2007-0486
Little, K. L., Bohrer, B. M., Maison, T., Liu, Y., Stein, H. H., & Boler, D. D. (2015). Effects of feeding canola meal from high-protein or conventional varieties of canola seeds on growth performance, carcass characteristics, and cutability of pigs. *Journal of Animal Science*, *93*(3), 1284-1297. https://doi.org/10.2527/jas.2014-8359
Liu, H. Y., Ivarsson, E., Dicksved, J., Lundh, T., & Lindberg, J. E. (2012). Inclusion of Chicory (Cichorium intybus L.) in pigs' diets affects the intestinal microenvironment and the gut microbiota. *Applied and Environmental Microbiology*, *78*(12), 4102-4109. https://doi.org/10.1128/aem.07702-11
Liu, Y., Jaworski, N. W., Rojas, O. J., & Stein, H. H. (2016). Energy concentration and amino acid digestibility in high protein canola meal, conventional canola meal, and in soybean meal fed to growing pigs. *Animal Feed Science and Technology*, *212*, 52-62. https://doi.org/10.1016/j.anifeedsci.2015.11.017

Loh, G., Eberhard, M., Brunner, R. M., Hennig, U., Kuhla, S., Kleessen, B., & Metges, C. C. (2006). Inulin alters the intestinal microbiota and short-chain fatty acid concentrations in growing pigs regardless of their basal diet. *The Journal of Nutrition*, *136*(5), 1198-1202. https://doi.org/10.1093/jn/136.5.1198
Lomascolo, A., Uzan-Boukhris, E., Sigoillot, J.-C., & Fine, F. (2012). Rapeseed and sunflower meal: a review on biotechnology status and challenges. *Applied Microbiology and Biotechnology*, *95*(5), 1105-1114. https://doi.org/10.1007/s00253-012-4250-6
Loy, D. D., & Lundy, E. L. (2019). Chapter 23 - Nutritional Properties and Feeding Value of Corn and Its Coproducts. In S. O. Serna-Saldivar (Ed.), *Corn (Third Edition)* (pp. 633-659). AACC International Press. https://doi.org/10.1016/B978-0-12-811971-6.00023-1
Lukić, B., Ferenčaković, M., Šalamon, D., Čačić, M., Orehovački, V., Iacolina, L., Curik, I., & Cubric-Curik, V. (2020). Conservation genomic analysis of the Croatian indigenous Black Slavonian and Turopolje pig breeds. *Frontiers in genetics*, *11*, 261. https://doi.org/10.3389/fgene.2020.00261
Lutwyche, R. (2019). *The pig : a natural history*. Princeton University Press. https://doi.org/10.2307/j.ctvd58rfq
Ly, N. T. H., Ngoan, L. D., Verstegen, M. W. A., & Hendriks, W. H. (2010). Ensiled and dry cassava leaves, and sweet potato vines as a protein source in diets for growing Vietnamese Large WhitexMong Cai pigs. *Asian-Australasian Journal of Animal Sciences*, *23*(9), 1205-1212. https://doi.org/10.5713/ajas.2010.90591
Ly, N. T. H., Ngoan, L. D., Verstegen, M. W. A., & Hendriks, W. H. (2011). Inclusion of ensiled Cassava KM94 leaves in diets for growing pigs in Vietnam reduces growth rate but increases profitability. *Asian-Australasian Journal of Animal Sciences*, *24*(8), 1157-1163. https://doi.org/10.5713/ajas.2011.10451
Ma, X., Hu, J., Shang, Q., Liu, H., & Piao, X. (2019). Chemical composition, energy content and amino acid digestibility in cottonseed meals fed to growing pigs. *Journal of Applied Animal Research*, *47*(1), 280-288. https://doi.org/10.1080/09712119.2019.1626241
Madsen, A., Jakobsen, K., & Mortensen, H. P. (1992). Influence of dietary fat on carcass fat quality in pigs. A review. *Acta Agriculturae Scandinavica, Section A — Animal Science*, *42*(4), 220-225. https://doi.org/10.1080/09064709209410132
Maison, T., & Stein, H. H. (2014). Digestibility by growing pigs of amino acids in canola meal from North America and 00-rapeseed meal and 00-rapeseed expellers from Europe1. *Journal of Animal Science*, *92*(8), 3502-3514. https://doi.org/10.2527/jas.2014-7748
Martens, S. D., Tiemann, T. T., Bindelle, J., Peters, M., & Lascano, C. E. (2012). Alternative plant protein sources for pigs and chickens in the tropics - nutritional value and constraints: a review. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, *113*(2), 101-123. https://jarts.info/index.php/jarts/article/view/2012092441794/191
Martinez-Amezcua, C., Parsons, C. M., Singh, V., Srinivasan, R., & Murthy, G. S. (2007). Nutritional characteristics of corn distillers dried grains with solubles as affected by the amounts of grains versus solubles and different processing techniques. *Poultry Science*, *86*(12), 2624-2630. https://doi.org/10.3382/ps.2007-00137
Mayorga, E. J., Renaudeau, D., Ramirez, B. C., Ross, J. W., & Baumgard, L. H. (2019). Heat stress adaptations in pigs. *Animal Frontiers*, *9*(1), 54-61. https://doi.org/10.1093/af/vfy035
McClelland, K. M., Rentfrow, G., Cromwell, G. L., Lindemann, M. D., & Azain, M. J. (2012). Effects of corn distillers dried grains with solubles on quality traits of pork. *Journal of Animal Science*, *90*(11), 4148-4156. https://doi.org/10.2527/jas.2011-4779
McDonald, P., Henderson, N., & Heron, S. (1991). *The biochemistry of silage* (2nd ed ed.) [Bibliographies

Non-fiction]. Chalcombe. http://ezproxy.massey.ac.nz/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat00245a&AN=massey.b1488147&site=eds-live&scope=site

McDonnell, P., O'Shea, C.J., Callan, J.J., O'Doherty, J.V. (2011). The response of growth performance, nitrogen, and phosphorus excretion of growing—finishing pigs to diets containing incremental levels of maize dried distiller's grains with solubles. *Animal Feed Science and Technology*, *169*(1-2), 104-112. https://doi.org/10.1016/j.anifeedsci.2011.06.001

McGhee, M. L., & Stein, H. H. (2018). Apparent and standardized ileal digestibility of AA and starch in hybrid rye, barley, wheat, and corn fed to growing pigs. *Journal of Animal Science*, *96*(8), 3319-3329. https://doi.org/10.1093/jas/sky206

McGlone, J. J. (2013). The future of pork production in the world: Towards sustainable, welfare-positive Systems. *Animals*, *3*(2), 401-415. https://doi.org/10.3390/ani3020401

Mejicanos, G. A., & Nyachoti, C. M. (2018). Effect of tail-end dehulling of canola meal on apparent and standardized ileal digestibility of amino acids when fed to growing pigs. *Animal Feed Science and Technology*, *243*, 102-111. https://doi.org/10.1016/j.anifeedsci.2018.07.011

Mekonnen, M. M., & Hoekstra, A. Y. (2012). A Global Assessment of the Water Footprint of Farm Animal Products. *Ecosystems*, *15*(3), 401-415. https://doi.org/10.1007/s10021-011-9517-8

Mekonnen, M. M., Neale, C. M. U., Ray, C., Erickson, G. E., & Hoekstra, A. Y. (2019). Water productivity in meat and milk production in the US from 1960 to 2016. *Environment International*, *132*, 105084. https://doi.org/10.1016/j.envint.2019.105084

Men, L. T., Yamasaki, S., Caldwell, J. S., Yamada, R., Takada, R., & Taniguchi, T. (2006). Effect of farm household income levels and rice-based diet or water hyacinth (Eichhornia crassipes) supplementation on growth/cost performances and meat indexes of growing and finishing pigs in the Mekong Delta of Vietnam. *Animal Science Journal*, *77*(3), 320-329. https://doi.org/10.1111/j.1740-0929.2006.00355.x

Millet, S., Moons, C. P., Van Oeckel, M. J., & Janssens, G. P. (2005). Welfare, performance and meat quality of fattening pigs in alternative housing and management systems: a review. *Journal of the Science of Food and Agriculture*, *85*(5), 709-719. https://doi.org/10.1002/jsfa.2033

Miltenburg, G. A. J., Wensing, T., Smulders, F. J. M., & Breukink, H. J. (1992). Relationship between blood hemoglobin, plasma and tissue iron, muscle heme pigment, and carcass color of veal1. *Journal of Animal Science*, *70*(9), 2766-2772. https://doi.org/10.2527/1992.7092766x

Montagne, L., Pluske, J. R., & Hampson, D. J. (2003). A review of interactions between dietary fibre and the intestinal mucosa, and their consequences on digestive health in young non-ruminant animals. *Animal Feed Science and Technology*, *108*(1), 95-117. https://doi.org/10.1016/S0377-8401(03)00163-9

Moon, J. S., Kwon, I. K., & Chae, B. J. (2004). Effects of wet feeding of diets with or without food waste on growth performance and carcass characteristics in finishing pigs. *Asian-Australasian Journal of Animal Sciences*, *17*(4), 504-510. https://doi.org/10.5713/ajas.2004.504

Morel, P., Pluske, J., Pearson, G., & Moughan, P. (1999). A standard nutrient matrix for New Zealand feedstuffs. In. Massey University, Palmerston North, New Zealand.

Mottet, A., de Haan, C., Falcucci, A., Tempio, G., Opio, C., & Gerber, P. (2017). Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. *Global Food Security*, *14*(January 2016), 1-8. https://doi.org/10.1016/j.gfs.2017.01.001

Mozhiarasi, V., & Natarajan, T. S. (2022). Slaughterhouse and poultry wastes: management practices, feedstocks for renewable energy production, and recovery of value added products. *Biomass Conversion and Biorefinery*. https://doi.org/10101007/s13399-022-02352-0

Mumm, R. H., Goldsmith, P. D., Rausch, K. D., & Stein, H. H. (2014). Land usage attributed to corn ethanol production in the United States: sensitivity to technological advances in corn grain yield, ethanol conversion, and co-product utilization. *Biotechnology for Biofuels*, *7*(1), 61. https://doi.org/10.1186/1754-6834-7-61

Myer, R. O., & Brendemuhl, J. H. (2004). 4H Project Guide: Swine Nutrition. *EDIS*, *2004 (8)*, 3. https://journals.flvc.org/edis/article/view/111321

Myrie, S. B., Bertolo, R. F., Sauer, W. C., & Ball, R. O. (2008). Effect of common antinutritive factors and fibrous feedstuffs in pig diets on amino acid digestibilities with special emphasis on threonine. *Journal of Animal Science*, *86*(3), 609-619. https://doi.org/10.2527/jas.2006-793

Nde, D. B., & Foncha, A. C. (2020). Optimization methods for the extraction of vegetable oils: A review. *Processes*, *8*(2), 209. https://www.mdpi.com/2227-9717/8/2/209

Nelson, S. L., & Sanregret, J. D. (1997). Response of pigs to bitter-tasting compounds. *Chemical Senses*, *22*(2), 129-132. https://doi.org/10.1093/chemse/22.2.129

Nemechek, J. E., Tokach, M. D., Dritz, S. S., Goodband, R. D., & DeRouchey, J. M. (2014). Evaluation of standardized ileal digestible valine:lysine, total lysine:crude protein, and replacing fish meal, meat and bone meal, and poultry byproduct meal with crystalline amino acids on growth performance of nursery pigs from seven to twelve kilograms. *Journal of Animal Science*, *92*(4), 1548-1561. https://doi.org/10.2527/jas.2013-6322

Ngoc, T. T. B., Len, N. T., & Lindberg, J. E. (2013). Impact of fibre intake and fibre source on digestibility, gut development, retention time and growth performance of indigenous and exotic pigs. *animal*, *7*(5), 736-745. https://doi.org/10.1017/S1751731112002169

Nguyen, T. T., Chidgey, K. L., Wester, T. J., & Morel, P. C. H. (2022). Provision of lucerne in the diet or as a manipulable enrichment material enhances feed efficiency and welfare status for growing-finishing pigs. *Livestock science*, *264*, 105065. https://doi.org/10.1016/j.livsci.2022.105065

Nhu Phuc, B. H., Ogle, B., & Lindberg, J. E. (2000). Effect of replacing soybean protein with cassava leaf protein in cassava root meal based diets for growing pigs on digestibility and N retention. *Animal Feed Science and Technology*, *83*(3), 223-235. https://doi.org/10.1016/S0377-8401(99)00136-4

Niemi, J. K., Sevón-Aimonen, M. L., Pietola, K., & Stalder, K. J. (2010). The value of precision feeding technologies for grow-finish swine. *Livestock science*, *129*(1-3), 13-23. https://doi.org/10.1016/j.livsci.2009.12.006

Nilzén, V., Babol, J., Dutta, P. C., Lundeheim, N., Enfält, A. C., & Lundström, K. (2001). Free range rearing of pigs with access to pasture grazing — effect on fatty acid composition and lipid oxidation products. *Meat science*, *58*(3), 267-275. https://doi.org/10.1016/S0309-1740(00)00164-9

Noblet, J., & Le Goff, G. (2001). Effect of dietary fibre on the energy value of feeds for pigs. *Animal Feed Science and Technology*, *90*(1), 35-52. https://doi.org/10.1016/S0377-8401(01)00195-X

Noblet, J., & van Milgen, J. (2004a). Energy value of pig feeds: Effect of pig body weight and energy evaluation system. *Journal of Animal Science*, *82*(suppl_13), E229-E238. https://doi.org/10.1016/j.livsci.2009.12.006

Noblet, J., & van Milgen, J. (2004b). Energy value of pig feeds: Effect of pig body weight and energy evaluation system1. *Journal of Animal Science*, *82*(suppl_13), E229-E238. https://doi.org/https://doi.org/10.2527/2004.8213_supplE229x

NRC. (2012). *Nutrient requirements of swine*. National Academies Press.

