EVALUATION OF GLYCERINE AS A CO-PRODUCT OF BIODIESEL PRODUCTION FOR THE PIG INDUSTRY

Report prepared for the
Pork Co-operative Research Centre

By

Dr Jo Pluske
SciEcons Consulting,
PO Box 1604
Subiaco WA 6904
AUSTRALIA

May 2007

Established and supported under the Australian Government's Cooperative Research Centres Program

SciEcons
Consulting

Executive Summary

This report is based on a desktop review of the potential supply and use of glycerine as a feed ingredient in the Australian pig industry. While the focus of the review was on glycerine derived from production of biodiesel in Australia, the report shows that pig producers could use imported glycerine sourced from other biodiesel-producing countries.

Feed grain prices are of growing concern in Australia and the pig industry needs to explore alternative dietary components that will reduce cost of production if it is to remain competitive in the international pork market. The supply of glycerine, as a co-product of biodiesel production, is increasing in Australia and may be an economically viable replacement for some grain in pig diets.

Currently, biodiesel plants are located or are planned for all States and Territories except for Tasmania and the Australian Capital Territory. Almost all of these plants are located in areas where pig production occurs and hence supplying producers with glycerine should be relatively straight forward. Glycerine is chemically stable within a temperature range of 17 and 54°C, and hence it should be possible to transport the product from these suppliers and (or) import glycerine from international suppliers.

Glycerine is a viscous liquid with a sweet taste and preliminary studies have indicated that animal-feed-quality glycerine can be incorporated into the pig diet. However, there has been little research done to ascertain the effect on feed quality and acceptance of diets using different glycerine feedstocks. Furthermore, there has been little research done on the influence that glycerine in a pig diet has on pig growth and meat quality.

Information on price of glycerine in Australia is limited and thus a least-cost feed formulation package was used to determine the cost at which glycerine would be considered for inclusion in a pig diet. With recognition of the assumptions made in the model and different outcomes for the various age classes of pigs, the model indicated that generally glycerine would have to cost less than AUS$170 per tonne before pig producers would consider it as a feed component, bearing in mind that they have access to competing sources of energy. This value is slightly more than the lowest cost (that the author is aware of) that has been reported for glycerine in Australia.

Given the high price of animal feed, potentially cost-effective prices of glycerine and preliminary research indicating that glycerine may be suitable for animal diets, there is potential to introduce glycerine into pig diets in Australia. As a result of the findings in this study the following recommendations have been made:

1. The chemical properties of crude glycerine will vary depending on the feedstock source and the manufacturing process. Currently there is little knowledge concerning the variation in glycerine attributes and how it affects quality of animal feed. It is recommend that attempts be made to contact all known Australian biodiesel/glycerine producers to request representative glycerine samples that will be subsequently analysed, particularly for GE, oil, methanol, ash and minerals, including Na;

2. Currently there appears to be limited dialogue between glycerine producers and the pig industry regarding product quality and requirements. In addition to requesting glycerine samples from producers, information pertaining to feed-grade glycerine availability (quantity, quality and possible minimum price) should also be requested.

3. It is recommended that feeding trials measuring growth performance, carcass specification and meat quality at different levels of glycerine inclusion in the diet should be conducted contingent upon the findings in recommendations 1 and 2. These studies should focus initially on grower and finisher pigs, but studies with weaner pigs could also be considered given the energy deficit encountered after weaning and glycerine's gluconeogenic capacity.

Table of Contents

Executive Summary .... **i**

List of figures .... **v**

List of tables .... **vi**

1. Introduction **1**

2. Methodology **2**

3. The biodiesel and glycerine production process **2**

4. Glycerine as an animal feedstuff **4**

4.1. Likely content of nutrients and variation *4*

4.2. Anti-nutritional properties *6*

5. Research on glycerine in animal diets **7**

5.1. Glycerine metabolism *7*

5.2. Potential advantages of glycerine in pig diets *8*

5.3. Potential disadvantages of glycerine in pig diets *11*

5.4. Glycerine in poultry diets *11*

5.5. Glycerine in ruminant diets *12*

6. Biodiesel and glycerine in the global market **12**

6.1. Global energy sources *12*

6.2. Biodiesel production *13*

6.3. Future viability of the biodiesel industry *15*

6.4. Manufacturing glycerine *18*

6.5. Competition for glycerine from other industries *19*

7. Glycerine supply, handling and availability **20**

7.1. Possible supply chains for the pork industry *20*

7.2. Handling and storage issues *22*

7.3. Where in Australia glycerine will be available *23*

8. Likely cost of glycerine for pig feed **25**

8.1. Market supply for biodiesel and glycerine *25*

8.2. Market demand for biodiesel and glycerine *27*

8.3. Global glycerine pricing *28*

8.4. The cost of glycerine in Australian pig diets *29*

9. Conclusion **31**

10. Limitations **32**

11. Recommendations **32**

12. **Acknowledgements** 32

13. **References** 33

Appendix: Description of the GMI model 40

List of figures

Figure 1 The formula for glycerol. 2

Figure 2 Biodiesel production process and feedstock sources. 3

Figure 3 A schematic presentation of glycerine metabolism in the body. 8

Figure 4 A biodiesel market overview showing the interconnections between biodiesel and other markets including diesel, biomass oil, feedstocks, and glycerine. 16

Figure 5 Supply chains for glycerine entering the pork supply chain with *Chain A* showing production of glycerine to its use by farmers and *Chain B* indicating how glycerine is part of the larger chain from input suppliers to consumers. 21

Figure 6 A map of Australia showing the approximate locations of towns with functioning or planned biodiesel plants and an estimated distribution of pig producers in 2005. 24

Figure 7 Changing oil prices over the years 2004 to 2006 and reasons for those changes. 26

Figure 8 Industrial use of corn in the USA is increasing compared to other uses for corn. 27

List of tables

Table 1 The total weight of the glycerine layer, the weight of glycerol, the glycerol concentration and the nutrient and energy analysis of the crude glycerine samples for various feedstocks. 5

Table 2 Analysis results of macro elements, carbon and nitrogen found in the crude glycerine after separation from the oil[1].Data shown are in the format of average ± standard deviation. 6

Table 3 The dry matter intake, daily live weight gain and feed conversion ratio for pigs feed glycerine at varying levels in two trials. 9

Table 4 The daily live weight gain, percentage fatty acid in the back-fat and metabolisable energy increase compared to Group1 for pigs fed various diets. 10

Table 5 Current (as of 2004-05) and proposed biodiesel production capacity, 2005-06 to 2009-10 (ML). 14

Table 6 Biodiesel production capacity in Australia: short-term outlook[1]. 23

Table 7 The number of sows, as of June 2004, in each of the States of Australia and the percentage of the total in each State. 25

Table 8 The equivalent quantity of glycerine in USA and Australian dollars. 29

Table 9 Least-cost diet information for weaner, grower and finisher pigs and the maximum costs for tallow, molasses and glycerine in pig diets. 30

1. Introduction

The Australian pork industry has to devise strategies for improving efficiency and reducing the cost of production, as emphasised by Campbell (2006). A strategy to reduce the cost of production for Australian pig producers is to consider the use of novel by-products in feed, as discussed at the Pork Cooperative Research Centre's Workshop, "Novel Feeds Ingredients" held in August 2006. One such product that arose as a potential feed ingredient from the workshop was glycerine, a co-product of biodiesel production.

In refining plant or animal oil into biodiesel, glycerine evolves as a co-product. Glycerol is the alcohol component of all triglycerides found in animal and plant tissues (Pond *et al.* 2005). It is the simplest trihydric alcohol and is the name preferred for the pure chemical, although the commercial product is usually called glycerin [glycerine[1]] (McGraw-Hill 2005).

When pure, glycerine is a colorless, odorless, viscous liquid with a sweet taste (McGraw-Hill 2005). It is completely soluble in water and alcohol but is only slightly soluble in many common solvents, such as ether, ethyl acetate, and dioxane and is insoluble in hydrocarbons (McGraw-Hill 2005). Glycerol boils at 290°C at atmospheric pressure, melts at around 17°C and has a specific gravity of 1.26 at 25°C with a molecular weight of 92 (McGraw-Hill 2005).

Biodiesel production in Australia is increasing with capacity in 2005 being around 15.5 ML per year with an expected short to medium term increase of 508 ML (Biofuels Taskforce 2005). As a consequence glycerine production is also increasing but to date there has been little research done on the suitability of this co-product being used in animal diets.