Nuez Ortín, W. G., & Yu, P. (2009). Nutrient variation and availability of wheat DDGS, corn DDGS and blend DDGS from bioethanol plants. *Journal of the Science of Food and Agriculture*, *89*(10), 1754-1761. https://doi.org/10.1002/jsfa.3652

OECD/FAO. (2019). *OECD-FAO Agricultural Outlook 2019-2028*. O. Publishing. http://ezproxy.massey.ac.nz/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsoec&AN=edsoec.agr.outlook.2019.en&site=eds-live&scope=site

OECD/FAO. (2020). *OECD-FAO Agricultural Outlook 2020-2029*. https://www.oecd-ilibrary.org/content/publication/1112c23b-en

OECD/FAO. (2022). *OECD-FAO Agricultural Outlook 2022-2031*. https://doi.org/10101787/19428846-en

Oksbjerg, N., Strudsholm, K., Lindahl, G., & Hermansen, J. E. (2005). Meat quality of fully or partly outdoor reared pigs in organic production. *Acta Agriculturae Scandinavica Section a-Animal Science*, *55*(2-3), 106-112. https://doi.org/10.1080/09064700510009324

Oliveira, M. S. F., Wiltafsky, M. K., Lee, S. A., Kwon, W. B., & Stein, H. H. (2020). Concentrations of digestible and metabolizable energy and amino acid digestibility by growing pigs may be reduced by autoclaving soybean meal. *Animal Feed Science and Technology*, *269*, 114621. https://doi.org/10101016/j.anifeedsci.2020.114621

Olumodeji, S. G. (2021). *Effect of dietary fibre affecting ad libitum feed intake and feeding behaviour of growing-finishing pigs fed a using single-spaced electronic feeders* [Masters, Massey University]. http://hdl.handle.net/10179/17303

Oryschak, M. A., Smit, M. N., & Beltranena, E. (2020). Brassica napus and Brassica juncea extruded-expelled cake and solvent-extracted meal as feedstuffs for laying hens: Lay performance, egg quality, and nutrient digestibility. *Poultry Science*, *99*(1), 350-363. https://doi.org/10.3382/ps/pez501

Parashar, A., & Udayabanu, M. (2016). Gut microbiota regulates key modulators of social behavior. *European Neuropsychopharmacology*, *26*(1), 78-91. https://doi.org/10.1016/j.euroneuro.2015.11.002

Park, H.-S., Min, B., & Oh, S.-H. (2017). Research trends in outdoor pig production - A review. *Asian-Australasian journal of Animals sciences*, *30*(9), 1207-1214. https://doi.org/10.5713/ajas.17.0330

Pauly, C., Spring-Staehli, P., O'Doherty, J. V., Kragten, S. A., Dubois, S., Messadène, J., & Bee, G. (2010). The effects of method of castration, rearing condition and diet on sensory quality of pork assessed by a trained panel. *Meat science*, *86*(2), 498-504. https://doi.org/10.1016/j.meatsci.2010.05.042

Pedersen, L. J., Herskin, M. S., Forkman, B., Halekoh, U., Kristensen, K. M., & Jensen, M. B. (2014). How much is enough? The amount of straw necessary to satisfy pigs' need to perform exploratory behaviour. *Applied Animal Behaviour Science*, *160*, 46-55. https://doi.org/10.1016/j.applanim.2014.08.008

Peng, M. J., Wang, Z. H., Peng, S., Zhang, M. L., Duan, Y. H., Li, F. N., Shi, S. Y., Yang, Q. L., & Zhang, C. W. (2019). Dietary supplementation with the extract from Eucommia ulmoides leaves changed epithelial restitution and gut microbial community and composition of weanling piglets. *PLoS ONE*, *14*(9), Article e0223002. https://doi.org/10.1371/journal.pone.0223002

Peters, J. L., Sutton, A. J., Jones, D. R., Abrams, K. R., & Rushton, L. (2008). Contour-enhanced meta-analysis funnel plots help distinguish publication bias from other causes of asymmetry. *Journal of Clinical Epidemiology*, *61*(10), 991-996. https://doi.org/10.1016/j.jclinepi.2007.11.010

Phengsavanh, P., & Lindberg, J. E. (2013). Effect of replacing soybean protein with protein from porcupine joint vetch (Aeschynomene histrix BRA 9690) and stylo (Stylosanthes guianensis Composite) leaf meal on growth performance of native (Moo Lath) Lao pigs. *Tropical Animal*

Health and Production, *45*(8), 1795-1802. https://doi.org/http://doi.org/10.1007/s11250-013-0437-9
Phuc, B. H. N., & Lindberg, J. E. (2000). Ileal and total tract digestibility in growing pigs given cassava root meal diets with inclusion of cassava leaves, leucaena leaves and groundnut foliage. *Animal Science*, *71*(2), 301-308. https://doi.org/10.1017/S1357729800055144
Picardy, J. A., Pietrosemoli, S., Griffin, T. S., & Peters, C. J. (2019). Niche pork: Comparing pig performance and understanding producer benefits, barriers and labeling interest. *Renewable Agriculture and Food Systems*, *34*(1), 7-19. https://doi.org/10.1017/S1742170517000230
Pietrosemoli, S., & Tang, C. (2020). Animal welfare and production challenges associated with pasture pig systems: A review. *Agriculture*, *10*(6), 223. https://doi.org/10.3390/agriculture10060223
Pomar, C., & Remus, A. (2019). Precision pig feeding: a breakthrough toward sustainability. *Animal Frontiers*, *9*(2), 52-59. https://doi.org/10.1093/af/vfz006
Powley, J. S., Cheeke, P. R., England, D. C., Davidson, T. P., & Kennick, W. H. (1981). Performance of growing-finishing swine fed high levels of Alfalfa meal: Effects of Alfalfa level, dietary additives and antibiotics. *Journal of Animal Science*, *53*(2), 308-316. https://doi.org/10.2527/jas1981.532308x
Presto Åkerfeldt, M., Nihlstrand, J., Neil, M., Lundeheim, N., Andersson, H. K., & Wallenbeck, A. (2019). Chicory and red clover silage in diets to finishing pigs—influence on performance, time budgets and social interactions. *Organic Agriculture*, *9*(1), 127-138. https://doi.org/10.1007/s13165-018-0216-z
Ramonet, Y., Meunier-Salaün, M. C., & Dourmad, J. Y. (1999). High-fiber diets in pregnant sows: digestive utilization and effects on the behavior of the animals. *Journal of Animal Science*, *77*(3), 591-599. https://doi.org/10.2527/1999.773591x
Rattanasomboon, T., Wester, T. J., Smith, S. L., & Morel, P. C. H. (2019). Nutritive value of plantain and chicory for pigs. *Livestock science*, *223*(November 2018), 8-15. https://doi.org/10.1016/j.livsci.2019.02.016
Recharla, N., Kim, D., Ramani, S., Song, M., Park, J., Balasubramanian, B., Puligundla, P., & Park, S. (2019). Dietary multi-enzyme complex improves In Vitro nutrient digestibility and hind gut microbial fermentation of pigs. *PLoS ONE*, *14*(5), e0217459. https://doi.org/10.1371/journal.pone.0217459
Regnier, C., Jaguelin, Y., Noblet, J., & Renaudeau, D. (2012). Ileal digestibility of amino acids of cassava, sweet potato, cocoyam and erythrina foliages fed to growing pigs [Article]. *animal*, *6*(4), 586-593. https://doi.org/10.1017/s1751731111001959
Reig, M., Aristoy, M. C., & Toldrá, F. (2013). Variability in the contents of pork meat nutrients and how it may affect food composition databases. *Food Chemistry*, *140*(3), 478-482. https://doi.org/10.1016/j.foodchem.2012.11.085
Renaudeau, D., Jensen, S. K., Ambye-Jensen, M., Adler, S., Bani, P., Juncker, E., & Stødkilde, L. (2022). Nutritional values of forage-legume-based silages and protein concentrates for growing pigs. *animal*, *16*(7), 100572. https://doi.org/10.1016/j.animal.2022.100572
Rérat, A. (1978). Digestion and absorption of carbohydrates and nitrogenous matters in the hindgut of the omnivorous nonruminant animal. *Journal of Animal Science*, *46*(6), 1808-1837. https://doi.org/10.2527/jas1978.4661808x
Resano, H., Perez-Cueto, F. J. A., de Barcellos, M. D., Veflen-Olsen, N., Grunert, K. G., & Verbeke, W. (2011). Consumer satisfaction with pork meat and derived products in five European countries. *Appetite*, *56*(1), 167-170. https://doi.org/10.1016/j.appet.2010.10.008
Reverter, M., Lundh, T., & Lindberg, J. (1999). Ileal amino acid digestibilities in pigs of barley-based diets with inclusion of lucerne (Medicago sativa), white clover (Trifolium repens), red clover (Trifolium pratense) or perennial ryegrass (Lolium perenne). *The British journal of nutrition*, *82*, 139-147. https://doi.org/10.1017/S0007114599001294

RFA. (2016). *2016 Ethanol industry outlook: Fueling a high octane future*. https://ethanolrfa.org/wp-content/uploads/2016/02/Ethanol-Industry-Outlook-2016.pdf

RFA. (2020). *2020 Ethanol industry outlook: Forcus Forward*. https://ethanolrfa.org/wp-content/uploads/2020/02/2020-Outlook-Final-for-Website.pdf

Ribeiro, L. B., Bankuti, F. I., da Silva, M. U., Ribeiro, P. M., Silva, J. M., Sato, J., Bortolo, M., & Vasconcellos, R. S. (2019). Oxidative stability and nutritional quality of poultry by-product meal: An approach from the raw material to the finished product. *Animal Feed Science and Technology*, *255*, 114226. https://doi.org/10.1016/j.anifeedsci.2019.114226

Richard, J., Payne, G., Desjardins, A., Maragos, C., Norred, W., & Pestka, J. (2003). *Mycotoxins: Risks in plant, animal and human systems*.

Ritchie, H., & Roser, M. (2021). Forests and deforestation. *Our World in Data*. https://ourworldindata.org/forests-and-deforestation

Robert, S., Matte, J. J., Farmer, C., Girard, C. L., & Martineau, G. P. (1993). High-fibre diets for sows: effects on stereotypies and adjunctive drinking. *Applied Animal Behaviour Science*, *37*(4), 297-309. https://doi.org/10.1016/0168-1591(93)90119-A

Rodrigues, I., & Chin, L. (2012). A comprehensive survey on the occurrence of mycotoxins in maize dried distillers' grain and solubles sourced worldwide. *World Mycotoxin Journal*, *5*(1), 83-88. https://doi.org/10.3920/WMJ2011.1308

Rodriguez, D. A., Lee, S. A., & Stein, H. H. (2020). Digestibility of amino acids, but not fiber, fat, or energy, is greater in cold-fermented, low-oil distillers dried grains with solubles (DDGS) compared with conventional DDGS fed to growing pigs. *Journal of Animal Science*, *98*(10). https://doi.org/10.1093/jas/skaa297

Rodríguez, D. A., Sulabo, R. C., González-Vega, J. C., & Stein, H. H. (2013). Energy concentration and phosphorus digestibility in canola, cottonseed, and sunflower products fed to growing pigs. *Canadian Journal of Animal Science*, *93*(4), 493-503. https://doi.org/10.4141/cjas2013-020

Rosenfelder, P., Eklund, M., & Mosenthin, R. (2013). Nutritive value of wheat and wheat by-products in pig nutrition: A review. *Animal Feed Science and Technology*, *185*(3), 107-125. https://doi.org/10.1016/j.anifeedsci.2013.07.011

Rosenvold, K., & Andersen, H. J. (2003). Factors of significance for pork quality—a review. *Meat science*, *64*(3), 219-237. https://doi.org/10101016/S0309-1740(02)00186-9

Rossi, W., & Davis, D. A. (2012). Replacement of fishmeal with poultry by-product meal in the diet of Florida pompano Trachinotus carolinus L. *Aquaculture*, *338-341*, 160-166. https://doi.org/10.1016/j.aquaculture.2012.01.026

Roth-Maier, D. A., Böhmer, B. M., & Roth, F. X. (2004). Effects of feeding canola meal and sweet lupin (L. luteus, L. angustifolius) in amino acid balanced diets on growth performance and carcass characteristics of growing-finishing pigs. *Animal Research*, *53*(1), 21-34. https://doi.org/10.1051/animres:2003048

Roth-Maier, D. A., Bohmera, B. M., & Roth, F. X. (2004). Effects of feeding canola meal and sweet lupin (L-luteus, L-angustifolius) in amino acid balanced diets on growth performance and carcass characteristics of growing-finishing pigs. *Animal Research*, *53*(1), 21-34. https://doi.org/10.1051/animres:2003048

Salemdeeb, R., zu Ermgassen, E. K. H. J., Kim, M. H., Balmford, A., & Al-Tabbaa, A. (2017). Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options. *Journal of Cleaner Production*, *140*, 871-880. https://doi.org/10.1016/j.jclepro.2016.05.049

Salminen, E. A., & Rintala, J. A. (2002). Semi-continuous anaerobic digestion of solid poultry slaughterhouse waste: effect of hydraulic retention time and loading. *Water Research*, *36*(13), 3175-3182. https://doi.org/10.1016/S0043-1354(02)00010-6
Samolinska, W., Grela, E. R., & Kiczorowska, B. (2019). Effects of inulin extracts and inulin-containing plants on haematobiochemical responses, plasma mineral concentrations, and carcass traits in growing-finishing pigs. *Journal of Elementology*, *24*(2), 711-726. https://doi.org/http://doi.org/10.5601/jelem.2018.23.4.1707
Samolinska, W., Grela, E. R., Kowalczuk-Vasilev, E., Kiczorowska, B., Klebaniuk, R., & Hanczakowska, E. (2020). Evaluation of garlic and dandelion supplementation on the growth performance, carcass traits, and fatty acid composition of growing-finishing pigs. *Animal Feed Science and Technology*, *259*, Article 114316. https://doi.org/10.1016/j.anifeedsci.2019.114316
Sánchez-Muros, M., Barroso, F. G., & Manzano-Agugliaro, F. (2014). Insect meal as renewable source of food for animal feeding: a review. *Journal of Cleaner Production*, *65*, 16-27. https://doi.org/10.1016/j.jclepro.2013.11.068
Sather, A. P., Jones, S. D. M., Schaefer, A. L., Colyn, J., & Robertson, W. M. (1997). Feedlot performance, carcass composition and meat quality of free-range reared pigs. *Canadian Journal of Animal Science*, *77*(2), 225-232. https://doi.org/10.4141/A96-093
Saunders, J. A., & Rosentrater, K. A. (2009). Properties of solvent extracted low-oil corn distillers dried grains with solubles. *Biomass and Bioenergy*, *33*(10), 1486-1490. https://doi.org/10.1016/j.biombioe.2009.07.004
Schöne, F., Groppel, B., Hennig, A., Jahreis, G., & Lange, R. (1997). Rapeseed meals, methimazole, thiocyanate and iodine affect growth and thyroid. Investigations into glucosinolate tolerance in the pig. *Journal of the Science of Food and Agriculture*, *74*(1), 69-80. https://doi.org/10.1002/(SICI)1097-0010(199705)74:1<69::AID-JSFA771>3.0.CO;2-0
Seabolt, B., van Heugten, E., Kim, S., Ange-van Heugten, K., & Roura, E. (2010). Feed preferences and performance of nursery pigs fed diets containing various inclusion amounts and qualities of distillers coproducts and flavor. *Journal of Animal Science*, *2010*(88), 3725-3738. https://doi.org/10.2527/jas.2009-2640
Shang, Q., Liu, H., Wu, D., Mahfuz, S., & Piao, X. (2021). Source of fiber influences growth, immune responses, gut barrier function and microbiota in weaned piglets fed antibiotic-free diets. *Animal Nutrition*, *7*(2), 315-325. https://doi.org/10.1016/j.aninu.2020.12.008
Shayo, C. M., & Udén, P. (1999). Nutritional uniformity of crude protein fractions in some tropical browse plants estimated by two in vitro methods. *Animal Feed Science and Technology*, *78*(1), 141-151. https://doi.org/10.1016/S0377-8401(98)00260-0
Shelton, J. L., Hemann, M. D., Strode, R. M., Brashear, G. L., Ellis, M., McKeith, F. K., Bidner, T. D., & Southern, L. L. (2001). Effect of different protein sources on growth and carcass traits in growing-finishing pigs. *Journal of Animal Science*, *79*(9), 2428-2435. https://doi.org/10102527/2001.7992428x
Shim, Y. H., Chae, B. J., & Lee, J. H. (2003). Effects of phytase and carbohydrases supplementation to diet with a partial peplacement of soybean meal with rapeseed meal and cottonseed meal on growth performance and nutrient digestibility of growing pigs. *Asian-Australasian Journal of Animal Sciences*, *16*(9), 1339-1347. https://doi.org/10.5713/ajas.2003.1339
Shirley, R. B., & Parsons, C. M. (2001). Effect of ash content on protein quality of meat and bone meal. *Poultry Science*, *80*(5), 626-632. https://doi.org/10.1093/ps/80.5.626
Shurson, G. C., Tilstra, H., & Kerr, B. J. (2012). Impact of United States biofuels co-products on the feed industry. In H. P. S. Makkar (Ed.), *Biofuel co-products as livestock feed - Opportunities and challenges*. Food & Agriculture Organization.

Siddik, M. A. B., Chungu, P., Fotedar, R., & Howieson, J. (2019). Bioprocessed poultry by-product meals on growth, gut health and fatty acid synthesis of juvenile barramundi, Lates calcarifer (Bloch). *PLoS ONE*, *14*(4), e0215025. https://doi.org/10101371/journal.pone.0215025
Simopoulos, A. P. (1999). Essential fatty acids in health and chronic disease. *The American Journal of Clinical Nutrition*, *70*(3), 560s-569s. https://doi.org/10.1093/ajcn/70.3.560s
Smit, M. N., & Beltranena, E. (2017). Increasing dietary inclusions of camelina cake fed to pigs from weaning to slaughter: Safety, growth performance, carcass traits, and n-3 enrichment of pork1. *Journal of Animal Science*, *95*(7), 2952-2967. https://doi.org/10.2527/jas.2016.1308
Smit, M. N., Landero, J. L., Young, M. G., & Beltranena, E. (2018). Effects of feeding canola meal or soy expeller at two dietary net energy levels on growth performance, dressing and carcass characteristics of barrows and gilts. *Animal Feed Science and Technology*, *235*, 166-176. https://doi.org/10.1016/j.anifeedsci.2017.11.013
Smit, M. N., Seneviratne, R. W., Young, M. G., Lanz, G., Zijlstra, R. T., & Beltranena, E. (2014). Feeding increasing inclusions of canola meal with distillers dried grains and solubles to growing-finishing barrows and gilts. *Animal Feed Science and Technology*, *189*, 107-116. https://doi.org/10.1016/j.anifeedsci.2013.12.012
Smulders, D., Verbeke, G., Mormède, P., & Geers, R. (2006). Validation of a behavioral observation tool to assess pig welfare. *Physiology & Behavior*, *89*(3), 438-447. https://doi.org/10.1016/j.physbeh.2006.07.002
So, K. K. Y., & Duncan, R. W. (2021). Breeding Canola (Brassica napus L.) for protein in feed and food. *Plants (Basel, Switzerland)*, *10*(10), 2220. https://doi.org/10.3390/plants10102220
Song, R., Chen, C., Johnston, L. J., Kerr, B. J., Weber, T. E., & Shurson, G. C. (2014). Effects of feeding diets containing highly peroxidized distillers dried grains with solubles and increasing vitamin E levels to wean–finish pigs on growth performance, carcass characteristics, and pork fat composition. *Journal of Animal Science*, *92*(1), 198-210. https://doi.org/10.2527/jas.2013-6334
Song, R., Chen, C., Wang, L., Johnston, L. J., Kerr, B. J., Weber, T. E., & Shurson, G. C. (2013). High sulfur content in corn dried distillers grains with solubles protects against oxidized lipids by increasing sulfur-containing antioxidants in nursery pigs1. *Journal of Animal Science*, *91*(6), 2715-2728. https://doi.org/10.2527/jas.2012-5350
Song, R., Csallany, A. S., & Shurson, G. (2011). Evaluation of lipid peroxidation level in corn dried distillers grains with solubles (DDGS). *Journal of Animal Science*, *89*(Suppl 3), 64.
Soto, E., Hoz, L., Ordóñez, J. A., Hierro, E., Herranz, B., López-Bote, C., & Cambero, M. I. (2008). Impact of feeding and rearing systems of Iberian pigs on volatile profile and sensory characteristics of dry-cured loin. *Meat science*, *79*(4), 666-676. https://doi.org/10.1016/j.meatsci.2007.10.031
Spiehs, M. J., Whitney, M. H., & Shurson, G. C. (2002). Nutrient database for distiller's dried grains with solubles produced from new ethanol plants in Minnesota and South Dakota. *Journal of Animal Science*, *80*(10), 2639-2645. https://doi.org/10.1093/ansci/80.10.2639
Squires, E. J., Bone, C., & Cameron, J. (2020). Pork production with entire males: Directions for control of boar taint. *Animals*, *10*(9), 1665. https://www.mdpi.com/2076-2615/10/9/1665
Stanford, C. B. (1999). *The hunting apes: Meat eating and the origins of human behavior*. Princeton University Press.
Statista. (2019). *Worldwide production of grain in 2019/20, by type*. Retrieved 26/11/2020 from https://www.statista.com/statistics/263977/world-grain-production-by-type/

Stein, H., & Lange, K. D. (2007). Alternative feed ingredients for pigs. *7th Annual London Swine conference*, *3-4*(April), 103-119.

Stein, H. H., Lagos, L. V., & Casas, G. A. (2016). Nutritional value of feed ingredients of plant origin fed to pigs. *Animal Feed Science and Technology*, *218*, 33-69. https://doi.org/10.1016/j.anifeedsci.2016.05.003

Stein, H. H., & Shurson, G. C. (2009). Board-invited review: The use and application of distillers dried grains with solubles in swine diets. *Journal of Animal Science*, *87*(4), 1292-1303. https://doi.org/10.2527/jas.2008-1290

Stewart, C. L., O'Connell, N. E., & Boyle, L. (2008). Influence of access to straw provided in racks on the welfare of sows in large dynamic groups. *Applied Animal Behaviour Science*, *112*(3), 235-247. https://doi.org/10.1016/j.applanim.2007.09.006

Studnitz, M., Jensen, M. B., & Pedersen, L. J. (2007). Why do pigs root and in what will they root?: A review on the exploratory behaviour of pigs in relation to environmental enrichment. *Applied Animal Behaviour Science*, *107*(3), 183-197. https://doi.org/10.1016/j.applanim.2006.11.013

Sung, J. Y., Wiltafsky-Martin, M. K., Caroline González-Vega, J., & Adeola, O. (2022). Autoclaving time-related reduction in metabolizable energy of poultry meal is greater in growing pigs compared with broiler chickens. *Journal of Animal Science*, *100*(5). https://doi.org/10101093/jas/skac117

Szumacher-Strabel, M., Stochmal, A., Cieslak, A., Kozłowska, M., Kuznicki, D., Kowalczyk, M., & Oleszek, W. (2019). Structural and quantitative changes of saponins in fresh alfalfa compared to alfalfa silage. *Journal of the Science of Food and Agriculture*, *99*(5), 2243-2250. https://doi.org/10.1002/jsfa.9419

Taheripour, F., Hertel, T. W., Tyner, W. E., Beckman, J. F., & Birur, D. K. (2010). Biofuels and their by-products: Global economic and environmental implications. *Biomass and Bioenergy*, *34*(3), 278-289. https://doi.org/10.1016/j.biombioe.2009.10.017

Tan, K. T., Lee, K. T., Mohamed, A. R., & Bhatia, S. (2009). Palm oil: Addressing issues and towards sustainable development. *Renewable and Sustainable Energy Reviews*, *13*(2), 420-427. https://doi.org/10.1016/j.rser.2007.10.001

Terlouw, C., Berne, A., & Astruc, T. (2009). Effect of rearing and slaughter conditions on behaviour, physiology and meat quality of Large White and Duroc-sired pigs. *Livestock science*, *122*(2), 199-213. https://doi.org/10.1016/j.livsci.2008.08.016

Thacker, P. (2006). Nutrient digestibility, performance and carcass traits of growing-finishing pigs fed diets containing dried wheat distiller's grains with solubles. *Canadian Journal of Animal Science*, *86*(4), 527-529. https://doi.org/10.4141/A06-025

Thacker, P. A. (2001). Effect of enzyme supplementation on the performance of growing-ginishing pigs fed barley-based diets supplemented with soybean meal or canola meal. *Asian-Australasian Journal of Animal Sciences*, *14*(7), 1008-1013. https://doi.org/10.5713/ajas.2001.1008

Thacker, P. A., & Haq, I. (2008). Nutrient digestibility, performance and carcass traits of growing-finishing pigs fed diets containing graded levels of dehydrated lucerne meal [Article]. *Journal of the Science of Food and Agriculture*, *88*(11), 2019-2025. https://doi.org/10.1002/jsfa.3314

Tibbetts, G. W., Seerley, R. W., & McCampbell, H. C. (1987). Poultry offal ensiled with Lactobacillus Acidophilus for growing and finishing swine diets. *Journal of Animal Science*, *64*(1), 182-190. https://doi.org/10102527/jas1987.641182x

Tozawa, A., Tanaka, S., & Sato, S. (2016). The effects of components of grazings system on welfare of fattening pigs. *Asian-Australasian Journal of Animal Sciences*, *29*(3), 428-435. https://doi.org/10.5713/ajas.15.0190

Tripathi, M. K., & Mishra, A. S. (2007). Glucosinolates in animal nutrition: A review. *Animal Feed Science and Technology*, *132*(1), 1-27. https://doi.org/10.1016/j.anifeedsci.2006.03.003

Tsai, T., Dove, C. R., Cline, P. M., Owusu-Asiedu, A., Walsh, M. C., & Azain, M. (2017). The effect of adding xylanase or β-glucanase to diets with corn distillers dried grains with solubles (CDDGS) on growth performance and nutrient digestibility in nursery pigs. *Livestock science*, *197*, 46-52. https://doi.org/10.1016/j.livsci.2017.01.008
Tsikira, S., Wester, T., Jenkinson, C., Nguyen, T., & Morel, P. (2021). 43. Effect of dietary inclusion of forage crops on ileal amino acid and apparent energy digestibilities in pigs. *Animal-science proceedings*, *12*(2), 205.
UN. (2019). *World population prospects 2019: Highlights*.
Council Regulation (EC) No 834/2007 of 28 June 2007 on organic production and labelling of organic products and repealing Regulation (EEC) No 2092/91, 189 (2007). https://eur-lex.europa.eu/eli/reg/2007/834/oj

Urriola, P. E., Hoehler, D., Pedersen, C., Stein, H. H., & Shurson, G. C. (2009). Amino acid digestibility of distillers dried grains with solubles, produced from sorghum, a sorghum-corn blend, and corn fed to growing pigs. *Journal of Animal Science*, *87*(8), 2574-2580. https://doi.org/10.2527/jas.2008-1436
van de Weerd, H. A., & Day, J. E. L. (2009). A review of environmental enrichment for pigs housed in intensive housing systems. *Applied Animal Behaviour Science*, *116*(1), 1-20. https://doi.org/10.1016/j.applanim.2008.08.001
Van der Werf, H. M. G., Petit, J., & Sanders, J. (2005). The environmental impacts of the production of concentrated feed: the case of pig feed in Bretagne. *Agricultural Systems*, *83*(2), 153-177. https://doi.org/10101016/j.agsy.2004.03.005
van Kempen, T. A. T. G., van Heugten, E., Moeser, A. J., Muley, N. S., & Sewalt, V. J. H. (2006). Selecting soybean meal characteristics preferred for swine nutrition. *Journal of Animal Science*, *84*(6), 1387-1395. https://doi.org/10.2527/2006.8461387x
Van Kernebeek, H. R., Oosting, S. J., Van Ittersum, M. K., Bikker, P., & De Boer, I. J. (2016). Saving land to feed a growing population: consequences for consumption of crop and livestock products. *The International Journal of Life Cycle Assessment*, *21*(5), 677-687. https://doi.org/10.1007/s11367-015-0923-6
Van Zanten, H. H. E., Herrero, M., Van Hal, O., Röös, E., Muller, A., Garnett, T., Gerber, P. J., Schader, C., & De Boer, I. J. M. (2018). Defining a land boundary for sustainable livestock consumption. *Global Change Biology*, *24*(9), 4185-4194. https://doi.org/10.1111/gcb.14321

Vanrolleghem, W., Tanghe, S., Verstringe, S., Bruggeman, G., Papadopoulos, D., Trevisi, P., Zentek, J., Sarrazin, S., & Dewulf, J. (2019). Potential dietary feed additives with antibacterial effects and their impact on performance of weaned piglets: A meta-analysis. *The Veterinary Journal*, *249*, 24-32. https://doi.org/10.1016/j.tvjl.2019.04.017
Vetter, J. (2000). Plant cyanogenic glycosides. *Toxicon*, *38*(1), 11-36. https://doi.org/10.1016/S0041-0101(99)00128-2
Volpato, J. A., Ribeiro, L. B., Torezan, G. B., da Silva, I. C., Martins, I. d. O., Genova, J. L., de Oliveira, N. T. E., Carvalho, S. T., Carvalho, P. L. d. O., & Vasconcellos, R. S. (2022). Characterization of the variations in the industrial processing and nutritional variables of poultry by-product meal. *Poultry Science*, *101*(7), 101926. https://doi.org/10.1016/j.psj.2022.101926
Vos, R., & Bellù, L. G. (2019). Global trends and challenges to food and agriculture into the 21st century. *Sustainable Food and Agriculture*, 11-30. https://doi.org/10.1016/b978-0-12-812134-4.00002-9
Wahlstrom, R. C., German, C. S., & Libal, G. W. (1970). Corn distillers dried grains with solubles in growing-finishing swine rations. *Journal of Animal Science*, *30*(4), 532-535. https://doi.org/10.2527/jas1970.304532x

Wang, D. F., Zhou, L. L., Zhou, H. L., Hu, H. C., & Hou, G. Y. (2020). Chemical composition and protective effect of guava (Psidium guajava L.) leaf extract on piglet intestines. *Journal of the Science of Food and Agriculture*. https://doi.org/10.1002/jsfa.10904

Weiss, E., Aumiller, T., Spindler, H. K., Rosenfelder, P., Eklund, M., Witzig, M., Jørgensen, H., Bach Knudsen, K. E., & Mosenthin, R. (2016). Wheat and barley differently affect porcine intestinal microbiota. *Journal of the Science of Food and Agriculture*, *96*(6), 2230-2239. https://doi.org/10.1002/jsfa.7340

Wenk, C. (2001). The role of dietary fibre in the digestive physiology of the pig. *Animal Feed Science and Technology*, *90*(1), 21-33. https://doi.org/10.1016/S0377-8401(01)00194-8

White, H. M., Richert, B. T., Radcliffe, J. S., Schinckel, A. P., Burgess, J. R., Koser, S. L., Donkin, S. S., & Latour, M. A. (2009). Feeding conjugated linoleic acid partially recovers carcass quality in pigs fed dried corn distillers grains with solubles. *Journal of Animal Science*, *87*(1), 157-166. https://doi.org/10.2527/jas.2007-0734

Whitney, M. H., Shurson, G. C., Johnston, L. J., Wulf, D. M., & Shanks, B. C. (2006). Growth performance and carcass characteristics of grower-finisher pigs fed high-quality corn distillers dried grain with solubles originating from a modern Midwestern ethanol plant. *Journal of Animal Science*, *84*(12), 3356-3363. https://doi.org/10.2527/jas.2006-099

Widmer, M. R., McGinnis, L. M., Wulf, D. M., & Stein, H. H. (2008). Effects of feeding distillers dried grains with solubles, high-protein distillers dried grains, and corn germ to growing-finishing pigs on pig performance, carcass quality, and the palatability of pork. *Journal of Animal Science*, *86*(8), 1819-1831. https://doi.org/10.2527/jas.2007-0594

Widyaratne, G., & Zijlstra, R. (2007). Nutritional value of wheat and corn distiller's dried grain with solubles: Digestibility and digestible contents of energy, amino acids and phosphorus, nutrient excretion and growth performance of grower-finisher pigs. *Canadian Journal of Animal Science*, *87*(1), 103-114. https://doi.org/10.4141/A05-070

Willett, W. C. (2012). Dietary fats and coronary heart disease. *Journal of Internal Medicine*, *272*(1), 13-24. https://doi.org/10.1111/j.1365-2796.2012.02553.x

Wiseman, J., Cole, D. J. A., & Lewis, D. (1982). Energy values in pig nutrition:3. The digestible and metabolizable energy content of barley, wheat, maize, oats and rye. *The Journal of Agricultural Science*, *98*(1), 89-97. https://doi.org/10.1017/S0021859600041149

Wiseman, M., McBride, B., Li, J., Wey, D., Zhu, J., & de Lange, C. F. M. (2017). Effects of steeped or fermented distillers dried grains with solubles on growth performance in weanling pigs. *Journal of Animal Science*, *95*(8), 3563-3578. https://doi.org/10.2527/jas.2017.1478

Wiseman, T. G., Mahan, D. C., Peters, J. C., Fastinger, N. D., Ching, S., & Kim, Y. Y. (2007). Tissue weights and body composition of two genetic lines of barrows and gilts from twenty to one hundred twenty-five kilograms of body weight. *Journal of Animal Science*, *85*(7), 1825-1835. https://doi.org/10.2527/jas.2006-407

Wood, J. D., Richardson, R. I., Nute, G. R., Fisher, A. V., Campo, M. M., Kasapidou, E., Sheard, P. R., & Enser, M. (2004). Effects of fatty acids on meat quality: a review. *Meat science*, *66*(1), 21-32. https://doi.org/10101016/S0309-1740(03)00022-6