The purpose of this report is to produce a desktop review of the potential supply and use of glycerine as a feed ingredient in the Australian pig industry. While the focus will be on glycerine derived from production of biodiesel in Australia, there may be opportunities for importing glycerine from other countries that are producing biodiesel, and this should not be overlooked.

[1] In the literature glycerol is interchanged with glycerine and glycerin. For consistency and where appropriate, the words glycerol and glycerin will be replaced by glycerine in this report.

2. Methodology

The focus of this desktop study will be on glycerine produced during the manufacture of biodiesel and its potential for use in animal diets. In particular the nature of glycerine will be reviewed in terms of its suitability as a feed component, its availability to Australian pig producers, and ease at which it can be stored and handled. Information on price of glycerine in Australia is limited and hence scenarios have been conducted using a feed formulation package to determine the price at which glycerine could be included in a pig diet for pigs at different phases of growth. Recommendations regarding future research associated with glycerine in the pig industry will also be made.

3. The biodiesel and glycerine production process

Glycerine can be produced by transesterification, whereby oil or animal fat is converted into biodiesel (Lemke 2006). Oil is commonly derived from plants such as canola, mustard, sunflower, safflower, soybean and corn (Hobbs 2003). One hundred litres of oil or fat ideally produces 100 litres of biodiesel and 10 litres of glycerine (Alberta Gov 2007). Alternatively Lammers *et al.* (2007b) suggest that with current refinement processes, for every litre of biodiesel produced 79 g of crude glycerine is created.

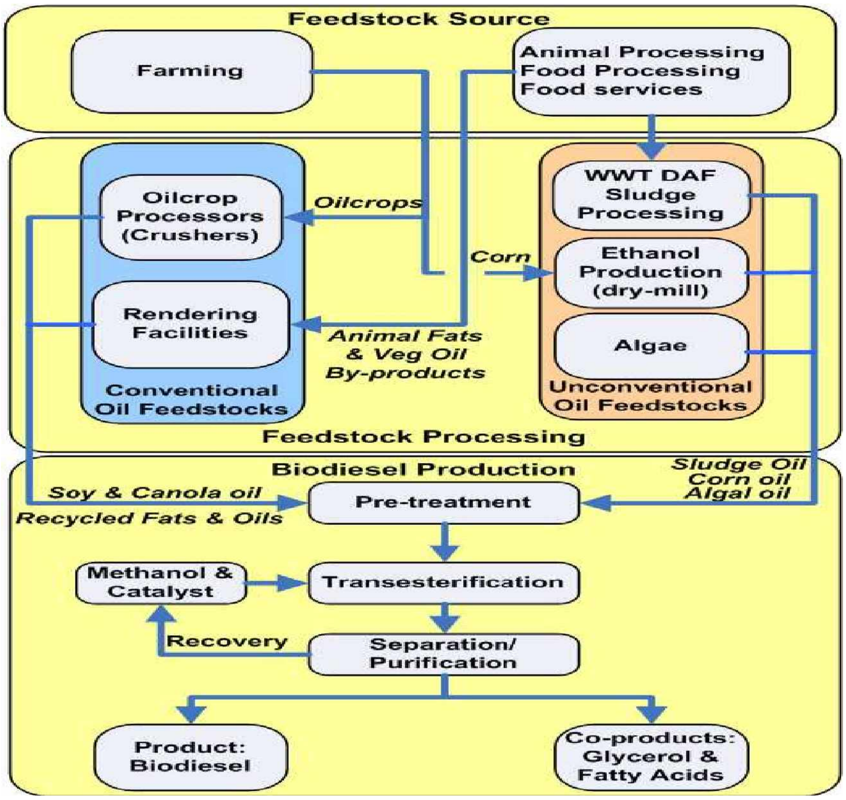
Crude glycerine has a glycerol (Figure 1) content within the range of 75 to 85% and must be refined if it is to achieve food grade approval (Toohey *et al.* 2003). The refined form should be between 95 and 99% pure (Bonnardeaux 2006) and is directed predominately to the human markets. Most glycerine is manufactured to meet these stringent requirements as specified under the United States Pharmacopeia (USP), the Food Chemicals Codex (FCC) and (or) the Food Grade Kosher (glycerine prepared and maintained in strict compliance with the laws and customs of the Orthodox Jewish religion) (Bonnardeaux 2006). Hamilton (2004) noted that glycerine must be sourced from non-animal feedstocks so that it can be termed Kosher quality. Technical grades of glycerine that are not certified as USP or FCC must conform only to the specifications and terms agreed upon in the transaction between buyer and seller (Bonnardeaux 2006).

$HOCH_2$
|
$HOCH$
|
$HOCH_2$

Source: (Pond *et al.* 2005)

Figure 1 The formula for glycerol.

Along with glycerine, three fatty acids are produced during the biodiesel production process and hence diesel engines do not need modification to run on this fuel (Best 2006). Converting crop products into biodiesel can also produce feed components such as rapeseed meal (Best 2006). Bantz and Deaton (2006) have summarized the biodiesel production process as reproduced in Figure 2. They noted that proposed unconventional feedstock sources (shaded orange in Figure 2) include oil extracted from wastewater sludge, corn oil from ethanol processing and algae.



Source: (Bantz and Deaton 2006)

Figure 2 Biodiesel production process and feedstock sources.

4. Glycerine as an animal feedstuff

Biodiesel production is increasing and hence new uses for glycerine will become important (Miller 2006). Glycerol has a very low mammalian toxicity (McGraw-Hill 2005) and as suggested by Biodiesel Technote (2006) and Lammers *et al.* (2007b) its use as a feed component in animal diets shows promise.

4.1. Likely content of nutrients and variation

Most biodiesel feedstocks are derived from vegetable oils, first-use animal fats and waste greases (Kotrba 2006). The use of animal fat cannot generally be used as animal feed for ruminants because of issues associated with BSE (Anon 2005). However, according to State regulations as explained for example by DPI (2007) for Victoria, it may be used as a feed component. The regulations are in accordance with: the American Oil Chemists Society with regard to tallow composition measurements; and Parts 5, 6 and 7 of the Australian Renderers Association (ARA) for collection, filtration (or centrifugation) and packaging (Millar 2005). These regulations do not extend to pigs and poultry in Australia and they are permitted to consume feeds derived from tallow (Cook 2007).

Soybean oil (mainly used in the United States), palm oil (Malaysia) and rapeseed and sunflower oil (Europe) are the main feedstocks for biodiesel production (ABARE 2006). Vegetable oils derived from canola [or rapeseed], sunflowers and soybeans are generally low in saturated fats and are considered the easiest and least expensive to process (Kotrba 2006).

According to Hancock (2005), mustard could be a valuable oilseed crop that has potential as an alternative break-crop to canola especially in the drier regions of the Western Australian wheatbelt. Mustard meal is used mainly as an animal feed source with preliminary studies completed by Zijlstra *et al.* (2005) indicating that pigs will have a 5% increase in weight gain if fed mustard meal instead of canola meal. Should mustard be used in biodiesel production these benefits may also be relevant for the co-product, glycerine. Mustard has high levels of glucosinolates and as noted by Weiss *et al.* (2006), oil and subsequent meal with high levels of glucosinolates and erucic acid reduces palatability and (or) are toxic to some animals. They also point out that erucic acid has been shown to be a potential health hazard to humans.

While refining glycerine to a chemically pure substance would increase its use, due to its cost it is generally not economically feasible for small to medium-sized plants and hence the interest in using it for feed production (Thompson and He 2006). Thompson and He (2006) stated that the efficacy of using crude glycerol as an animal feed supplement is unclear and although it is deemed to be non-toxic there are issues of ingestion that should be worked before a feeding trial is attempted. Hence following the biodiesel process, Thompson and He (2006) conducted analytical tests on the crude glycerine as it was recovered after separation from the fuel without further processing. The feedstocks were from two varieties of mustard, rapeseed, canola, soybean, crambe and waste vegetable oils (WVO). The analysis of crude glycerine from various sources is reproduced in Table 1.

Table 1 The total weight of the glycerine layer, the weight of glycerol, the glycerol concentration and the nutrient and energy analysis of the crude glycerine samples for various feedstocks.