Woyengo, T. A., Beltranena, E., & Zijlstra, R. T. (2014). Controlling feed cost by including alternative ingredients into pig diets: A review. *Journal of Animal Science*, *92*(4), 1293-1305. https://doi.org/10102527/jas.2013-7169

Xu, G., Baidoo, S. K., Johnston, L. J., Bibus, D., Cannon, J. E., & Shurson, G. C. (2010a). The effects of feeding diets containing corn distillers dried grains with solubles, and withdrawal period of distillers dried grains with solubles, on growth performance and pork quality in grower-finisher pigs. *Journal of Animal Science*, *88*(4), 1388-1397. https://doi.org/10.2527/jas.2008-1403

Xu, G., Baidoo, S. K., Johnston, L. J., Bibus, D., Cannon, J. E., & Shurson, G. C. (2010b). Effects of feeding diets containing increasing content of corn distillers dried grains with solubles to grower-finisher pigs on growth performance, carcass composition, and pork fat quality. *Journal of Animal Science*, *88*(4), 1398-1410. https://doi.org/10.2527/jas.2008-1404

Yoon, S. Y., Yang, Y. X., Shinde, P. L., Choi, J. Y., Kim, J. S., Kim, Y. W., Yun, K., Jo, J. K., Lee, J. H., Ohh, S. J., Kwon, I. K., & Chae, B. J. (2010). Effects of mannanase and distillers dried grain with solubles on growth performance, nutrient digestibility, and carcass characteristics of grower-finisher pigs. *Journal of Animal Science*, *88*(1), 181-191. https://doi.org/https://doi.org/10.2527/jas.2008-1741

Young, V. R., & Pellett, P. L. (1994). Plant proteins in relation to human protein and amino acid nutrition. *The American Journal of Clinical Nutrition*, *59*(5), 1203S-1212S. https://doi.org/10.1093/ajcn/59.5.1203S

Zachariasova, M., Dzuman, Z., Veprikova, Z., Hajkova, K., Jiru, M., Vaclavikova, M., Zachariasova, A., Pospichalova, M., Florian, M., & Hajslova, J. (2014). Occurrence of multiple mycotoxins in European feedingstuffs, assessment of dietary intake by farm animals. *Animal Feed Science and Technology*, *193*, 124-140. https://doi.org/10.1016/j.anifeedsci.2014.02.007

Zhao, J., Bai, Y., Zhang, G., Liu, L., & Lai, C. (2020). Relationship between dietary fiber fermentation and volatile fatty acids' concentration in growing pigs. *Animals*, *10*(2), 263. https://www.mdpi.com/2076-2615/10/2/263

Zier, C. E., Jones, R. D., & Azain, M. J. (2004). Use of pet food-grade poultry by-product meal as an alternate protein source in weanling pig diets. *Journal of Animal Science*, *82*(10), 3049-3057. https://doi.org/10102527/2004.82103049x

Zijlstra, R. T., & Beltranena, E. (2013). Alternative feedstuffs in swine diet. In L. Chiba (Ed.), *Sustainable swine nutrition* (pp. 229-253). Wiley-Blackwell. https://doi.org/10.1002/9781118491454

Zijlstra, R. T., & Beltranena, E. (2019). Co-products in swine nutrition and feed formulation. In M. W. A. V. a. L. B. Wouter H. Hendriks (Ed.), *Poultry and pig nutrition challenges of the 21st century* (pp. 245-262). Wageningen Academic. https://doi.org/10.3920/978-90-8686-884-1

Zmudzińska, A., Bigorowski, B., Banaszak, M., Roślewska, A., Adamski, M., & Hejdysz, M. (2020). The effect of diet based on legume seeds and rapeseed meal on pig performance and meat quality. *Animals*, *10*(6), 1084. https://doi.org/10103390/ani10061084

Zwicker, B., Weber, R., Wechsler, B., & Gygax, L. (2015). Degree of synchrony based on individual observations underlines the importance of concurrent access to enrichment materials in finishing pigs. *Applied Animal Behaviour Science*, *172*, 26-32. https://doi.org/10.1016/j.applanim.2015.08.037

APPENDICES

Supplementary Table 1. Studies included in the meta-analysis

Author	Oilseed Type[1]	Replacement level (%)	Growth stage	Initial weight (kg)	Finish weight (kg)	Breed
Baidoo et al. (1987)	CM	25	Grower	20.2	61.3	Lacombe × (Landrace x Yorkshire)
		100				
		25				
		50				
		75				
		100				
		25	Finisher	61.9	92.4	
		50				
		75				
		100				
Bell and Keith (1987)	CM	50	Grower	23.1	57.2	Lacombe x (Yorkshire x Landrace)
		50				
		100				
		100				
		50	Finisher	57.2	100.2	
		50				
		100				
		100				
Castell and Cliplef (1993)	CM	100	Grower	25	62	Landrace x Yorkshire
		100	Finisher	62	96.6	
Corino et al. (1991)	RPSM	50	Grower	22.7	NP	Not report
		75				
		50	Finisher	NP	NP	
		75				
Cortamira et al. (2000)	SFM	100	Grower	29.4	NP	Yorkshire ×Duroc
		100	Grower			
		100	Grower	30.3	NP	
		100	Grower			
Fang et al. (2007)	RPSM	26	Grower	22.7	69.6	(Large Yorkshire x Landrace) x Duroc
		42				

Hilbrands et al. (2021)*	CLM	5	Grower-finisher	35.2	126.4	Duroc x (Yorkshire x Landrace)
		10				
		15				
Kaczmarek et al. (2019)	RPSM	65	Grower	43	74.70	(Large White × Landrace) × (Hampshire × Pietrain)
		100	Finisher	74.70	102.7	
Kargopoulos et al. (2018)	RPSM	2	Grower	21.3	51	Large White × Landrace
		26				
		79	Finisher	51	86.6	
		100				
Li et al. (2017)	RPSM	10	Grower	35.9	62	Duroc × (Landrace × Yorkshire)
		20	Grower			
Lina et al. (2016)	CM	20	Grower	29.9	60.33	Not report
		35				
		30	Finisher	60.37	90.37	
		83				
Little et al. (2015)	CM	33	Grower	27.4	57.1	G-Performer x Fertilis 25
		66				
		100				
		33	Finisher	57.1	114.2	
		67				
		100				
Qin et al. (2015)*	CSM	100	Finisher	88.8	112.3	Duroc × (Landrace × Yorkshire)
Roth-Maier et al. (2004)	CM	34	Grower	32.7	59.9	Landrace x Pietrain
		67				
		100				
		34	Finisher	59.9	117.8	
		67				
		100				
Shelton et al. (2001)	CM	100	Grower	30	NP	Yorkshire x (Yorkshire × Landrace)
	SFM	100				
	CM	100	Finisher	NP	114	
	SFM	100				
Shi et al. (2016)	RPSM	48	Grower	40.8	NP	NP
		48	Finisher	NP	NP	

Siljander-Rasi et al. (1996)	RPSM	33	Grower	25.3	51.2	Landrace x Yorkshire
		66				
		100				
		33	Finisher	51.2	100.2	
		66				
		100				
Śmiecińska et al. (2021)	RPSM	50	Grower	26	67	Hybrid DanBred
	RPSM	100	Finisher	67	104	
Smit et al. (2014)	CM	75	Grower	29.9	70	PIC380×Large White/Landrace
		90				
		100				
		100				
		100	Finisher	70	117	
		100				
		100				
		100				
Smit et al. (2018)	CM	100	Grower	33	65.9	PIC380× Large White/Landrace
		100	Finisher	65.9	109.1	
Sobotka and Fiedorowicz-Szatkowska (2021)	RPSM	50	Grower	26.29	66.11	Landrace x Yorkshire
		100	Finisher	66.11	105.11	
Szabo et al. (2001)	SFM	72	Grower	30	60	Landrace
		72	Finisher	60	105	
Thacker (2001)	CM	100	Grower	26.2	50.3	Canabred x Camborough
		100	Finisher	50.3	77.9	
Thacker and Bowland (1980)	CM	100	Grower	24	53	Lacombe x Yorkshire
		100	Finisher	53	92	
Torres-Pitarch et al. (2014)	RPSM	38	Grower	42.4	70	Pietrain × (Landrace × Large White)
		72	Finisher	70	116.3	
Velayudhan et al. (2017)	CM	33	Grower	20	44.00	(Yorkshire × Landrace) × Duroc
		66				
		100				
Xie et al. (2012)	RPSM	51	Finisher	62.7	86.6	Duroc×(Landrace×Yorkshire)

Yun et al. (2017)	CM	18	Finisher	50.71	NP	(Yorkshire × Landrace) × Duroc

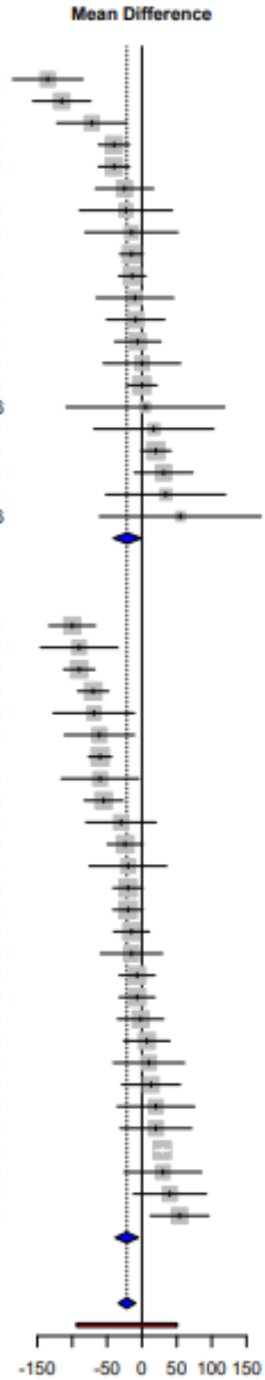
** Only used data to analyse carcass yield and meat quality*

[1] CLM: Camelina meal; CM: Canola meal; CSM: cotton seed meal; SFM: Sunflower meal; RPSM: Rapeseed meal

NP: not reported

Author	Experimental ADG (g/day)	SD	Control ADG (g/day)	SD	MD	95%-CI	Weight
level_replace = low							
Corino C. et al, 1991a	635	51.2	770	36.2	-135.00	[-185.17; -84.83]	1.8%
Shi et al, 2016	838	36.7	953	36.7	-115.00	[-156.53; -73.47]	2.1%
Torres-Pitarch A. et al, 2014	818	62.4	890	62.4	-72.00	[-121.93; -22.07]	1.8%
Baidoo S.K. et al, 1987c	740	27.7	780	13.9	-40.00	[-62.20; -17.80]	2.5%
Baidoo S.K. et al, 1987d	740	27.7	780	13.9	-40.00	[-62.20; -17.80]	2.5%
Fang, Z.F. et al, 2007b	828	60.0	853	42.4	-25.00	[-66.56; 16.56]	2.1%
Zhongchao Li et al, 2017b	906	63.5	929	48.0	-23.00	[-89.52; 43.52]	1.5%
Zhongchao Li et al, 2017a	914	63.5	929	41.6	-15.00	[-81.55; 51.55]	1.5%
Baidoo S.K. et al, 1987a	765	12.0	780	8.5	-15.00	[-31.65; 1.65]	2.7%
Wiesław S. and Elwira F., 2021	915	18.5	929	18.5	-14.00	[-33.38; 5.38]	2.6%
Velayudhan, D.E. et al, 2017a	860	49.0	870	28.3	-10.00	[-65.46; 45.46]	1.7%
Fang, Z.F. et al, 2007a	844	60.0	853	42.4	-9.00	[-50.56; 32.56]	2.1%
Siljander-Rasi, H.et al, 1996a	780	37.6	786	20.6	-6.00	[-38.96; 26.96]	2.3%
Little K. L. et al, 2015a	840	63.2	840	34.6	0.00	[-55.38; 55.38]	1.7%
Bell J. M. , Keith M. O. ,1987b	740	31.0	740	15.5	0.00	[-21.48; 21.48]	2.6%
Lina M.P. S. et al, 2016a	895	106.2	890	105.6	5.00	[-108.58; 118.58]	0.8%
Kargopoulos A. et al, 2018a	866	62.0	849	43.8	17.00	[-68.89; 102.89]	1.1%
Bell J. M. , Keith M. O. ,1987a	760	31.0	740	15.5	20.00	[-1.48; 41.48]	2.6%
Dora A. R. et al, 2004a	806	37.0	775	37.0	31.00	[-10.87; 72.87]	2.1%
Kargopoulos A. et al, 2018b	883	62.0	849	43.8	34.00	[-51.89; 119.89]	1.1%
Lina M.P. S. et al, 2016b	945	112.2	890	105.6	55.00	[-60.77; 170.77]	0.7%
Random effects model					-21.16	[-40.92; -1.39]	39.8%
Heterogeneity: $I^2 = 75\%$, $\tau^2 = 1193.7862$, $p < 0.01$							
level_replace = high							
Thacker P.A., 2001	600	37.9	700	37.9	-100.00	[-133.22; -66.78]	2.3%
Thacker P.A., Bowland P., 1980	620	80.0	710	80.0	-90.00	[-145.44; -34.56]	1.7%
Baidoo S.K. et al, 1987f	690	27.7	780	13.9	-90.00	[-112.20; -67.80]	2.5%
Baidoo S.K. et al, 1987e	710	27.7	780	13.9	-70.00	[-92.20; -47.80]	2.5%
Castell A. G., Cliplef R. L., 1993	743	42.0	812	42.0	-69.00	[-127.21; -10.79]	1.6%
Corino C. et al, 1991b	709	51.2	770	36.2	-61.00	[-111.17; -10.83]	1.8%
Baidoo S.K. et al, 1987b	720	12.0	780	8.5	-60.00	[-76.65; -43.35]	2.7%
Velayudhan, D.E. et al, 2017c	810	49.0	870	28.3	-60.00	[-115.46; -4.54]	1.7%
Smit M.N. et al, 2018	928	49.0	983	49.0	-55.00	[-82.72; -27.28]	2.4%
Cortamira C. et al, 2000b	540	45.1	570	47.6	-30.00	[-80.22; 20.22]	1.8%
Smit M.N. et al, 2014b	918	29.1	942	15.9	-24.00	[-49.48; 1.48]	2.5%
Velayudhan, D.E. et al, 2017b	850	49.0	870	28.3	-20.00	[-75.46; 35.46]	1.7%
Bell J. M. , Keith M. O. ,1987c	720	31.0	740	15.5	-20.00	[-41.48; 1.48]	2.6%
Bell J. M. , Keith M. O. ,1987d	720	31.0	740	15.5	-20.00	[-41.48; 1.48]	2.6%
Smit M.N. et al, 2014c	927	29.1	942	13.0	-15.00	[-40.49; 10.49]	2.5%
Kaczmarek P. et al, 2019	914	62.0	929	62.0	-15.00	[-59.37; 29.37]	2.0%
Smit M.N. et al, 2014a	935	29.1	942	13.0	-7.00	[-32.49; 18.49]	2.5%
Smit M.N. et al, 2014d	935	29.1	942	15.9	-7.00	[-32.48; 18.48]	2.5%
Siljander-Rasi, H.et al, 1996c	784	37.6	786	23.8	-2.00	[-34.97; 30.97]	2.3%
Siljander-Rasi, H.et al, 1996b	793	37.6	786	20.6	7.00	[-25.96; 39.96]	2.3%
Cortamira C. et al, 2000c	790	50.8	780	50.2	10.00	[-41.04; 61.04]	1.8%
Dora A. R. et al, 2004c	788	37.0	775	37.0	13.00	[-28.87; 54.87]	2.1%
Little K. L. et al, 2015c	860	63.2	840	40.0	20.00	[-35.42; 75.42]	1.7%
Cortamira C. et al, 2000d	800	51.4	780	50.2	20.00	[-31.27; 71.27]	1.8%
Szabo´C. et al, 2001	596	19.3	567	19.3	29.00	[17.85; 40.15]	2.7%
Little, K. L.et al, 2015b	870	63.2	840	34.6	30.00	[-25.38; 85.38]	1.7%
Cortamira C. et al, 2000a	610	50.9	570	47.6	40.00	[-12.31; 92.31]	1.8%
Dora A. R. et al, 2004b	829	37.0	775	37.0	54.00	[12.13; 95.87]	2.1%
Random effects model					-21.93	[-38.06; -5.81]	60.2%
Heterogeneity: $I^2 = 88\%$, $\tau^2 = 1344.4174$, $p < 0.01$							
Random effects model					**-21.64**	**[-33.68; -9.61]**	**100.0%**
Prediction interval						**[-93.57; 50.29]**	

Heterogeneity: $I^2 = 84\%$, $\tau^2 = 1243.5297$, $p < 0.01$
Test for subgroup differences: $\chi^2_1 = 0.00$, df = 1 ($p = 0.95$)

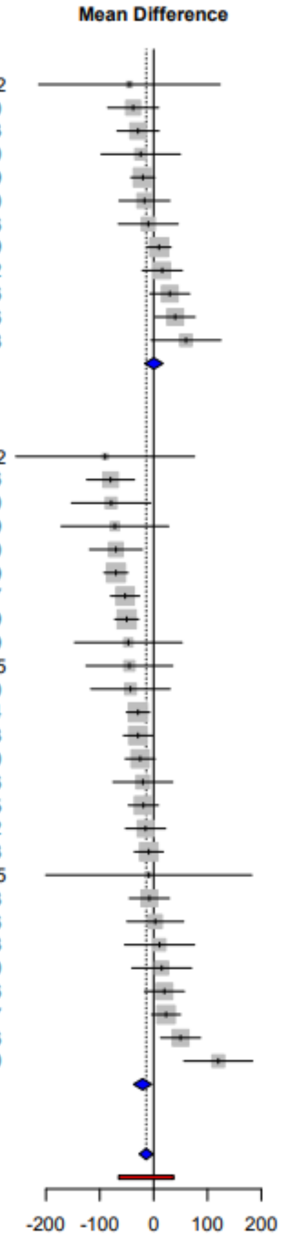


Supplementary Figure 1. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on pig daily weight gain at low- and high-level during grower stage

Author	Experimental ADG (g/day)	SD	Control ADG (g/day)	SD	MD	95%-CI	Weight
level_replace = low							
Lina M.P. S. et al, 2016a	945	152.0	990	159.2	-45.00	[-213.37; 123.37]	0.4%
Hyeok M. Y. et al, 2017b	751	53.8	789	38.0	-38.00	[-85.13; 9.13]	2.5%
Shi et al, 2016	758	34.3	787	34.3	-29.00	[-67.81; 9.81]	3.0%
Dora A. R. et al, 2004a	913	65.0	937	65.0	-24.00	[-97.55; 49.55]	1.5%
Baidoo S.K. et al, 1987d	880	27.7	900	13.9	-20.00	[-42.20; 2.20]	4.1%
Hyeok M. Y. et al, 2017a	772	53.8	789	38.0	-17.00	[-64.13; 30.13]	2.5%
Little K. L. et al, 2015a	980	63.2	990	34.6	-10.00	[-65.38; 45.38]	2.1%
Baidoo S.K. et al, 1987c	910	27.7	900	13.9	10.00	[-12.20; 32.20]	4.1%
Siljander-Rasi, H.et al, 1996a	903	42.4	887	23.2	16.00	[-21.15; 53.15]	3.1%
Bell J. M. , Keith M. O. ,1987a	810	53.3	780	26.6	30.00	[-6.90; 66.90]	3.1%
Bell J. M. , Keith M. O. ,1987b	820	53.3	780	26.6	40.00	[3.10; 76.90]	3.1%
Corino C. et al, 1991a	837	66.2	777	46.8	60.00	[-4.87; 124.87]	1.7%
Random effects model					0.43	[-16.26; 17.12]	31.1%
Heterogeneity: $I^2 = 47\%$, $\tau^2 = 0$, $p = 0.03$							
level_replace = high							
Lina M.P. S. et al, 2016b	900	144.7	990	159.2	-90.00	[-255.88; 75.88]	0.4%
Thacker P.A., 2001	720	50.6	800	50.6	-80.00	[-124.35; -35.65]	2.7%
Dora A. R. et al, 2004c	858	65.0	937	65.0	-79.00	[-152.55; -5.45]	1.5%
Kargopoulos A. et al, 2018b	655	72.0	727	50.9	-72.00	[-171.77; 27.77]	0.9%
Thacker P.A., Bowland P., 1980	710	80.0	780	60.0	-70.00	[-119.00; -21.00]	2.4%
Baidoo S.K. et al, 1987f	830	27.7	900	13.9	-70.00	[-92.20; -47.80]	4.1%
Smit M.N. et al, 2014c	958	30.7	1011	13.7	-53.00	[-79.88; -26.12]	3.8%
Baidoo S.K. et al, 1987e	850	27.7	900	13.9	-50.00	[-72.20; -27.80]	4.1%
Kargopoulos A. et al, 2018a	680	72.0	727	50.9	-47.00	[-146.77; 52.77]	0.9%
Torres-Pitarch A. et al, 2014	995	100.5	1040	100.5	-45.00	[-125.42; 35.42]	1.3%
Dora A. R. et al, 2004b	894	65.0	937	65.0	-43.00	[-116.55; 30.55]	1.5%
Szabo´C. et al, 2001	708	37.4	737	37.4	-29.00	[-50.62; -7.38]	4.1%
Smit M.N. et al, 2014d	982	30.7	1011	16.8	-29.00	[-55.90; -2.10]	3.8%
Smit M.N. et al, 2018	1028	49.0	1053	49.0	-25.00	[-52.72; 2.72]	3.7%
Little, K. L.et al, 2015b	970	63.2	990	34.6	-20.00	[-75.38; 35.38]	2.1%
Wiesław S. and Elwira F., 2021	986	26.5	1005	26.5	-19.00	[-46.76; 8.76]	3.7%
Siljander-Rasi, H.et al, 1996b	872	42.4	887	23.2	-15.00	[-52.15; 22.15]	3.1%
Smit M.N. et al, 2014b	1002	30.7	1011	16.8	-9.00	[-35.90; 17.90]	3.8%
Peng Xie et al, 2012	788	119.5	797	119.5	-9.00	[-200.24; 182.24]	0.3%
Siljander-Rasi, H.et al, 1996c	879	42.4	887	26.8	-8.00	[-45.15; 29.15]	3.1%
Kaczmarek P. et al, 2019	1056	73.6	1053	73.6	3.00	[-49.67; 55.67]	2.2%
Corino C. et al, 1991b	788	66.2	777	46.8	11.00	[-53.87; 75.87]	1.7%
Little K. L. et al, 2015c	1005	63.2	990	40.0	15.00	[-40.42; 70.42]	2.1%
Bell J. M. , Keith M. O. ,1987d	800	53.3	780	26.6	20.00	[-16.90; 56.90]	3.1%
Smit M.N. et al, 2014a	1034	30.7	1011	13.7	23.00	[-3.88; 49.88]	3.8%
Bell J. M. , Keith M. O. ,1987c	830	53.3	780	26.6	50.00	[13.10; 86.90]	3.1%
Castell A. G., Cliplef R. L., 1993	902	46.0	782	46.0	120.00	[56.25; 183.75]	1.8%
Random effects model					-20.42	[-37.12; -3.72]	68.9%
Heterogeneity: $I^2 = 74\%$, $\tau^2 = 805.4313$, $p < 0.01$							
Random effects model					**-13.84**	**[-26.56; -1.11]**	**100.0%**
Prediction interval						**[-64.86; 37.19]**	

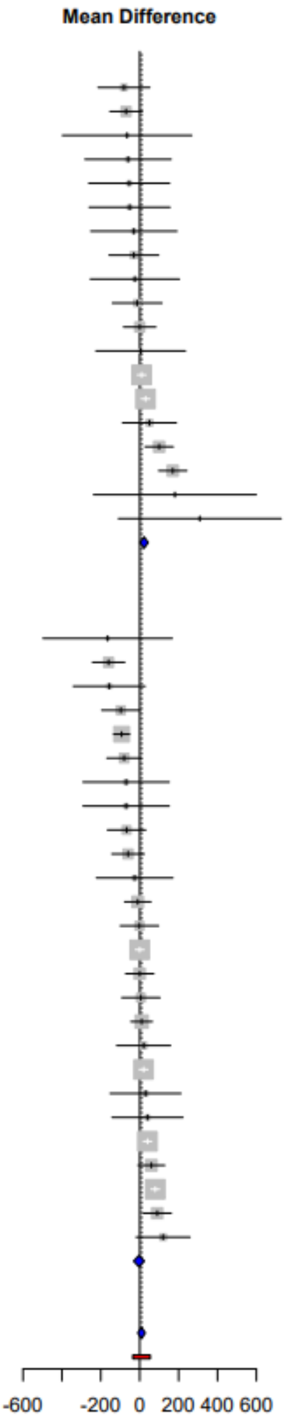
Heterogeneity: $I^2 = 72\%$, $\tau^2 = 604.4789$, $p < 0.01$

Test for subgroup differences: $\chi^2_1 = 3.52$, df = 1 ($p = 0.06$)

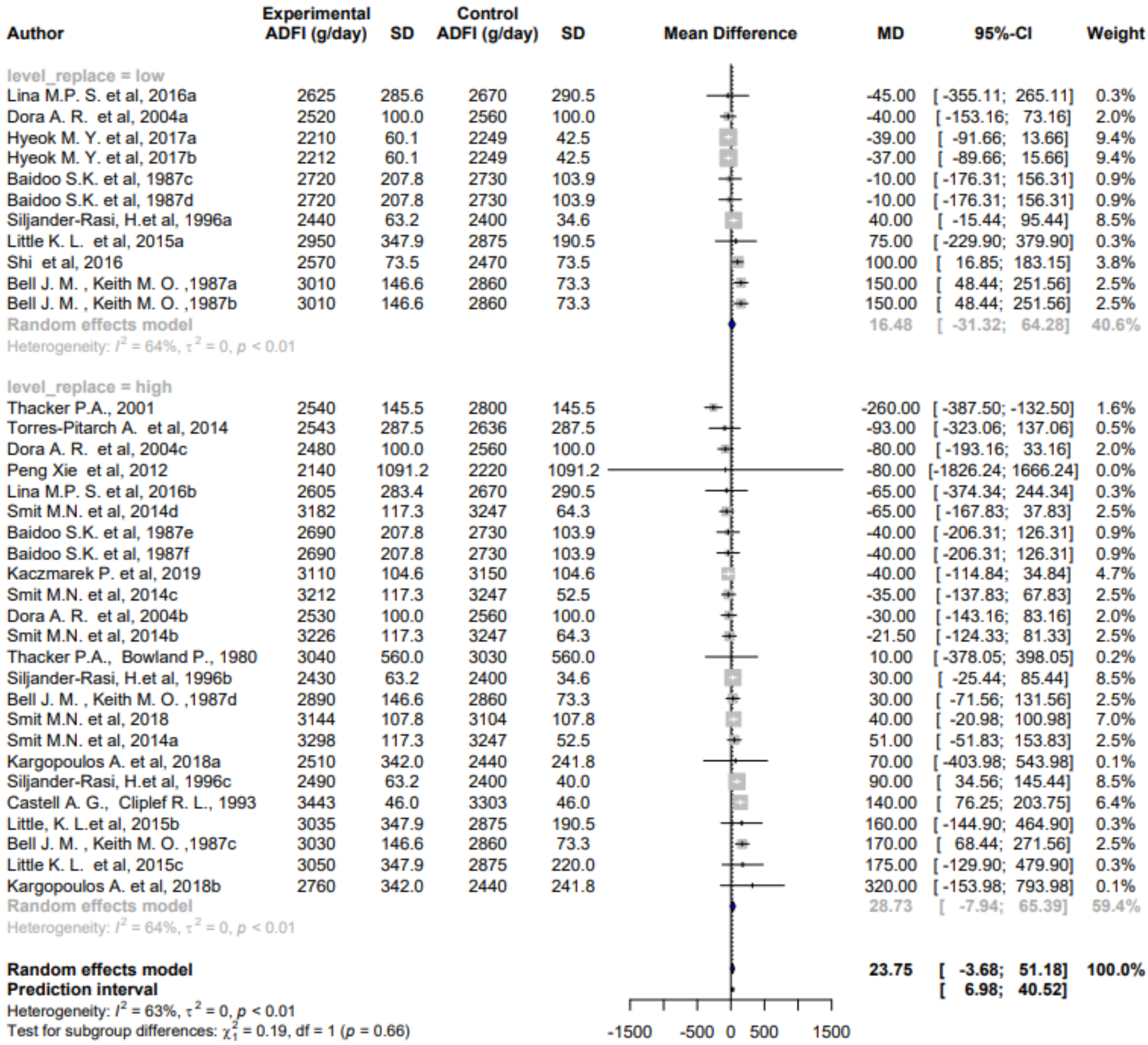


Supplementary Figure 2. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on pig daily weight gain at low- and high-level during finisher stage