Feed stocks	Ida Gold Mustard	PacGold Mustard	Rapeseed	Canola	Soybean	Crambe	WVO[1]
Glycerol +MeOH+Cat (g)	13.61 ± 0.19	13.27 ± 0.40	15.23 ± 0.20	15.94 ± 0.27	16.16 ± 0.47	17.58 ± 1.07	25.26 ± 0.62
Glycerol (g)	8.56 ± 0.35	8.35 ± 0.16	10.01 ± 0.06	10.80 ± 0.26	10.96 ± 0.48	10.98 ± 0.40	19.35 ± 0.82
Glycerol concentration (%wt)	62.9 ± 2.30	62.9 ± 0.65	65.7 ± 1.19	67.8 ± 1.02	67.8 ± 1.12	62.5 ± 2.16	76.6 ± 4.11
Fat, %	2.03	1.11	9.74	13.1	7.98	8.08	60.1
Carbohydrates, %	82.8	83.8	75.5	75.2	76.2	78.6	26.9
Protein, %	0.14	0.18	0.07	0.06	0.05	0.44	0.23
Calories, kJ/kg	14.6	14.5	16.3	17.5	15.8	16.3	27.2
Ash, % [2]	2.80	1.90	0.70	0.65	2.73	0.25	5.50

[1] WVO glycerine had higher levels of unreacted glycerides and soaps.

[2]The ash contained in crude glycerine is mainly sodium from the catalyst.

Source: (Thompson and He 2006)

Thompson and He (2006) suggested that nutritional data generated for the glycerine of the first-use oil samples show that it is mostly carbohydrate and could reasonably be mixed with high protein meal and used as a feed supplement. They also observed that given the higher fat content of WVO glycerine, it could be used as a supplement for fat in animal diets.

Another consideration with using glycerine is the mineral content. Table 2 shows the variation in macro and micro mineral content in crude glycerine samples derived from different feedstocks. Variation in mineral content can be caused by the processing method.

Table 2 Analysis results of macro elements, carbon and nitrogen found in the crude glycerine after separation from the oil[1].Data shown are in the format of average ± standard deviation.

Feedstocks	IdaGold Mustard	PacGold Mustard	Rapeseed	Canola	Soybean	Crambe	WVO
Calcium ppm	11.7±2.9	23.0±1.0	24.0±1.7	19.7±1.5	11.0±0.0	163.3±11.6	BDL
Potassium ppm	BDL	BDL	BDL	BDL	BDL	216.7±15.3	BDL
Magnesium ppm	3.9±1.0	6.6±0.4	4.0±0.3	5.4±0.4	6.8±0.2	126.7±5.8	0.4±0.0
Phosporus ppm	25.3±1.2	48.0±2.0	65.0±2.0	58.7±6.8	53.0±4.6	136.7±57.7	12.0±1.5
Sulfur ppm	21.0±2.9	16.0±1.4	21.0±1.0	14.0±1.5	BDL	128.0±7.6	19.0±1.8
Sodium %wt[2]	1.2±0.2	1.2±0.1	1.1±0.1	1.1±0.1	1.2±0.1	1.1±0.1	1.4±0.2
Carbon %wt	24.0±0.0	24.3±0.6	25.3±0.6	26.3±0.6	26.0±1.0	24.0±0.0	37.7±0.6
Nitrogen %wt	0.04±0.02	0.04±0.01	0.05+/-0.01	0.05±0.01	0.04±0.03	0.06±0.02	0.12±0.01

[1] BDL indicates values that are below the detection limit for the corresponding analytical method. The detection limits in ppm were as follows: calcium – 2, potassium – 40, Magnesium – 0.20, sodium – 80, phosphorus – 5, sulfur – 15, carbon – 200 and nitrogen – 100.

[2]Sodium, which was quantified as an ion, represents the catalyst (sodium methylate, $NaOCH_3$) used in the reaction.

Source: (Thompson and He 2006)

As pointed out by Thompson and He (2006), the carbon and nitrogen levels in the glycerine samples were similar for all feedstocks with carbon at about 25% and nitrogen at 0.05%. The only exception to this observation was that the carbon content in the glycerine sample derived from WVO was 50% higher than that of the average, perhaps due to the presence of soaps and dissolved unreacted glycerides and esters (Thompson and He 2006). A desirable effect of the biodiesel process is that generally the elements are concentrated in the glycerine phase. High levels of e.g. calcium and phosphorus in the crambe glycerine compared to the others was most likely due to the soil conditions in North Dakota where the seeds were grown (Thompson and He 2006).

As discussed in Section 4.2 below, the methanol content in the aforementioned glycerine samples should be considered. Assuming half of the 19.54 g of methanol was used up in the reaction, of the remaining 9.77g, approximately 46% of it was in the ester layer and 54% went with the glycerol phase and hence Thompson and He (2006) concluded that the crude glycerol in this study contained 23.4 to 37.5% methanol resulting in a relatively low viscosity.

4.2. Anti-nutritional properties

According to Doppenberg and Van Der Aar (2007), a major concern of crude or feed-grade glycerine (80%) is the methanol content that remains as a residue (maximum 0.5%) after processing. Methanol has a low evaporation point (65°C) so it will be lost during feed pelleting possibly causing a hazard in the mill (Doppenberg and Van Der Aar 2007). Doppenberg and Van Der Aar (2007) also noted that in non-pelletised meal feeds and protein supplements fed to non-ruminants, there is a possible health risk associated with consumption of the meat from these animals. While they point out that the methanol content of glycerine poses this health risk, they do not provide any evidence for the effect.

As noted in ISU (2007) methanol can be toxic and hence swine and poultry producers interested in trying glycerine as part of a feed ration would need to work with the biodiesel plant to make sure methanol levels are below the Food and Drug Administration (FDA) approved level of 150 parts per million in the glycerine. There appears to be no indication as to what this level is in Australia. Hence, as a guide following the FDA standard may be appropriate. As reported by Ferguson (2007) methanol received at high levels can result in blindness in pigs and chickens but given the levels of methanol in glycerine there appears to be no evidence of any adverse side-effects in animals fed glycerine.

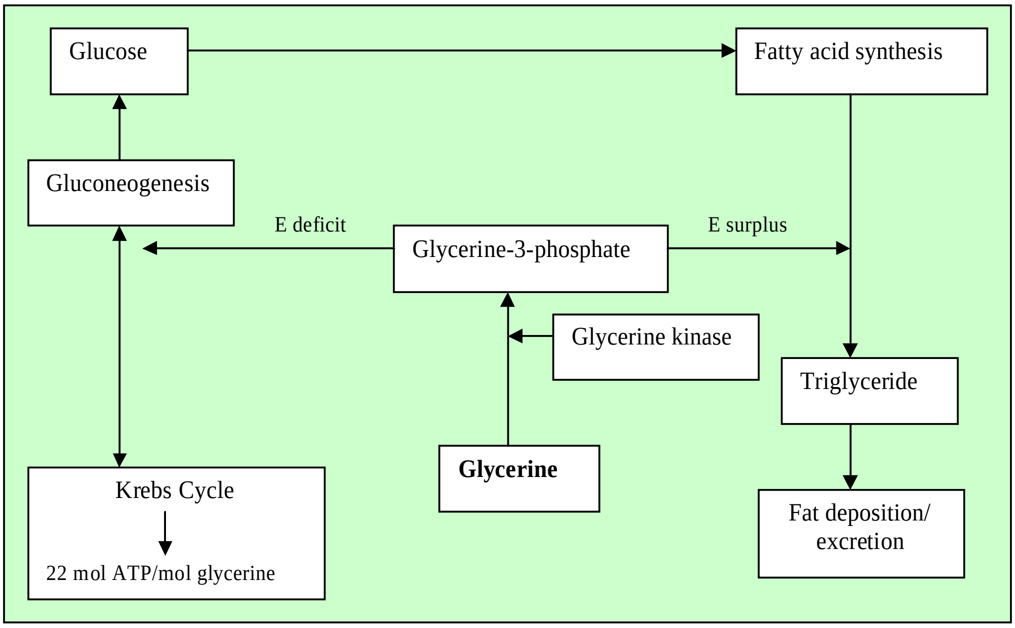
Tyson *et al.* (2004) suggested that the key problem with biodiesel glycerine is the salt content and impurities that are introduced by using recycled feedstocks, with the least desirable contaminant in crude glycerine being the spent salts from the esterification reactions. These and can represent 10 to 30% of the crude glycerine by weight depending on the feedstock and process. Doppenberg and Van Der Aar (2007) are not quite so pessimistic and noted that because sodium hydroxide can be used as a catalyst for hydrolysis and is combined with hydrochloric acid, the sodium chloride content of glycerine increases to just 6% and thereby restricts the amount of glycerine that can be included in the diet.