Author	Experimental ADFI (g/day)	SD	Control ADFI (g/day)	SD	MD	95%-CI	Weight
level_replace = low							
Torres-Pitarch A. et al, 2014	1820	166.3	1901	166.3	-81.00	[-214.05; 52.05]	0.9%
Velayudhan, D.E. et al, 2017a	1630	73.5	1700	42.4	-70.00	[-153.15; 13.15]	2.1%
Baidoo S.K. et al, 1987a	2105	240.0	2170	169.7	-65.00	[-397.62; 267.62]	0.2%
Baidoo S.K. et al, 1987d	1800	277.1	1860	138.6	-60.00	[-281.74; 161.74]	0.4%
Zhongchao Li et al, 2017a	2039	198.4	2093	129.9	-54.00	[-261.89; 153.89]	0.4%
Zhongchao Li et al, 2017b	2041	198.4	2093	150.0	-52.00	[-259.89; 155.89]	0.4%
Baidoo S.K. et al, 1987c	1830	277.1	1860	138.6	-30.00	[-251.74; 191.74]	0.4%
Fang, Z.F. et al, 2007a	2058	184.0	2088	130.1	-30.00	[-157.50; 97.50]	1.0%
Lina M.P. S. et al, 2016a	1985	211.6	2010	214.3	-25.00	[-254.07; 204.07]	0.3%
Fang, Z.F. et al, 2007b	2075	184.0	2088	130.1	-13.00	[-140.50; 114.50]	1.0%
Shi et al, 2016	2380	73.5	2380	73.5	0.00	[-83.15; 83.15]	2.1%
Lina M.P. S. et al, 2016b	2015	214.8	2010	214.3	5.00	[-225.21; 235.21]	0.3%
Siljander-Rasi, H.et al, 1996a	1500	25.3	1490	13.9	10.00	[-12.17; 32.17]	8.1%
Dora A. R. et al, 2004a	1750	20.0	1720	20.0	30.00	[7.37; 52.63]	8.0%
Little K. L. et al, 2015a	2000	158.1	1950	86.6	50.00	[-88.59; 188.59]	0.9%
Bell J. M. , Keith M. O. ,1987b	2060	104.7	1960	52.3	100.00	[27.45; 172.55]	2.6%
Bell J. M. , Keith M. O. ,1987a	2130	104.7	1960	52.3	170.00	[97.45; 242.55]	2.6%
Kargopoulos A. et al, 2018a	1973	302.0	1792	213.5	181.00	[-237.54; 599.54]	0.1%
Kargopoulos A. et al, 2018b	2101	302.0	1792	213.5	309.00	[-109.54; 727.54]	0.1%
Random effects model					22.46	[1.41; 43.51]	31.6%
Heterogeneity: $I^2 = 48\%$, $\tau^2 = 0$, $p < 0.01$							
level_replace = high							
Baidoo S.K. et al, 1987b	2005	240.0	2170	169.7	-165.00	[-497.62; 167.62]	0.2%
Velayudhan, D.E. et al, 2017c	1540	73.5	1700	42.4	-160.00	[-243.15; -76.85]	2.1%
Thacker P.A., Bowland P., 1980	2117	266.7	2273	266.7	-156.67	[-341.45; 28.12]	0.5%
Smit M.N. et al, 2014c	2109	112.3	2206	50.2	-97.00	[-195.40; 1.40]	1.6%
Smit M.N. et al, 2018	2214	73.5	2306	73.5	-93.00	[-134.58; -51.42]	5.2%
Thacker P.A., 2001	1720	101.2	1800	101.2	-80.00	[-168.70; 8.70]	1.9%
Baidoo S.K. et al, 1987e	1790	277.1	1860	138.6	-70.00	[-291.74; 151.74]	0.4%
Baidoo S.K. et al, 1987f	1790	277.1	1860	138.6	-70.00	[-291.74; 151.74]	0.4%
Smit M.N. et al, 2014d	2138	112.3	2206	61.5	-67.50	[-165.90; 30.90]	1.6%
Velayudhan, D.E. et al, 2017b	1640	73.5	1700	42.4	-60.00	[-143.15; 23.15]	2.1%
Castell A. G., Cliplef R. L., 1993	2322	142.0	2348	142.0	-26.00	[-222.80; 170.80]	0.4%
Cortamira C. et al, 2000b	1770	63.0	1780	63.4	-10.00	[-77.90; 57.90]	2.8%
Smit M.N. et al, 2014b	2204	112.3	2206	61.5	-1.50	[-99.90; 96.90]	1.6%
Dora A. R. et al, 2004c	1720	20.0	1720	20.0	0.00	[-22.63; 22.63]	8.0%
Bell J. M. , Keith M. O. ,1987d	1960	104.7	1960	52.3	0.00	[-72.55; 72.55]	2.6%
Smit M.N. et al, 2014a	2212	112.3	2206	50.2	6.00	[-92.40; 104.40]	1.6%
Kaczmarek P. et al, 2019	2390	77.5	2380	77.5	10.00	[-45.44; 65.44]	3.7%
Little K. L. et al, 2015c	1970	158.1	1950	100.0	20.00	[-118.59; 158.59]	0.9%
Dora A. R. et al, 2004b	1740	20.0	1720	20.0	20.00	[-2.63; 42.63]	8.0%
Cortamira C. et al, 2000c	2160	181.4	2130	178.9	30.00	[-152.05; 212.05]	0.5%
Cortamira C. et al, 2000d	2170	182.3	2130	178.9	40.00	[-142.37; 222.37]	0.5%
Siljander-Rasi, H.et al, 1996b	1530	25.3	1490	13.9	40.00	[17.83; 62.17]	8.1%
Cortamira C. et al, 2000a	1840	65.5	1780	63.4	60.00	[-8.80; 128.80]	2.8%
Siljander-Rasi, H.et al, 1996c	1570	25.3	1490	16.0	80.00	[57.83; 102.17]	8.1%
Bell J. M. , Keith M. O. ,1987c	2050	104.7	1960	52.3	90.00	[17.45; 162.55]	2.6%
Little, K. L.et al, 2015b	2070	158.1	1950	86.6	120.00	[-18.59; 258.59]	0.9%
Random effects model					-3.68	[-31.02; 23.66]	68.4%
Heterogeneity: $I^2 = 78\%$, $\tau^2 = 1130.6817$, $p < 0.01$							
Random effects model					**9.37**	**[-10.02; 28.77]**	**100.0%**
Prediction interval						**[-35.49; 54.23]**	
Heterogeneity: $I^2 = 70\%$, $\tau^2 = 448.3141$, $p < 0.01$							
Test for subgroup differences: $\chi^2_1 = 2.47$, df = 1 ($p = 0.12$)							



Supplementary Figure 3. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on pig daily feed intake at low- and high-level during grower stage

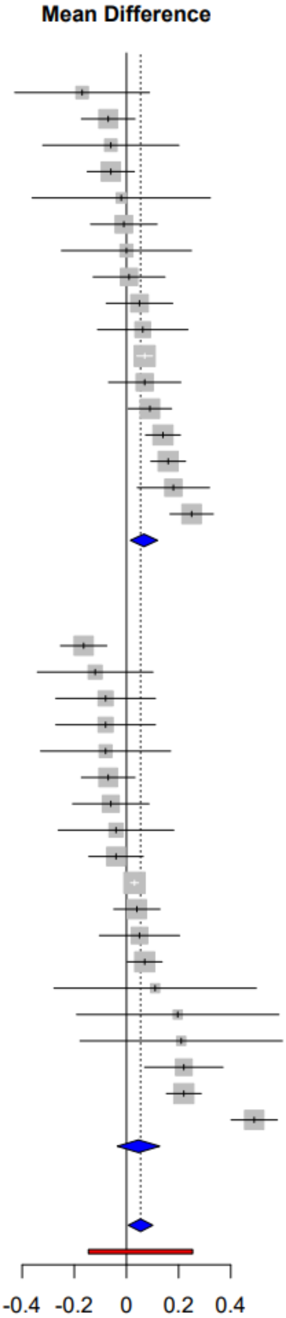


Supplementary Figure 4. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on pig daily feed intake at low- and high-level during finisher stage

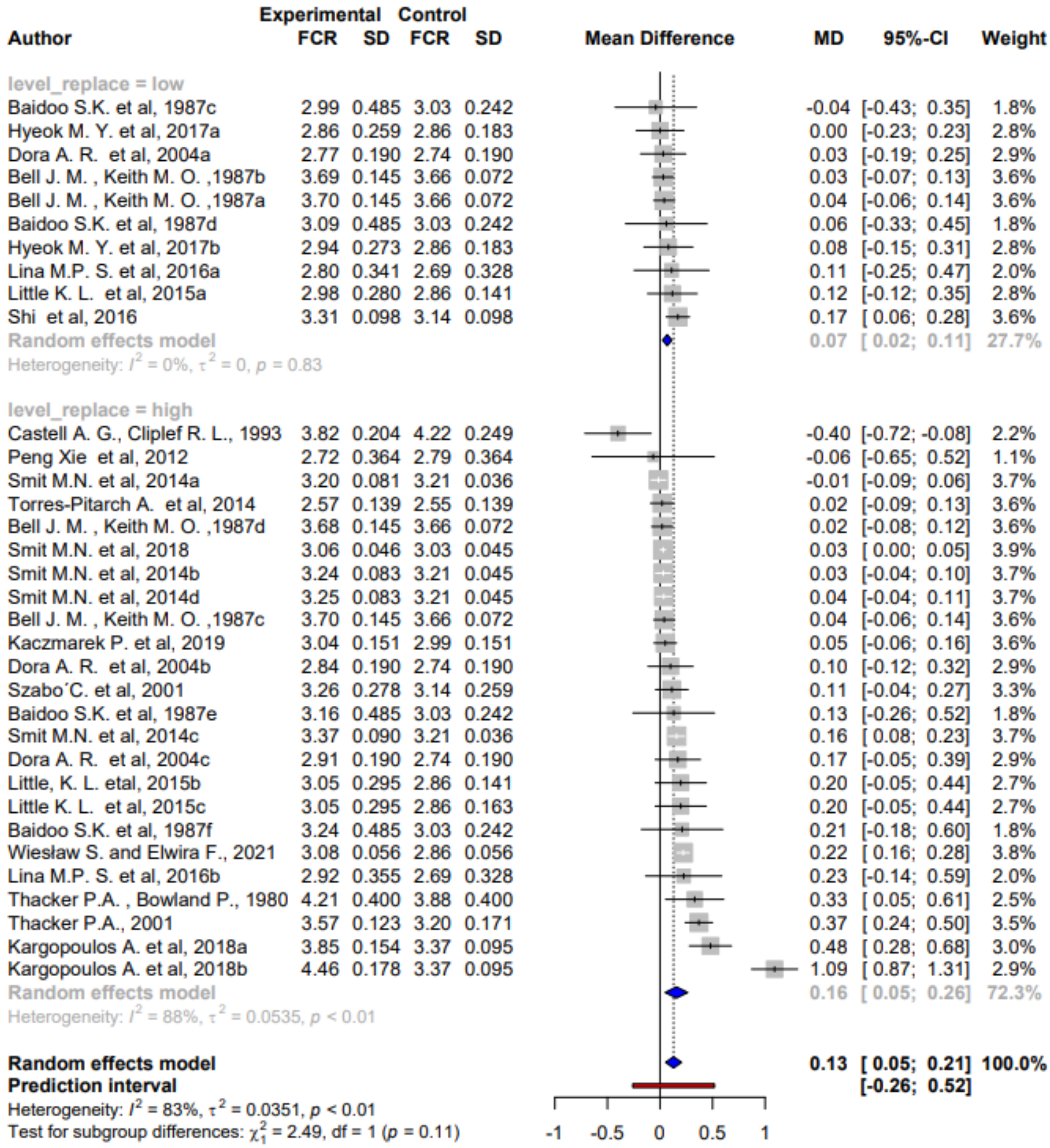
Author	Experimental FCR	Experimental SD	Control FCR	Control SD	MD	95%-CI	Weight
level_replace = low							
Lina M.P. S. et al, 2016a	2.08	0.188	2.25	0.204	-0.17	[-0.43; 0.09]	1.5%
Velayudhan, D.E. et al, 2017a	1.89	0.087	1.96	0.054	-0.07	[-0.17; 0.03]	3.4%
Lina M.P. S. et al, 2016b	2.19	0.198	2.25	0.204	-0.06	[-0.32; 0.20]	1.5%
Dora A. R. et al, 2004a	2.17	0.080	2.23	0.080	-0.06	[-0.15; 0.03]	3.6%
Zhongchao Li, et al, 2017a	2.22	0.315	2.24	0.221	-0.02	[-0.36; 0.32]	1.0%
Fang, Z.F. et al, 2007a	2.44	0.184	2.45	0.130	-0.01	[-0.14; 0.12]	3.0%
Baidoo S.K. et al, 1987a	2.78	0.220	2.78	0.127	0.00	[-0.25; 0.25]	1.6%
Zhongchao Li et al, 2017b	2.25	0.130	2.24	0.100	0.01	[-0.13; 0.15]	2.9%
Fang, Z.F. et al, 2007b	2.50	0.184	2.45	0.130	0.05	[-0.08; 0.18]	3.0%
Little K. L. et al, 2015a	2.53	0.203	2.47	0.106	0.06	[-0.11; 0.24]	2.4%
Wiesław S. and Elwira F., 2021	2.68	0.029	2.61	0.029	0.07	[0.04; 0.10]	4.3%
Baidoo S.K. et al, 1987d	2.47	0.173	2.40	0.087	0.07	[-0.07; 0.21]	2.9%
Torres-Pitarch A. et al, 2014	2.24	0.104	2.15	0.104	0.09	[0.01; 0.17]	3.7%
Bell J. M. , Keith M. O. ,1987b	2.80	0.096	2.66	0.048	0.14	[0.07; 0.21]	3.9%
Bell J. M. , Keith M. O. ,1987a	2.82	0.096	2.66	0.048	0.16	[0.09; 0.23]	3.9%
Baidoo S.K. et al, 1987c	2.58	0.173	2.40	0.087	0.18	[0.04; 0.32]	2.9%
Shi et al, 2016	2.71	0.073	2.46	0.073	0.25	[0.17; 0.33]	3.7%
Random effects model					0.07	[0.02; 0.12]	49.6%
Heterogeneity: $I^2 = 70\%$, $\tau^2 = 0.0038$, $p < 0.01$							
level_replace = high							
Szabo´C. et al, 2001	2.44	0.144	2.60	0.163	-0.16	[-0.25; -0.08]	3.6%
Dora A. R. et al, 2004b	2.11	0.277	2.23	0.160	-0.12	[-0.34; 0.10]	1.9%
Cortamira C. et al, 2000c	2.70	0.185	2.78	0.191	-0.08	[-0.27; 0.11]	2.2%
Cortamira C. et al, 2000d	2.70	0.185	2.78	0.191	-0.08	[-0.27; 0.11]	2.2%
Baidoo S.K. et al, 1987b	2.70	0.220	2.78	0.127	-0.08	[-0.33; 0.17]	1.6%
Velayudhan, D.E. et al, 2017c	1.89	0.087	1.96	0.054	-0.07	[-0.17; 0.03]	3.4%
Little K. L. et al, 2015c	2.27	0.163	2.33	0.109	-0.06	[-0.21; 0.09]	2.8%
Dora A. R. et al, 2004c	2.19	0.277	2.23	0.160	-0.04	[-0.26; 0.18]	1.9%
Velayudhan, D.E. et al, 2017b	1.92	0.090	1.96	0.054	-0.04	[-0.14; 0.06]	3.4%
Smit M.N. et al, 2018	2.38	0.028	2.35	0.027	0.03	[0.02; 0.05]	4.4%
Kaczmarek P. et al, 2019	2.60	0.124	2.56	0.124	0.04	[-0.05; 0.13]	3.6%
Little, K. L. etal, 2015b	2.38	0.179	2.33	0.094	0.05	[-0.10; 0.20]	2.7%
Bell J. M. , Keith M. O. ,1987d	2.73	0.096	2.66	0.048	0.07	[0.00; 0.14]	3.9%
Baidoo S.K. et al, 1987e	2.51	0.485	2.40	0.242	0.11	[-0.28; 0.50]	0.8%
Thacker P.A. , Bowland P., 1980	3.38	0.560	3.18	0.560	0.20	[-0.19; 0.58]	0.8%
Baidoo S.K. et al, 1987f	2.61	0.485	2.40	0.242	0.21	[-0.18; 0.60]	0.8%
Castell A. G., Cliplef R. L., 1993	3.11	0.116	2.89	0.100	0.22	[0.07; 0.37]	2.7%
Bell J. M. , Keith M. O. ,1987c	2.88	0.096	2.66	0.048	0.22	[0.15; 0.29]	3.9%
Thacker P.A., 2001	2.89	0.082	2.40	0.117	0.49	[0.40; 0.58]	3.6%
Random effects model					0.05	[-0.04; 0.13]	50.4%
Heterogeneity: $I^2 = 89\%$, $\tau^2 = 0.0151$, $p < 0.01$							
Random effects model					**0.05**	**[0.01; 0.10]**	**100.0%**
Prediction interval						**[-0.15; 0.25]**	

Heterogeneity: $I^2 = 85\%$, $\tau^2 = 0.0093$, $p < 0.01$

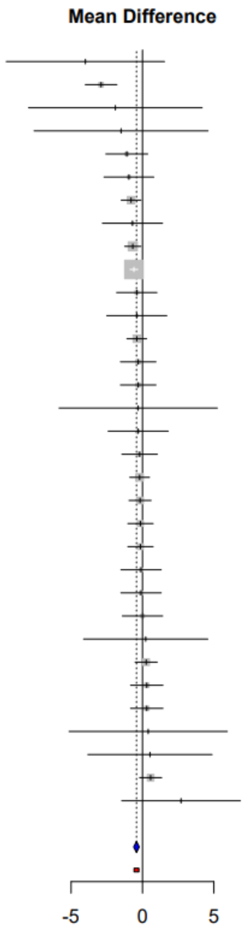
Test for subgroup differences: $\chi^2_1 = 0.21$, df = 1 ($p = 0.65$)



Supplementary Figure 5. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on FCR at low- and high-level during grower stage