5. Research on glycerine in animal diets

As reported by Best (2006), the suitability of glycerine for the animal feed industry is the major focus of current research based mainly on the premise that glycerine could replace molasses in pig diets, where molasses is used. He also acknowledged that there is minimal experience in using glycerine as a feed component and there is limited research and literature concerning feeding trials for non-ruminants.

5.1. Glycerine metabolism

Mourot *et al.* (1994) provided background information explaining how glycerol released from triacylglycerol catabolism is converted to glucose via phosphorylation to glycerol-3-phosphate (catalysed by glycerol kinase) that then enters gluconeogenesis in the liver. This provides a readily available energy source for the pig, which could be especially beneficial for the newly weaned pig that is commonly in a state of energy deficit. Glycerol consumed via the diet is absorbed paracellular by passive diffusion, and recently there is *in situ* evidence for the presence of a Na[+]-dependent carrier-mediated transport system for glycerol in the rat small intestine (Kato *et al*., 2005). Irrespective of the mechanism, glycerol will enter the liver via the portal vein and act as a gluconeogenic precursor in the same way as endogenous glycerol released from triacylglycerol catabolism. An overview of glycerine metabolism is outlined below in Figure 3.



Source: (Best 2006)

Figure 3 A schematic presentation of glycerine metabolism in the body.

5.2. Potential advantages of glycerine in pig diets

In the mid 1990's, a handful of studies were reported in the literature detailing the advantages of glycerine in pig diets. However, with the recent and dramatic increase in global biodiesel production and the abundance of glycerine, new avenues are being investigated for use of glycerine in pig diets.

Kijora *et al.* (1995) conducted an experiment to test glycerine as a component in diets of fattening pigs in two experiments using 48 pigs (Pietrain x F1, Landrace x German breed) and feeding up to 30% glycerol in barley-soya bean oil meal diets. Barley was replaced by glycerine that amounted to 5 and 10% glycerine (Trail 1) and 5, 10, 20 and 30% glycerine in Trail 2 (Table 3). Pigs fed 5 and 10% glycerine had an increased daily weight gain and they concluded that the sweet taste and the better feed structure of diets with glycerine supplementation was the reason for the higher feed intake in the groups with a glycerine supplement. A diet containing 30% glycerine resulted in the only feed conversion ratio that was significantly different from all other groups (Table 3). Kijora *et al.* (1995) found that glycerine in the diets did not change the carcass yield or the meat quality and pathological changes in the liver and kidney of the pigs were not found after feeding glycerine. They concluded that amounts of glycerine up to 10% in the diet are recommended.

Table 3 The dry matter intake, daily live weight gain and feed conversion ratio for pigs feed glycerine at varying levels in two trials.

	DM intake (kg)	Daily weight gain (kg)	Feed Conversion ratio
Trial 1 (average weight: 32kg)			
Control	1.98	0.631	3.14
5% glycerine	2.17	0.719	3.02
10% glycerine	2.23	0.745	2.99
Trial 2 (average weight: 31.2kg)			
Control	2.26	0.731	3.09
5% glycerine	2.44	0.770	3.17
10% glycerine	2.54	0.819	3.10
20% glycerine	2.32	0.704	3.30
30% glycerine	2.37	0.598	3.96

Source: (Kijora *et al.* 1995)

Kijora and Kupsch (1996) investigated the utilization of ‘crude’ and ‘pure’ glycerine (from biodiesel production with a dry matter of 77.6% and 99.7% and ash content of 18.7% and 4.8%, respectively) as a feed component in an experiment using 6 x 6 barrows (Pietrain x F1). The control diet contained no glycerine and the five other diets were supplemented with either 5 or 10% glycerine. Feed intake of pigs in the growing period was elevated by 7.5% in all groups that received glycerine compared to the control group. The improvement in the daily gain depended strongly on the actual intake of glycerine in this growing period and this effect wasn’t observed in the finishing period. The dietary treatments did not have any significant effects on meat quality.

Kijora (1997) completed a feeding experiment to determine the utilization of supplemented plant oil or free fatty acids in comparison with free fatty acids and glycerine. Five groups of six barrows (27 kg average body weight at the beginning) received the experimental diets for 14 weeks (Table 4). Pigs fed the basal diet plus 10% glycerol had the highest feed intake and daily weight gain. In terms of the feed conversion ratio, there was no significant difference between groups. Incorporation of glycerine in the diet appeared to decrease back-fat thickness and the palmitic acid and stearic acid contents were higher in pigs that were not fed additional fat (Kijora 1997).

Table 4 The daily live weight gain, percentage fatty acid in the back-fat and metabolisable energy increase compared to Group1 for pigs fed various diets.

	Daily weight gain (kg)	Polyenoic FA in back-fat (%)	ME increase compared to Group 1
Group 1	0.74	9.5	
Group 2	0.79	8.0	
Group 3	0.78	15.5	7.1% increase
Group 4	0.74	15.3	5.8% increase
Group 5	0.75	16.8	7.1% increase

Group 1: barley-soya meal (basal diet)

Group 2: basal diet+10% glycerine

Group 3: basal diet+3.2% fatty acids

Group 4: basal diet+2.4% fatty acids+0.8% glycerine

Group 5: basal diet+3.2% vegetable oil

Source: (Kijora 1997)

The sweet taste of glycerine promotes feed intake and average daily gain in swine and poultry diets (Doppenberg and Van Der Aar 2007). Given the current level of research, Doppenberg and Van Der Aar (2007) suggested that the maximum inclusion of glycerine for grower/finishing pigs should be 5%. Even so, studies reported by Best (2006) have indicated that up to 10% glycerine in the diet has shown a positive impact on feed intake and daily weight gain in pigs. The size and weight of pigs referred to in these studies were not reported in the article.

Lammers *et al.* (2007b) undertook a study aimed at comparing growth and performance of pigs of mixed gender, 21 days of age and weighing 7.9±1.2 kilograms when fed varying levels of crude glycerine. Groups of pigs were assigned to one of three isocaloric and isolysinic diets fed *ad libitum* and containing 0, 5, or 10% glycerine respectively. They found that crude glycerine can be fed to young pigs without altering growth and performance of the animal.

Lammers *et al.* (2007a) conducted two studies to find the apparent digestible energy (DE) value of crude glycerine, (as a co-product of biodiesel production). In the first study, 24 barrows with an average body weight of 11.0 ± 0.5 kilograms were fed 376 grams/day of a basal diet combined with 0, 19, 38, or 75 grams/day of crude glycerine. In the second study, 23 gilts with an average bodyweight of 109.6 ± 5.5 kilograms were fed 2.29 kilograms/day of a basal diet combined with 0, 115, 229, or 458 grams/day of crude glycerine. The apparent digestible energy (DE) value of crude glycerine was found to be 3386 ± 149 kilocalories/kilogram (14.16 ± 0.62 MJ/kg) for starter pigs, and 3772 ± 108 kilocalories/kilogram (15.77 ± 0.45 MJ/kg) for market pigs. Given that the gross energy of crude glycerine evaluated in this experiment was 3625 ± 25 kilocalories/kilogram (15.16 ± 0.10 MJ/kg), it was not significantly different ($P = 0.02$) from these DE values (Lammers *et al.* 2007a). The authors noted that the energy value of crude glycerine may be a function of glycerine purity and that the levels of methanol, sodium chloride, and potassium chloride (compounds that can be found in crude glycerine as a result of current biodiesel processing techniques) must be monitored to prevent excessive amounts in pig diets. This should form a key part of any quality assurance monitoring for using glycerine in diets for pigs in Australia.

Doppenberg and Van Der Aar (2007) proposed that glycerine added to the diet of finishing pigs increases the moisture holding capacity of pork produced from these pigs and this is of value to meat processors. Mourot *et al.* (1994) also suggested that dietary glycerine could increase the water holding capacity of muscles in pigs and hence provide a decrease in muscle drip and cooking losses.

Doppenberg and Van Der Aar (2007) suggested that glycerine may be most useful in diets prepared for lactating sows because it helps to prevent an excessive loss of backfat, enables better use of amino acids and reduces protein metabolism so increasing milk production, milk protein content and fertility.

5.3. Potential disadvantages of glycerine in pig diets

Glycerine is absorbed efficiently in the gut but at high inclusion rates in swine this efficiency decreases, possibly because the enzymatic activation of glycerine by glycerol kinase to glycerol-3-phosphate limits absorption and excess glycerine is then excreted via the urine (Doppenberg and Van Der Aar 2007).