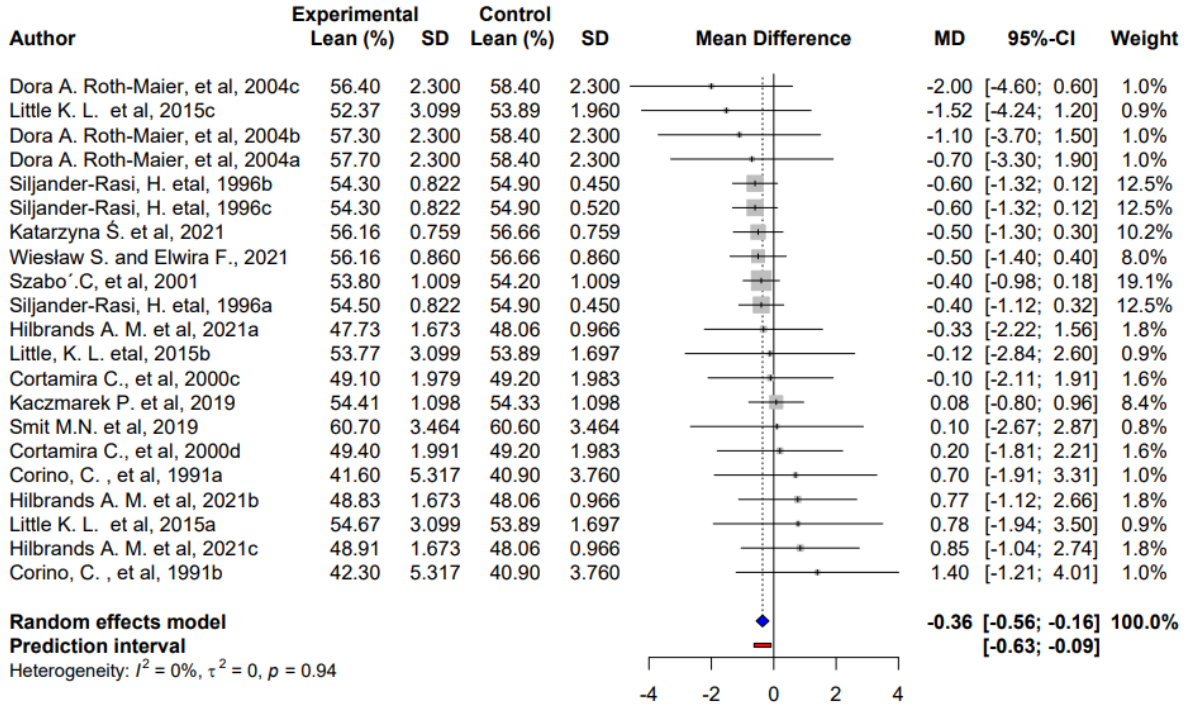
Supplementary Figure 6. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on FCR at low- and high-level during finisher stage



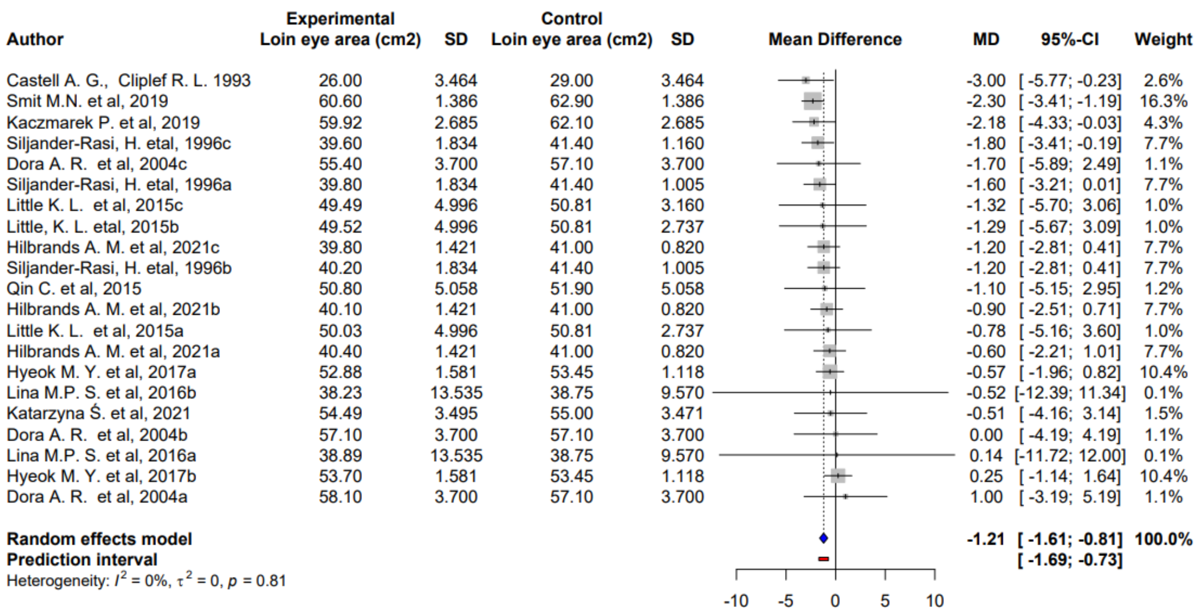
Author	Experimental Dessing (%)	SD	Control Dessing (%)	SD	MD	95%-CI	Weight
Brand T. S. et al , 1999c	73.40	7.211	77.40	4.472	-4.00	[-9.54; 1.54]	0.1%
Castell A. G., Cliplef R. L. 1993	72.00	1.386	74.90	1.386	-2.90	[-4.01; -1.79]	2.1%
Cortamira C., et al, 2000d	78.40	5.919	80.30	6.063	-1.90	[-7.98; 4.18]	0.1%
Cortamira C., et al, 2000c	78.80	5.949	80.30	6.063	-1.50	[-7.59; 4.59]	0.1%
Thacker P.A., 2001	75.60	1.499	76.70	1.499	-1.10	[-2.57; 0.37]	1.2%
Qin C., et al, 2015	75.65	2.182	76.60	2.182	-0.95	[-2.70; 0.80]	0.9%
Hilbrands A. M. et al, 2021c	73.60	0.612	74.40	0.354	-0.80	[-1.49; -0.11]	5.5%
Siljander-Rasi, H. etal, 1996c	73.50	2.403	74.20	1.520	-0.70	[-2.81; 1.41]	0.6%
Kaczmarek P. et al, 2019	80.63	0.710	81.31	0.710	-0.68	[-1.25; -0.11]	8.2%
Smit M.N. et al, 2019	78.30	0.346	78.90	0.346	-0.60	[-0.88; -0.32]	34.3%
Smit M.N. et al, 2014d	77.30	1.613	77.70	0.883	-0.40	[-1.81; 1.01]	1.3%
Siljander-Rasi, H. etal, 1996b	73.80	2.403	74.20	1.316	-0.40	[-2.51; 1.71]	0.6%
Hilbrands A. M. et al, 2021a	74.00	0.612	74.40	0.354	-0.40	[-1.09; 0.29]	5.5%
Dora A. R. et al, 2004a	79.10	1.100	79.40	1.100	-0.30	[-1.54; 0.94]	1.7%
Dora A. R. et al, 2004b	79.10	1.100	79.40	1.100	-0.30	[-1.54; 0.94]	1.7%
Brand T. S. et al , 1999b	77.10	7.211	77.40	4.000	-0.30	[-5.84; 5.24]	0.1%
Siljander-Rasi, H. etal, 1996a	73.90	2.403	74.20	1.316	-0.30	[-2.41; 1.81]	0.6%
Dora A. R. et al, 2004c	79.20	1.100	79.40	1.100	-0.20	[-1.44; 1.04]	1.7%
Hilbrands A. M. et al, 2021b	74.20	0.612	74.40	0.354	-0.20	[-0.89; 0.49]	5.5%
Little K. L. et al, 2015c	77.84	0.885	78.01	0.560	-0.17	[-0.95; 0.61]	4.4%
Wiesław S. and Elwira F., 2021	73.85	0.847	73.99	0.847	-0.14	[-1.03; 0.75]	3.3%
Katarzyna Ś. et al, 2021	73.85	0.847	73.99	0.847	-0.14	[-1.03; 0.75]	3.3%
Smit M.N. et al, 2014a	77.60	1.613	77.70	0.721	-0.10	[-1.51; 1.31]	1.3%
Smit M.N. et al, 2014b	77.60	1.613	77.70	0.883	-0.10	[-1.51; 1.31]	1.3%
Smit M.N. et al, 2014c	77.70	1.613	77.70	0.721	0.00	[-1.41; 1.41]	1.3%
Lina M.P. S. et al, 2016b	82.03	4.965	81.81	3.511	0.22	[-4.13; 4.58]	0.1%
Little, K. L. etal, 2015b	78.27	0.885	78.01	0.485	0.26	[-0.52; 1.04]	4.4%
Corino, C. , et al, 1991a	82.00	2.319	81.70	1.640	0.30	[-0.84; 1.44]	2.0%
Corino, C. , et al, 1991b	82.00	2.319	81.70	1.640	0.30	[-0.84; 1.44]	2.0%
Brand T. S. et al , 1999a	77.80	7.211	77.40	4.000	0.40	[-5.14; 5.94]	0.1%
Lina M.P. S. et al, 2016a	82.34	4.965	81.81	3.511	0.53	[-3.83; 4.88]	0.1%
Little K. L. et al, 2015a	78.58	0.885	78.01	0.485	0.57	[-0.21; 1.35]	4.4%
Thacker P.A. , Bowland P., 1980	81.90	6.000	79.20	6.000	2.70	[-1.46; 6.86]	0.2%
Random effects model					**-0.42**	**[-0.62; -0.22]**	**100.0%**
Prediction interval						**[-0.59; -0.25]**	

Heterogeneity: $I^2 = 26\%$, $\tau^2 = 0$, $p = 0.09$

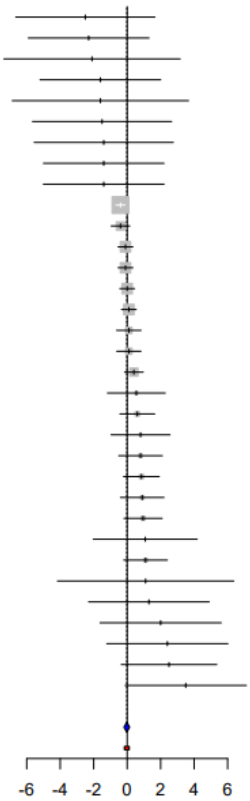
Supplementary Figure 7. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on dressing percentage



Supplementary Figure 8. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on lean percentage



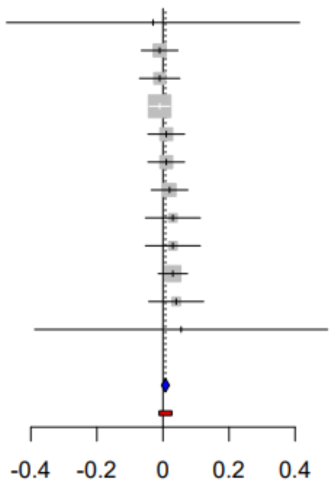
Supplementary Figure 9. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on loin eye muscle



Author	Experimental Backfat thickness	SD	Control Backfat thickness	SD	MD	95%-CI	Weight
Little, K. L. Etal, 2015b	17.80	4.743	20.30	2.598	-2.50	[-6.66; 1.66]	0.1%
Corino, C. , et al, 1991b	31.00	0.150	33.30	7.360	-2.30	[-5.91; 1.31]	0.2%
Hilbrands A. M. et al, 2021b	22.10	4.654	24.20	2.687	-2.10	[-7.37; 3.17]	0.1%
Brand T. S. et al , 1999c	17.50	4.687	19.10	2.907	-1.60	[-5.20; 2.00]	0.2%
Hilbrands A. M. et al, 2021c	22.60	4.654	24.20	2.687	-1.60	[-6.87; 3.67]	0.1%
Little, K. L. Etal, 2015c	18.80	4.743	20.30	3.000	-1.50	[-5.66; 2.66]	0.1%
Little, K. L. Etal, 2015a	18.90	4.743	20.30	2.598	-1.40	[-5.56; 2.76]	0.1%
Brand T. S. et al , 1999b	17.70	4.687	19.10	2.600	-1.40	[-5.00; 2.20]	0.2%
Corino, C. , et al, 1991a	31.90	0.150	33.30	7.360	-1.40	[-5.01; 2.21]	0.2%
Thacker P.A., Bowland P., 1980	7.80	0.400	8.20	0.400	-0.40	[-0.68; -0.12]	26.2%
Smit M.N. et al, 2019	18.50	0.693	18.90	0.693	-0.40	[-0.95; 0.15]	6.5%
Smit M.N. et al, 2014c	19.60	0.506	19.70	0.226	-0.10	[-0.54; 0.34]	10.2%
Smit M.N. et al, 2014d	19.60	0.506	19.70	0.277	-0.10	[-0.54; 0.34]	10.2%
Smit M.N. et al, 2014a	19.70	0.506	19.70	0.226	0.00	[-0.44; 0.44]	10.2%
Smit M.N. et al, 2014b	19.80	0.506	19.70	0.277	0.10	[-0.34; 0.54]	10.2%
Wiesław S., Elwira F., 2021	16.39	0.698	16.29	0.698	0.10	[-0.63; 0.83]	3.8%
Katarzyna Ś. et al, 2021	16.39	0.691	16.29	0.691	0.10	[-0.62; 0.82]	3.8%
Castell A. G. and Cliplef R. L., 1993	26.60	0.700	26.20	0.700	0.40	[-0.16; 0.96]	6.4%
Lina M.P. S. et al, 2016a	12.35	2.734	11.80	0.378	0.55	[-1.18; 2.28]	0.7%
Lina M.P. S. et al, 2016b	8.70	1.665	8.10	0.150	0.61	[-0.44; 1.65]	1.9%
Lina M.P. S. et al, 2016b	12.60	2.790	11.80	0.378	0.80	[-0.96; 2.56]	0.6%
Siljander-Rasi, H. etal, 1996a	23.80	1.486	23.00	0.814	0.80	[-0.50; 2.10]	1.2%
Lina M.P. S. et al, 2016a	8.95	1.712	8.10	0.150	0.85	[-0.22; 1.92]	1.8%
Siljander-Rasi, H. etal, 1996c	23.90	1.486	23.00	0.940	0.90	[-0.40; 2.20]	1.2%
Kaczmarek P. et al, 2019	22.96	1.427	22.01	1.427	0.95	[-0.19; 2.09]	1.5%
Qin C. et al, 2015	26.16	3.880	25.08	3.880	1.08	[-2.02; 4.18]	0.2%
Siljander-Rasi, H. etal, 1996b	24.10	1.486	23.00	0.814	1.10	[-0.20; 2.40]	1.2%
Hilbrands A. M. et al, 2021a	25.30	4.654	24.20	2.687	1.10	[-4.17; 6.37]	0.1%
Brand T. S. et al , 1999a	20.40	4.687	19.10	2.600	1.30	[-2.30; 4.90]	0.2%
Dora A. R. et al, 2004c	19.70	3.200	17.70	3.200	2.00	[-1.62; 5.62]	0.2%
Dora A. R. et al, 2004a	20.10	3.200	17.70	3.200	2.40	[-1.22; 6.02]	0.2%
Thacker P.A., 2001	25.20	2.913	22.70	2.913	2.50	[-0.35; 5.35]	0.2%
Dora A. R. et al, 2004b	21.20	3.200	17.70	3.200	3.50	[-0.12; 7.12]	0.2%
Random effects model					**-0.02**	**[-0.19; 0.15]**	**100.0%**
Prediction interval						**[-0.17; 0.13]**	

Heterogeneity: $I^2 = 26\%$, $\tau^2 = 0$, $p = 0.08$

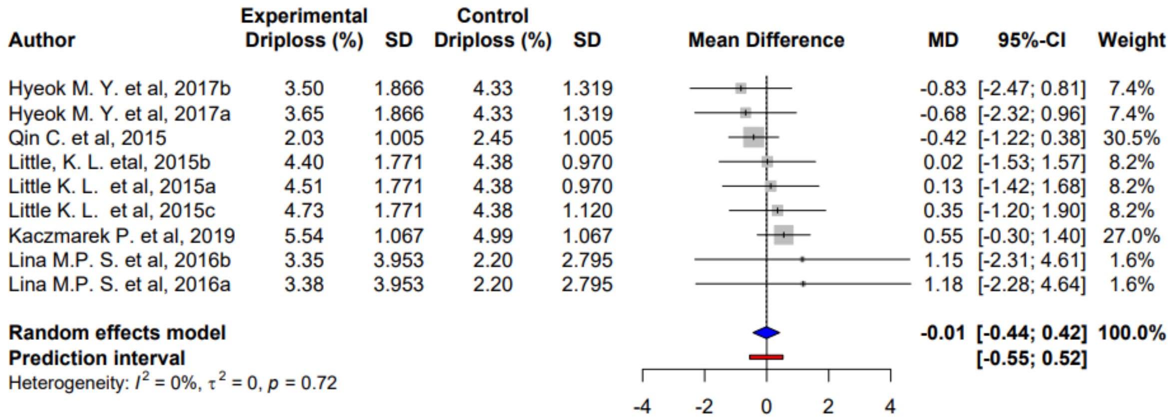
Supplementary Figure 10. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on backfat thickness