Goold *et al.* (1976) found that increasing levels of low glucosinolate (below 9%) rapeseed meal in the diet of pigs did not significantly affect voluntary feed intake, food conversion ratio, growth rate or dry matter digestibility. However, they found that food wastage significantly increased as the level of rapeseed meal in the diet was increased from 1.5 to 9.0% and the diet became less acceptable to young pigs. It is not evident in the literature whether glycerine derived from such sources such as rapeseed or canola would have a similar effect.

5.4. Glycerine in poultry diets

As reported by Best (2006), the theoretical metabolisable energy (ME) value of glycerine based on its gross energy content is 18.06 MJ/kg. Best (2006) also reported that ME figures obtained *in vivo* in poultry were around 17.5 MJ/kg indicating utilization efficiency of more than 96%. Ileal digestibility exceeded 97% in poultry (Best 2006). Used as an energy source, glycerine can be oxidized giving a yield of 22 moles ATP/mol (Doppenberg and Van Der Aar 2007).

Cerrate *et al.* (2006) suggested that glycerine produced as a by-product in the manufacture of biodiesel can be a useful energy source for use in broiler diets but noted that there are concerns regarding acceptable levels of residual methanol produced during the manufacturing process. In a University of Arkansas, Division of Agriculture media release written by Miller (2006), research done by Park Waldroup, Professor of Poultry Science, suggested that glycerine can be used as a dietary supplement for providing energy in typical USA broiler diets. Findings from this research indicated that they could feed up to 10% glycerine to chicks up to 16 days of age without impairing performance and 5% glycerine to diets for chicks grown to market age without detrimental effects on feed intake. It would appear that glycerine is a safe feed source for poultry and a pure calorie source that can provide energy for maintenance and growth without any adverse effects on meat quality (Miller 2006). However, additional research is needed to evaluate quality issues associated with its use and effects on feed texture and pellet quality (Miller 2006).

5.5. **Glycerine in ruminant diets**

Schröder and Südekum (1999) explored the possibility of using glycerine in diets for ruminants and concluded that the glucose precursor, glycerine, is an excellent feed constituent, even when included in an impure form. Glycerine may be included as an ingredient in mixed rations or pelleted concentrates where it may contribute to the hygienic quality of the feed (Schröder and Südekum 1999). The same authors concluded that glycerine of different purities can replace rapidly fermentable starches in diets for ruminants, up to concentrations of 10% of the diet dry matter, without negatively affecting feed and water intake, ruminal nutrient degradation and whole-tract nutrient digestibilities. They also recommended that economic assessment will be important if glycerine is to be included as a dietary ingredient for ruminants.

According to DeFrain *et al*. (2004) glycerine can alleviate the symptoms of ketosis when delivered as an oral drench to cows. Furthermore, they suggested that adding glycerine to the diet would eliminate the need for restraining cows for drenching yet would still deliver a glucogenic substrate, alleviate the fatty liver-ketosis complex, and improve lactation performance. Furthermore, Doppenberg and Van Der Aar (2007) proposed that propylene glycol (1,2-propanediol) can be replaced by glycerine (1,2,3-propanetriol) during the transition period of dairy cows so increasing lactose and milk production.

Pethick *et al*. (1999) suggested that supplementing the diet of sheep with a glycerol compound could improve meat quality. Initial observations from their study indicated that a mixture of glycerol and propylene glycol (3.5% and 1.5% respectively) doubles the water intake of lambs, although they implied that the ability of 'in feed' or oral carbohydrate sources which cause hyperglycemia to stimulate glycogen repletion in muscle requires further testing.

6. Biodiesel and glycerine in the global market

6.1. **Global energy sources**

Oil, synthetic crude oil (oil sands; extra heavy crude oil; shale oil), synthetic fuels (coal to liquids; gas to liquids), renewable biofuels and other energy sources such as thermal coal, all compete for space in the global energy market. Biofuels, such as ethanol and biodiesel, comprise less than 1% of global oil consumption (ABARE 2006). Ethanol is the most widely used renewable biofuel. However, over the past 10 years, acceptance of biodiesel as an alternative energy source has gradually increased.

6.2. Biodiesel production

Bender (1999) found that in 1998, Austrian government subsidies enabled some farmers to produce canola on set-aside land for biodiesel and by-product meal cake at almost no net cost to the farmers. However, he concluded that biodiesel was not economically feasible, and more research and technological development was recommended.

According to Passey (2002), biodiesel in 2002 was gaining worldwide acceptance especially in the USA and Europe. However, in Australia it was still considered a fledgling industry with future production being limited by factors such as provision of suitable feedstocks (oils and alcohol) from plant and animal sources. In virtually all countries in the world that have established a biofuels industry, government initiatives through legislation and financial incentive have been deemed necessary to encourage private industry to make significant investments in the manufacture of bioethanol and biodiesel (Hamilton 2004).

Globally, the largest two producers of biodiesel are the European Union (EU) and the USA, where significant investment and supportive government policies, including tax incentives and mandatory targets, have been implemented (ABARE 2006). There are 65 operational biodiesel plants operating in the USA with 50 plants under construction and a further eight are expanding operations (ABARE 2006).

Over 75% of total European biofuel production is biodiesel (Biofuels Taskforce 2005). Production in the EU increased from 1.9 million tonnes in 2004 to 3.1 million tonnes in 2005 with further growth of up to 6 million tonnes expected in the short term (ABARE 2006). In 2006-07, world demand for oilseed products is forecast to continue to grow strongly largely due to increasing demand for vegetable oils in industrial uses such as production of biodiesel (Lawrance 2006). Furthermore, there are predictions that output will increase by another 50% by 2010 resulting in extensive amounts of glycerine emerging in Europe (Best 2006). The Malaysian Government has approved 32 biodiesel related projects that are expected to produce 3 million tonnes of biodiesel (Lawrance 2006). Biodiesel is produced from a variety of feedstocks, including soybean oil (mainly used in the United States), palm oil (Malaysia) and rapeseed and sunflower oil (Europe) (ABARE 2006), and hence a large proportion of the resulting glycerine may be suitable for the animal industries. There is concern though that in order to supply the growing demand for high-oil-yielding crops for biodiesel production, palm tree plantations in developing parts of the world will expand so taking over native rainforests and other habitats (Kotrba 2006).

Biodiesel has only recently been made commercially available in Australia. As of August 2005, there were 10 licensed producers of biodiesel who collectively produced around 1 ML in 2003–04 (Biofuels Taskforce 2005). In 2005, biodiesel capacity was estimated to be around 15.5 ML per year with a short-to-medium term increase of 508 ML expected by mid 2007 and then it is thought that production will remain static until 2010 (Biofuels Taskforce 2005) (Table 5).

Table 5 Current (as of 2004-05) and proposed biodiesel production capacity, 2005-06 to 2009-10 (ML).

Biodiesel capacity	**2004–05**	**2005–06**	**2006–07**	**2007–08**	**2008–09**	**2009–10**
Biodiesel Industries Australia, Rutherford	0.5	20	20	20	20	20
Australian Biodiesel Group, Berkeley Vale NSW	15	40	45	45	45	45
Biodiesel Producers Australia	0	0	60.2	60.2	60.2	60.2
Australian Renewable Fuels, Adelaide SA	0	44.7	44.7	44.7	44.7	44.7
Riverina Biofuels	0	0	44.7	44.7	44.7	44.7
Australian Renewable Fuels, Picton WA	0	0	44.5	44.5	44.5	44.5
AJ Bush	0	0	60	60	60	60
Australian Biodiesel Group Queensland	0	0	40	40	40	40
Natural Fuels	0	0	150	150	150	150
Australian Farmers Fuel	0	0	15	15	15	15
Total biodiesel	**15.5**	**104.7**	**524.1**	**524.1**	**524.1**	**524.1**

Source: (Biofuels Taskforce 2005)

Australia's largest biodiesel refinery is owned by Natural Fuels Australia Limited (NFAL) and is located in Darwin (Francis 2006). NFAL plan to annually produce 147 million litres of biodiesel and 14,000 tonnes of pharma-grade glycerine (99.5%) (Selwood 2006). As NAFL plan to produce pharma-grade glycerine with Kosher certification, animal fats and used cooking oils will not be used as the feedstock but rather palm oil produced according to strict principles and criteria for sustainable production of palm oil (Selwood 2006). In searching through the literature there was no evidence of research having been done on the feed value of glycerine derived through the processing of palm oil. Clearly though if large amounts of glycerine from this source is to become available in Australia, then research should be instigated to assess its potential in diets for pigs.

According to Francis (2006), NFAL is committed to developing refineries at Botany Bay in NSW and in Singapore with plans to develop other refineries in Houston, Holland and Malaysia. NFAL also have soybean trials in the Northern Territory with the expectation that soy beans can support two industries including meal for livestock feed and alternative fuels.

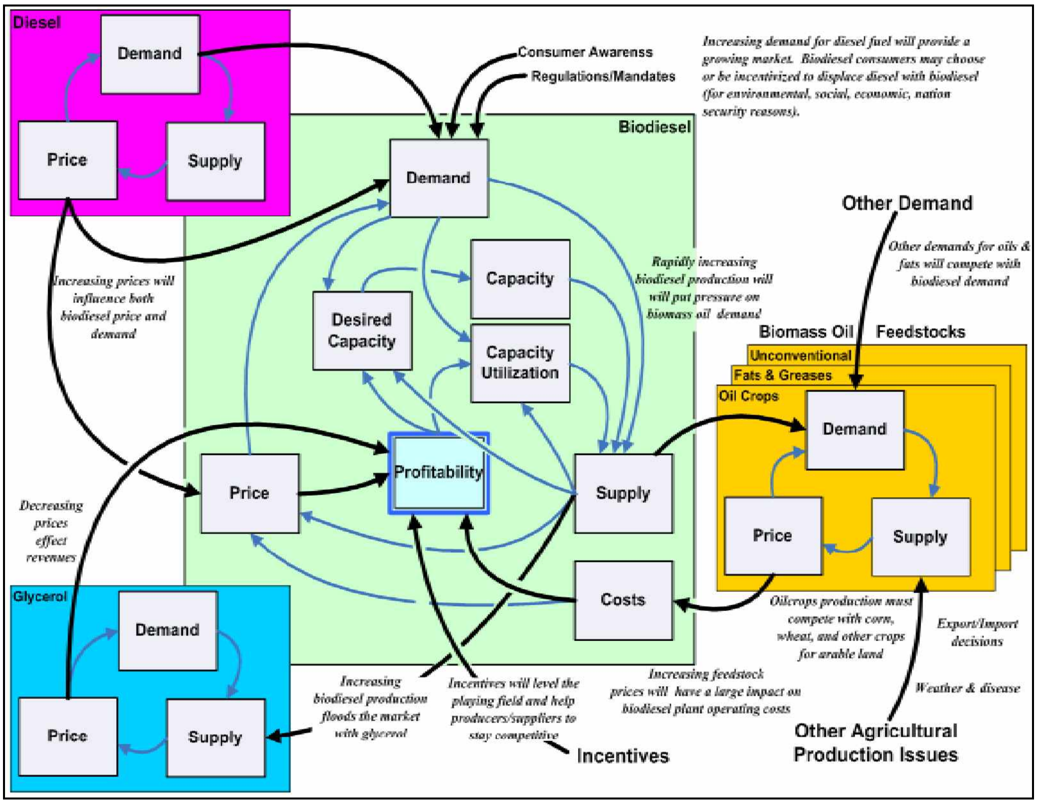
Conaghan (2006) reported that the cooperative, Northern Diesel Company in Western Australia, is successfully producing biodiesel from canola oil that is creating 70% less emissions than standard mineral diesel, is easier on engines and improves engine torque. For every tonne of canola, 400 kilograms is converted into oil and 600kg into canola meal (Conaghan 2006). The canola meal fetches around $300 a tonne as a high-protein feed but should biodiesel production increase this price may drop due to the maximum requirements in the diet being not more than 10% for sheep and cattle (Conaghan 2006). This may have positive ramifications for pig producers who also use canola meal in their diets. No mention was made in Conaghan's report regarding the use of the glycerine produced as a co-product. However, given a drop in meal prices, biodiesel producers may actively seek out markets for glycerine so that they have an additional revenue source.

Biodiesel production will be variable in quality and quantity until the industry stabilizes. According to Anon (2006b), Australian Biodiesel Group has ceased production at its Berkeley Vale plant following a $13.4 million loss for 2006 reportedly due to lower biodiesel sales than expected, the negative implications associated with the revision of the Federal fuel excise, the declining oil price, rising feedstock costs resulting from the drought and delays in achieving production efficiencies.

6.3. Future viability of the biodiesel industry

Investors in a biofuel processing facility face three major risk factor categories: (1) processing technology risks, (2) marketing and operation risks, and (3) government and regulatory risks (DAF 2006). Processing technology risks can be possibly minimized with good management. However, marketing and operation risks are more significant. Increases in input prices and (or) decreases in output prices (biodiesel and glycerine) potentially will decrease profit. The biofuels industry is currently a highly regulated industry that depends upon government policies and hence changes in these policies can increase or decrease biodiesel production (DAF 2006).

Bantz and Deaton (2006) showed the interconnections between biodiesel and other markets such as those for diesel, biomass oil, feedstocks, and glycerine (Figure 4). For example, with regard to feedstock availability and pricing, the biodiesel industry often competes with the food industry for feedstocks like soy oil, and hence this competition increases the cost and tightens availability of such oils (Kotrba 2006).



Source: (Bantz and Deaton 2006)

Figure 4 A biodiesel market overview showing the interconnections between biodiesel and other markets including diesel, biomass oil, feedstocks, and glycerine.

Hamilton (2004) proposed that biodiesel based upon vegetable oil sources would not be economic without some degree of excise relief, whilst biodiesel based on animal oils and (or) recycled oil are more likely to be viable operations without government support. Reflecting the combined effect of high world oil prices and government assistance to the industry, the rates of return potentially obtainable from biodiesel production are currently high but appear likely to fall significantly in the long term as world oil prices moderate, and as assistance to producers is reduced over the period July 2011 to July 2015[2] (Biofuels Taskforce 2005). Based on a 2005 study presented in Biofuels Taskforce (2005), new biodiesel production in Australia appears economically unviable in the long term although benefits accruing to the production of glycerine were not included in this analysis.

It was argued at a Western Australian State Government Assembly on 14 September 2005 and reported in WA Gov (2005), that net biodiesel production costs were estimated to be

[2] A fuel tax of 38.143c/L is applied to biodiesel, but imported and domestically produced biodiesel receive equivalent production grants—offsetting fuel tax until 1 July 2011, when an effective fuel tax will begin to be applied incrementally to these fuels (DAF 2006). The final fuel tax rates (net of production grants) will be 19.1c/L for biodiesel in 2015 (a 50% discount to the full energy content fuel tax rates) (DAF 2006).

below the cost of diesel. However, Kingwell and Plunkett (2006) suggested that currently, the economics of biodiesel production based on canola are unfavourable in most circumstances. They reasoned that diesel prices are not yet high enough to justify most individual farmers investing in their own on-farm production of biodiesel from canola. Nevertheless in the near term, especially if fuel prices continue to rise, it is conceivable that an economic case for biodiesel production could be made, especially in regions where fuel will become increasingly expensive (increasing by a further 15 to 30 cents per litre), where economies of size and capital sharing advantages could be on offer and (or) where cheap feedstock such as an improved industrial oilseed is available or is likely to be developed (Kingwell and Plunkett 2006). If smaller processors could viably supply pig producers in the Australian grain growing areas with glycerine then this could be an alternative feed source for pigs.

Production costs in the USA range from around US$0.80 a gallon (AUS$0.22/L)[3] for biodiesel from waste grease to US$1.14 a gallon (AUS$0.32/L) for biodiesel from soybean oil (ABARE 2006). The Biofuels Taskforce (2005) reported that at a *long-term* exchange rate of US$0.65, the required world oil price (West Texas Intermediate) would need to be between US$52 to 62 per barrel before biodiesel production in Australia would be a viable alternative (given no Government assistance and depending on feedstock). With government assistance, the price of oil would have to be between US$35 and US$45 per barrel.

The price of oil is hovering around the US$60 per barrel and with time, biodiesel production costs in Australia will decrease to at least mirror those of the USA. Costs for biodiesel production are directly influenced by feedstock considerations that account for about two-thirds of total production costs and may include variability in quality and chemical content, availability, flexibility to increase supply and cost of transport and pre-treatment (Alberta Gov 2007).