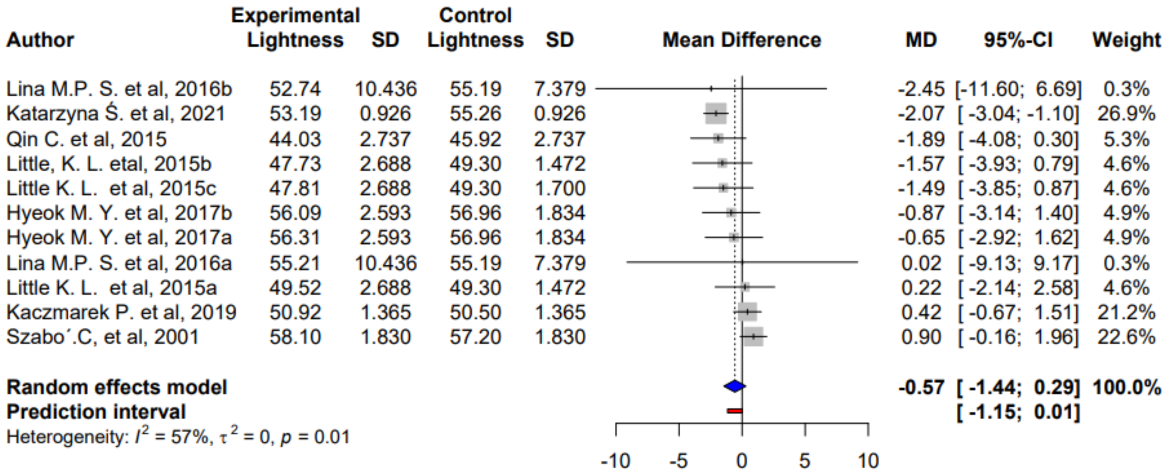
Author	Experimental pH	SD	Control pH	SD	MD	95%-CI	Weight
Lina M.P. S. et al, 2016a	5.49	0.506	5.52	0.358	-0.03	[-0.47; 0.41]	0.1%
Hyeok M. Y. et al, 2017a	5.27	0.063	5.28	0.045	-0.01	[-0.07; 0.05]	9.2%
Kaczmarek P. et al, 2019	5.68	0.076	5.69	0.076	-0.01	[-0.07; 0.05]	7.6%
Szabo´.C, et al, 2001	5.58	0.054	5.59	0.054	-0.01	[-0.04; 0.02]	28.6%
Castell A. G., Cliplef R. L., 1993	5.68	0.069	5.67	0.069	0.01	[-0.05; 0.07]	9.2%
Qin C. et al, 2015	5.48	0.069	5.47	0.069	0.01	[-0.05; 0.07]	9.2%
Hyeok M. Y. et al, 2017b	5.30	0.063	5.28	0.045	0.02	[-0.04; 0.08]	9.2%
Little K. L. et al, 2015a	5.51	0.095	5.48	0.052	0.03	[-0.05; 0.11]	4.1%
Little, K. L. etal, 2015b	5.51	0.095	5.48	0.052	0.03	[-0.05; 0.11]	4.1%
Katarzyna Ś. et al, 2021	5.50	0.042	5.47	0.042	0.03	[-0.01; 0.07]	14.4%
Little K. L. et al, 2015c	5.52	0.095	5.48	0.060	0.04	[-0.04; 0.12]	4.1%
Lina M.P. S. et al, 2016b	5.58	0.506	5.52	0.358	0.06	[-0.39; 0.50]	0.1%
Random effects model					**0.01**	**[0.00; 0.02]**	**100.0%**
Prediction interval						**[-0.01; 0.03]**	

Heterogeneity: $I^2 = 0\%$, $\tau^2 = 0$, $p = 0.96$

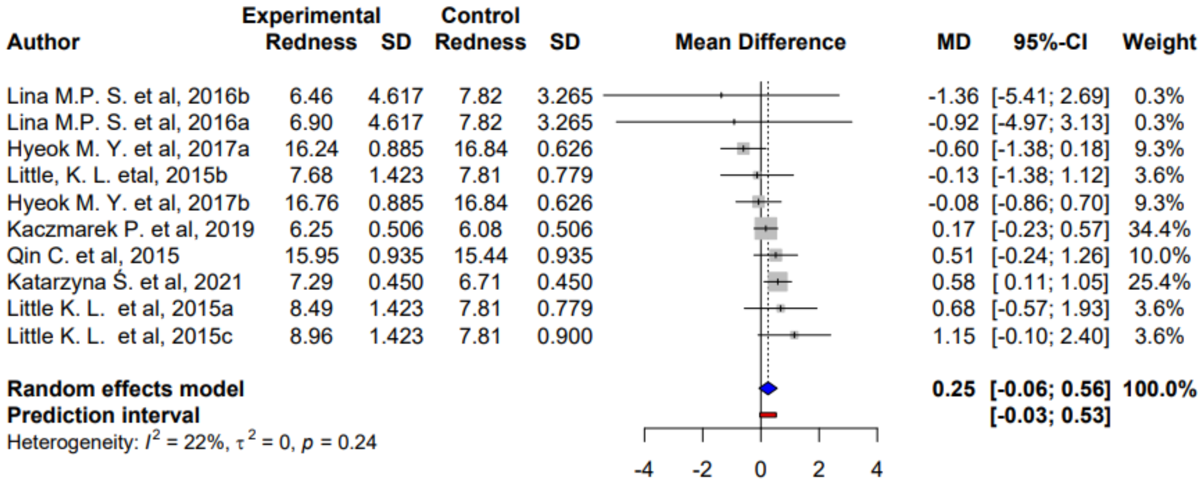
Supplementary Figure 11. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on pH



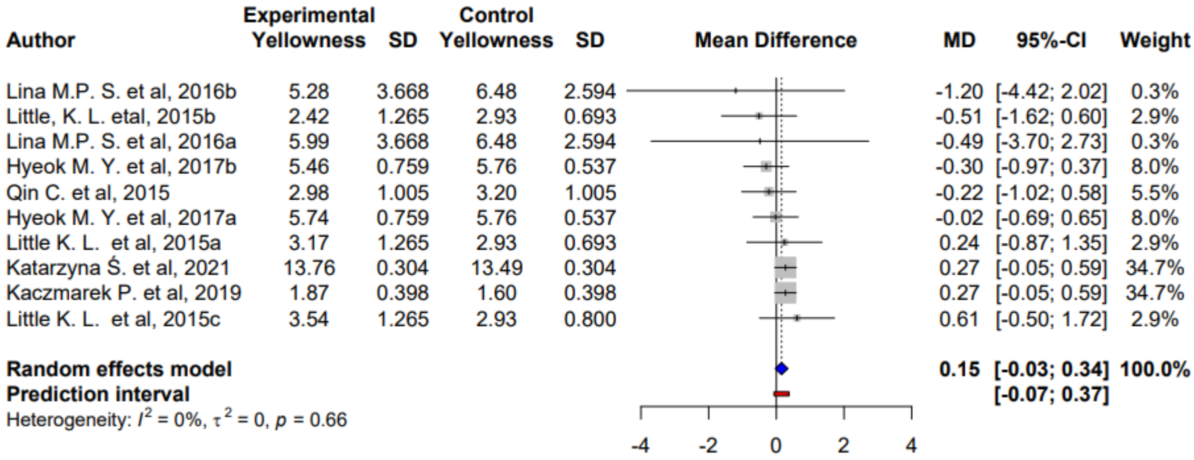
Supplementary Figure 12. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on pork driploss



Supplementary Figure 13. A forest plot describing the effect of replacing soybean meal with alternative oilseed meals on pork lightness



Supplementary Figure 14. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on pork redness



Supplementary Figure 15. A forest plot describing the effect of replacing soybean meal with the alternative oilseed meals on pork yellowness

REFERENCES OF APPENDIX

Baidoo, S. K., et al. (1987). Canola meal as a protein supplement for growing-finishing pigs. *Anim. Feed Sci. Technol.*, *18*(1), 37-44. https://doi.org/10.1016/0377-8401(87)90027-7

Bell, J. M., & Keith , M. O. (1987). Feeding value for pigs of canola meal derived from Westar and Triazine tolerant cultivars. *Can J Anim Sci*, *67*(3), 811-819. https://doi.org/10.4141/cjas87-084

Castell, A. G., & Cliplef, R. L. (1993). Evaluation of pea screenings and canola meal as a supplementary protein source in barley-based diets fed to growing-finishing pigs. *Can J Anim Sci*, *73*(1), 129-139. https://doi.org/10.4141/cjas93-012

Corino, C., et al. (1991). Influence of low-glucosinolate rapeseed meal on performance and thyroid hormone status of heavy pigs. *Anim. Feed Sci. Technol.*, *35*(3), 321-331. https://doi.org/10.1016/0377-8401(91)90138-I

Cortamira, O., et al. (2000). Evaluation of twice decorticated sunflower meal as a protein source compared with soybean meal in pig diets. *Asian-Australas J Anim Sci*, *13*(9), 1296-1303. https://doi.org/10.5713/ajas.2000.1296

Fang, Z. F., et al. (2007). Xylanase supplementation improved digestibility and performance of growing pigs fed chinese double-low rapeseed meal inclusion diets: In vitro and in vivo studies. *Asian-Australas J Anim Sci*, *20*(11), 1721-1728. https://doi.org/10.5713/ajas.2007.1721

Hilbrands, A. M., et al. (2021). Effects of increasing dietary inclusion of camelina cake on growth performance of growing-finishing pigs. *Translational Animal Science*, *5*(3). https://doi.org/10.1093/tas/txab140

Kaczmarek, P., et al. (2019). The effect of hydrothermally processed soybean- and rapeseed-based diets on performance, meat and carcass quality characteristics in growing-finishing pigs. *Annals of Animal Science*, *19*(4), 1083-1097. https://doi.org/10.2478/aoas-2019-0045

Kargopoulos, A., et al. (2018). Effect of dietary rape seed meal on growth performance and meat quality of growing-fattening pigs. *S. Afr. J. Anim. Sci.*, *48*(5), 897-906. https://doi.org/10.4314/sajas.v48i5.9

Li, Z., et al. (2017). Net energy of corn, soybean meal and rapeseed meal in growing pigs. *J. Anim. Sci. Biotechnol.*, *8*(1), 44. https://doi.org/10.1186/s40104-017-0169-1

Lina, M. P. S., et al. (2016). Performance and quantitative and qualitative carcass traits in pig fed on canola meal *Revista Caatinga*, *29*, 735-741. https://doi.org/10.1590/1983-21252016v29n325rc

Little, K. L., et al. (2015). Effects of feeding canola meal from high-protein or conventional varieties of canola seeds on growth performance, carcass characteristics, and cutability of pigs. *Journal of Animal Science*, *93*(3), 1284-1297. https://doi.org/10.2527/jas.2014-8359

Qin, C., et al. (2015). Influences of dietary protein sources and crude protein levels on intracellular free amino acid profile in the longissimus dorsi muscle of finishing gilts. *J. Anim. Sci. Biotechnol.*, *6*(1), 52. https://doi.org/10101186/s40104-015-0052-x

Roth-Maier, D. A., et al. (2004). Effects of feeding canola meal and sweet lupin (L. luteus, L. angustifolius) in amino acid balanced diets on growth performance and carcass characteristics of growing-finishing pigs. *Animal Research*, *53*(1), 21-34. https://doi.org/10.1051/animres:2003048

Shelton, J. L., et al. (2001). Effect of different protein sources on growth and carcass traits in growing-finishing pigs. *Journal of Animal Science*, *79*(9), 2428-2435. https://doi.org/10102527/2001.7992428x

Shi, C., et al. (2016). Effects of Aspergillus niger fermented rapeseed meal on nutrient digestibility, growth performance and serum parameters in growing pigs. *Anim Sci J*, *87*(4), 557-563. https://doi.org/10.1111/asj.12457

Siljander-Rasi, H., et al. (1996). Replacing soya bean meal with heat-treated, low-glucosinolate rapeseed meal does not affect the performance of growing-finishing pigs. *Anim. Feed Sci. Technol.*, *60*(1), 1-12. https://doi.org/10.1016/0377-8401(95)00920-5

Śmiecińska, K., et al. (2021). Carcass and meat quality in growing-finishing pigs fed diets with plant-based protein sources alternative to genetically modified soybean meal. *Agric Food Sci*, *30*(4), 146–157. https://doi.org/10.23986/afsci.110877

Smit, M. N., et al. (2018). Effects of feeding canola meal or soy expeller at two dietary net energy levels on growth performance, dressing and carcass characteristics of barrows and gilts. *Anim. Feed Sci. Technol.*, *235*, 166-176. https://doi.org/10.1016/j.anifeedsci.2017.11.013

Smit, M. N., et al. (2014). Feeding increasing inclusions of canola meal with distillers dried grains and solubles to growing-finishing barrows and gilts. *Anim. Feed Sci. Technol.*, *189*, 107-116. https://doi.org/10.1016/j.anifeedsci.2013.12.012

Sobotka, W., & Fiedorowicz-Szatkowska, E. (2021). The effect of replacing genetically modified soybean meal with 00-rapeseed meal, faba bean and yellow Lupine in grower-finisher fiets on nutrient digestibility, nitrogen retention, selected blood biochemical parameters and fattening performance of pigs. *Animals*, *11*(4). https://doi.org/10.3390/ani11040960

Szabo, C., et al. (2001). Effect of dietary protein source and lysine : DE ratio on growth performance, meat quality, and body composition of growing-finishing pigs. *Journal of Animal Science*, *79*(11), 2857-2865. https://doi.org/10.2527/2001.79112857x

Thacker, P. A. (2001). Effect of enzyme supplementation on the performance of growing-ginishing pigs fed barley-based diets supplemented with soybean meal or canola meal. *Asian-Australas J Anim Sci*, *14*(7), 1008-1013. https://doi.org/10.5713/ajas.2001.1008

Thacker, P. A., & Bowland, J. P. (1980). Influence of graded levels of dietary propionic acid on performance and carcass traits of swine fed diets supplemented with soybean meal or canola meal. *Can J Anim Sci*, *60*(4), 971-978. https://doi.org/10.4141/cjas80-115

Torres-Pitarch, A., et al. (2014). The inclusion of rapeseed meal in fattening pig diets, as a partial replacer of soybean meal, alters nutrient digestion, faecal composition and biochemical methane potential from faeces. *Anim. Feed Sci. Technol.*, *198*, 215-223. https://doi.org/10.1016/j.anifeedsci.2014.09.017

Velayudhan, D. E., et al. (2017). Effect of expeller extracted canola meal on growth performance, organ weights, and blood parameters of growing pigs. *Journal of Animal Science*, *95*(1), 302-307. https://doi.org/10.2527/jas.2016.1046

Xie, P., et al. (2012). Evaluation of extruded or unextruded double-low rapeseed meal and multienzymes preparation in pigs nutrition during the finishing phase of production. *Italian Journal of Animal Science*, *11*(2), e34. https://doi.org/10.4081/ijas.2012.e34

Yun, H. M., et al. (2017). Rapeseed meal and canola meal can partially replace soybean meal as a protein source in finishing pigs. *J Appl Anim Res*, *46*(1), 195-199. https://doi.org/10.1080/09712119.2017.1284076

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