Canola (including varieties that may be genetically modified), mustard, safflower, mustard hybrids (not edible) wild radish (not edible) Australian corn, fats and tallows, oil trees, rice bran and algae may all be sources for biodiesel (Hobbs 2003). Global supplies of oilseeds are forecast to remain largely unchanged in 2006-07 while increased demand for oilseeds and oilseed products will result in an increase in the price of oilseeds by around US$18 to an average of US$279 a tonne (Lawrance 2006). Australian canola prices are also forecast to increase in 2006-07, by AUS$55 a tonne to an average of AUS$427 a tonne for the year (Lawrance 2006). In August 2006 the price of palm oil was 23 % higher than in August 2005. For soybean oil, the price in August 2006 was 17% higher than in August 2005 and for canola oil the price in 2006 was 26% higher than twelve months earlier (Lawrance 2006).

The potential increase in costs of production may be off-set to some extend by increases in demand for biodiesel fuel. In Australia, there is a concentrated push for increased uses of ‘green’ fuel. Fuel made from vegetable oil has a number of distinct advantages over fossil fuel primarily because it is renewable and has positive environmental benefits (Hobbs 2003). Increases in biodiesel growth in Australia may occur due to occupational health and safety and environmental requirements and as such B5 (5% biodiesel blend) is likely to be the preferable delivery mechanism for biodiesel into the retail fuel market (DAF 2006).

---

[3] 1AUD = 0.7814 USD (RBA 2007)

Depending on the source of the oil or fat used in the production of biodiesel a greenhouse benefit of between 30 and 90% can be obtained with emissions having up to a 90% reduction in particulates and other carcinogenic components, along with a 50% reduction in carbon monoxide and unburnt hydrocarbons (Lake 2007). In a life cycle study of the energy balance of biodiesel, the USA Department of Energy and USA. Department of Agriculture found that for every one unit of fossil energy used in the biodiesel production cycle, 3.2 units of energy are gained when the fuel is burnt (Alberta Gov 2007). That is, a positive energy balance of 320% compared to ethanol representing only a 34% energy gain (Alberta Gov 2007).

Both government and industry recognise the benefits to be gained from renewable fuels and believe the additional cost is affordable in order to secure the long term future supply of transport fuels and an improved environment (Hamilton 2004). In 2003, the Australian government announced that it would fund a capital subsidy program at a rate of 16c/L of additional capacity to viable projects producing a minimum of 5 ML of biofuels (DAF 2006). In terms of biodiesel, Biodiesel Industries Australia (Rutherford, New South Wales) received $1.28 million for 8 ML; Biodiesel Producers Ltd (Barnawatha, Victoria) were granted $9.6 million for 60 ML; Australian Renewable Fuels Pty Ltd, (Port Adelaide, South Australia) gained $7.15 million for 44.7 ML; and Riverina Biofuels Pty Ltd, (Deniliquin, New South Wales) received $7.15 million for 44.7 ML (DAF 2006).

Furthermore, Premier Rann announced that by 1st March 2005, all South Australian metro trains and diesel buses will operate using 5% biodiesel, with the proportion to be increased progressively to 20% (Biofuels Taskforce 2005). On 14th September 2005, Mr D.T. Redman put forward to the Western Australian Government Assembly, the following motion, “that this house calls on the State Government to implement a task force to investigate the opportunities in Western Australia to develop a biofuels industry”. The motion was debated and supported by the house (WA Gov 2005). Moreover, the Australian Government has set a target of 350 million litres of biofuel (ethanol and biodiesel) by 2010 with an effective excise relief on biodiesel until 2011 (Selwood 2006). In 2006, manufacturers could claim a renewable fuels grant equal to the excise on fuel of 38.14 cent per litre, but this amount will decrease by 50% between 2011 and 2015 (Whittington 2006).

Hence the prospects for biodiesel expansion globally and more specifically in Australia are improving and technological advances will follow. Investigations are underway in many countries looking at alternative crops with biofuel potential. Shokes *et al.* (2006) for example, have suggested that winter-type canola varieties could replace wheat in a soybean-wheat-corn rotation in Virginia USA, while summer types are under development and could replace soybean in the rotation.

6.4. Manufacturing glycerine

Growth of oleochemical plants in Southeast Asia that produce glycerine as a byproduct from production of fatty acids, fatty alcohol, and soap, as well as growth in biodiesel production mainly in Western Europe has contributed to an excess in global supply of glycerine (UCAP 2006). The increasing production of glycerine and growth of bio-diesel plants has resulted in an abundant supply of glycerine leading to a price decline (Frost and Sullivan 2006). As a consequence, traditional glycerine plants are closing and other plants that use glycerine as a raw material are opening (McCoy 2006).

As a co-product from biodiesel production, Potter and McCaffery (2006) suggested that glycerine produced from small scale plants will have little or no value due to difficulties in marketing small amounts of glycerine. Processing crude glycerine is costly and generally out of the range of economic feasibility for small to medium-sized plants (Biodiesel TechNote 2006). In 2003, Symex Holdings had the only glycerine refinery in Australia with production estimated at 8,000 tonnes per annum (Toohey *et al.* 2003). However, crude glycerine can be used in animal feed and hence costs associated with processing are expected to be minimal.

6.5. Competition for glycerine from other industries

The price of glycerine[4] has declined and thus its range of uses is widening and industry is looking for new avenues for glycerine consumption (Frost and Sullivan 2006). Solvay are building a new plant to produce epichlorohydrin for use in epoxy resins, paper-reinforcing agents, and other products; Archer Daniels Midland plan to make propylene glycol from glycerine, instead of propylene oxide; Dow Chemical closed its glycerine plant in Freeport, Texas in early 2006 although still operates a plant in Germany; Procter and Gamble Chemicals shut its natural glycerine refinery in England in early 2006 (McCoy 2006). Hence some suppliers of refined glycerine may be moving out of the industry so freeing up crude glycerine. However, demand for crude glycerine may also be increasing in new industries that require it as an input. Consequently, the price of glycerine is likely to be relatively volatile in the short to medium-term until the industry stabilizes.

Glycerine derived as a biodiesel co-product has more than 1,500 uses with the main uses being in candy, cake mixes, medicines, lotions, shampoo, soaps, detergents and makeup and also increasingly so for industrial uses such as in emollients, lubricants, solvents and chemical-dispersing products (Lemke 2006). Rigorous development in science and technology has provided multi-faceted applications for glycerine ranging from personal care to technical applications (Frost and Sullivan 2006). Glycerine and other oleochemicals may have long-term potential as substitutes for petrochemical-sourced chemicals used in dispersants, cleaning aids and solvents and in replacing ethylene glycol in anti-freeze, monopropylene glycol in animal feeds and polyols in coatings resins (Milmo 2005). US companies, AURI and Central Bi-Products, are working on a patented process that uses glycerine to increase feather-meal density so the feed ingredient can be shipped farther to more markets (Lemke 2006).Increased biodiesel production and surplus glycerine supply is expected to result in innovative products incorporating glycerine in for example, plastics, agrochemicals, solvents, lubricants and additives (Alberta Gov 2007).

Larger scale biodiesel producers refine their crude glycerine and move it to markets in the food, pharmaceutical, and cosmetic industries (Biodiesel Technote 2006). Until recently, due to its high price, glycerine has been used entirely in these industries (Best 2006).

Crude glycerine is usually designated for the plastics and alkyd resins markets (Bonnardeaux 2006). Glycerine used for industrial uses does not require as much refining as it does for food or personal products and it can sell for around half the price of refined glycerine (Lemke 2006). In Western Australia, glycerine is currently being trialed by the Department

[4] Described in more detail in the section “Glycerine price” below

of Agriculture and Food for its potential to ameliorate non-wetting sands and if successful this could provide a use on farm without the need for further processing for sale (Whittington 2006).

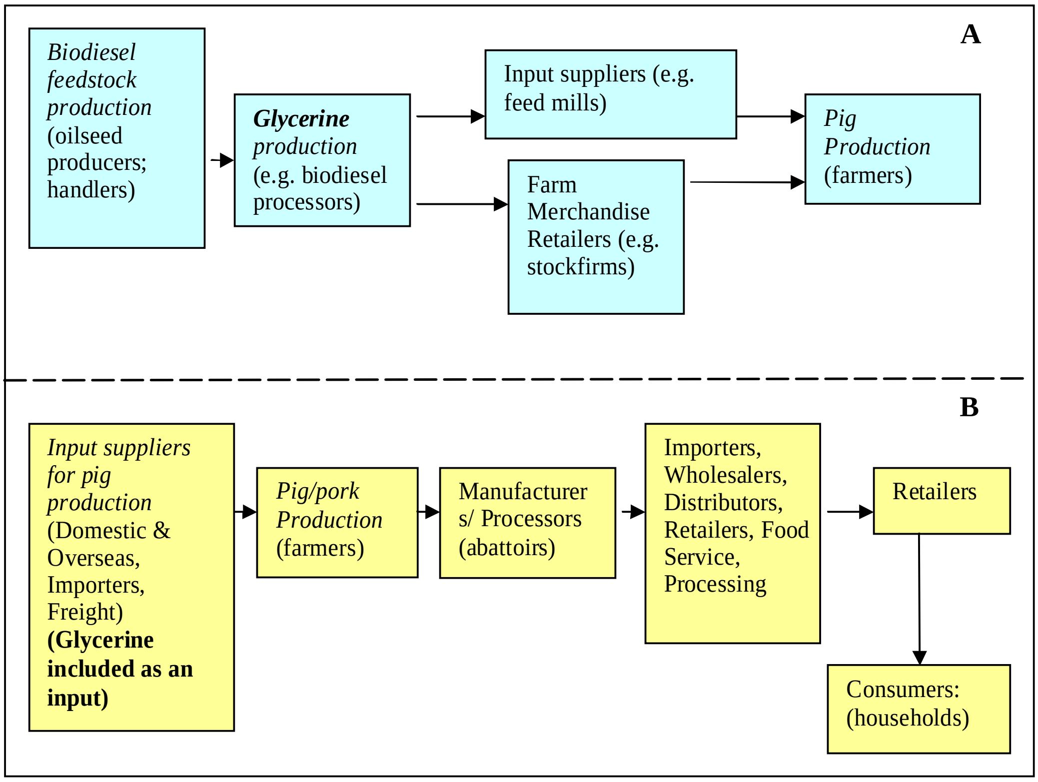
In the past, the company Solvay has been using epichlorohydrin to produce synthetic glycerine, but at present demand for synthetic glycerine has dropped due to the abundant supply of glycerine from oleochemical and biodiesel sources (Frost and Sullivan 2006). This oversupply of glycerine has led Solvay to reverse the traditional process and use glycerine as a raw material to produce epichlorohydrin, which is a fast growing chemical employed in the production of epoxy resins (Frost and Sullivan 2006). The glycerine used will be sourced from rapeseed feedstock and Solvay has entered into a contract with the French biodiesel producer Diester Industrie to supply the required glycerine (Frost and Sullivan 2006).

7. Glycerine supply, handling and availability

The availability and volume of glycerine as a co-product from biodiesel processing and its suitability for use in animal feeds will depend on several factors. Such factors may include the price of other energy sources for animal feed, supply of the inputs required to produce the biodiesel, glycerine storage and handling costs and the attitude of society towards climate change and global warming.

7.1. Possible supply chains for the pork industry

A pork supply chain stretches from ‘paddock to plate’ via feed growers, stockfeed millers, pig producers, processors and retailers to the consumer (Hargreaves 1999). Predominately these chains are driven by what the consumer wants (Hargreaves 1999). Hamilton (2004) acknowledged that it is important to ensure the product meets the required specification, and particularly with biodiesel this depends upon the nature and quality of the feed material. Assuming that glycerine is produced from feedstock acceptable in the animal industries and is not contaminated with hazardous components that may be introduced during processing, it will be totally acceptable as an input into animal diets. As it may have beneficial qualities (e.g. for animal or human health), marketing at various stages in the supply chain may be beneficial for the industry. More specifically, and based on Rola-Rubzen (2005), supply chains for glycerine becoming an input into pig/pork production can be depicted as in Figure 5. It is noted though that farmers growing for example canola could have the oil extracted and produce biodiesel and glycerine on their properties and feed the glycerine directly to livestock.



Based on: (Rola-Rubzen 2005)

Figure 5 Supply chains for glycerine entering the pork supply chain with *Chain A* showing production of glycerine to its use by farmers and *Chain B* indicating how glycerine is part of the larger chain from input suppliers to consumers.

Being a rural industry it is important that road access, labour, water and power are available for a viable glycerine production (Hamilton 2004). Such requirements are essential if the supply chain in Figure 5 is to function.

Having a financial arrangement between a number of sectors is not common in the pig industry but more sectors are initiating arrangement with benefits to all members, particularly during tough economic times (Hargreaves 1999). The need to survive means that effective pork supply chains must be established leading to increased efficiencies and decreased costs throughout the chain (Hargreaves 1999). There must be trust between chain members, agreement on sharing costs and gains, openness and reliability, balance in power between the links, good communication up and down the chain and the competence to manage the overall partnership (Hargreaves 1999). Cargill (2007) claims to be one of the largest producers of biodiesel in the USA with additional facilities around the world. With economies of scale, Cargill (2007) noted that they can provide supply chain consultation to make a biofuels business efficient and help to bring producers and their refining and blending customers together to market their biodiesel. Cargill (2007) reported that as a global leader in the marketing and producing of feed ingredients they can offer biodiesel producers a conduit for marketing glycerine.

7.2. Handling and storage issues

As Best (2006) reported, glycerine may be used in pellet production to assist in dust control and as a feed preservative. It may also help in maintaining textures and adding humectancy, control water activity and prolong shelf life in feeds (Frost and Sullivan 2006) because it inhibits mould growth (Doppenberg and Van Der Aar 2007).

The following description of handling and storage of glycerine is based on Dow (1999a). Glycerine will react with many compounds, including acids, isocyanates, chlorine and oxidizing agents and hence storage and handling equipment should be installed to avoid possible cross-contamination with other materials. Bulk storage and loading equipment should be designed to allow for periodic emptying and cleaning. New equipment should be hydrostatically tested prior to use. To ensure product quality, it is recommended that only dedicated equipment be used to store glycerine. For glycerine storage tanks stainless steel is recommended but fiberglass and plastic, of such quality that it doesn't have any adverse effects on quality, can also be used.

Bulk storage and loading areas should have easy access for tank trucks and maintenance equipment. Glycerine storage tanks should be designed to eliminate significant product residue after draining in order to facilitate cleaning. To ensure product quality, glycerine should never be mixed with other products and all piping should be dedicated for glycerine only. Filter elements can be constructed of cotton, polyester, polypropylene, nylon or stainless steel screen with element pore sizes of 10 to 75 microns being recommended. Hoses should be made of reinforced elastomer with cross-linked polyethylene liner or of flexible corrugated stainless steel. Welded seamless pipe is also recommended. Valves should be placed to allow easy access and operation. Glycerine flows well at temperatures of 32 to 49°C so if piping is located where ambient temperatures can fall below 17°C then tracing and insulation should be used. Any pipe heating system should have an upper limit to prevent excess temperatures above 54°C so as not to cause degradation of glycerine. For normal operations, a centrifugal pump is recommended for use with glycerine.

Glycerine is hygroscopic and hence bulk storage tanks should use nitrogen padding or air dryers to prevent moisture accumulation. Bulk storage facilities may need provisions for heating of the product if located in cold regions but care must be used when heating glycerine to avoid heat degradation of the product, as temperatures above 54°C (130°F) can cause accelerated degradation. The freezing point of glycerine is 17°C but as glycerine has the characteristic of supercooling it can remain in a liquid state even below its freezing point. However, to avoid unexpected crystallization, glycerine should be stored above 17°C. A self-cleaning white paint exterior is recommended on glycerine tanks to minimize the internal temperature changes that occur during 24-hour cycles. The reduced expansion and contraction of the contents (breathing) will decrease the demand for nitrogen or dry air.

Dow (1999b) provided a detailed description of safety issues to be considered when handling glycerine as summarized below. One of the desirable qualities of glycerine is its ease of handling from a personal safety viewpoint. A single prolonged exposure to glycerine is not likely to be absorbed in significant amounts through the skin and so is not likely to cause significant irritation. Glycerine can be removed by washing with water. It's important to note that if glycerine degrades forming by-products, the by-products will have different toxicological and physical properties from glycerine itself. To minimize quality degradation, glycerine should be used and stored below 54°C. In the presence of powerful oxidizing agents such as sodium hypochlorite or hypochlorous acid, a violent reaction may occur.

7.3. Where in Australia glycerine will be available

In Australia, glycerine will be available within the vicinity of biodiesel plants and further afield depending on the supply chain associated with that source, and location of feed manufacturers. Transport routes and other infrastructure are relatively advanced in Australia and hence should not impact negatively on the supply of glycerine.

Recent increases in crude oil prices and resultant petrodiesel prices have escalated interest in biodiesel and accelerated the number of production plants in Australia. GRDC (2006 summarised the production facilities, capacity of the plants and feedstocks used (Table 6).

Table 6 Biodiesel production capacity in Australia: short-term outlook[1].

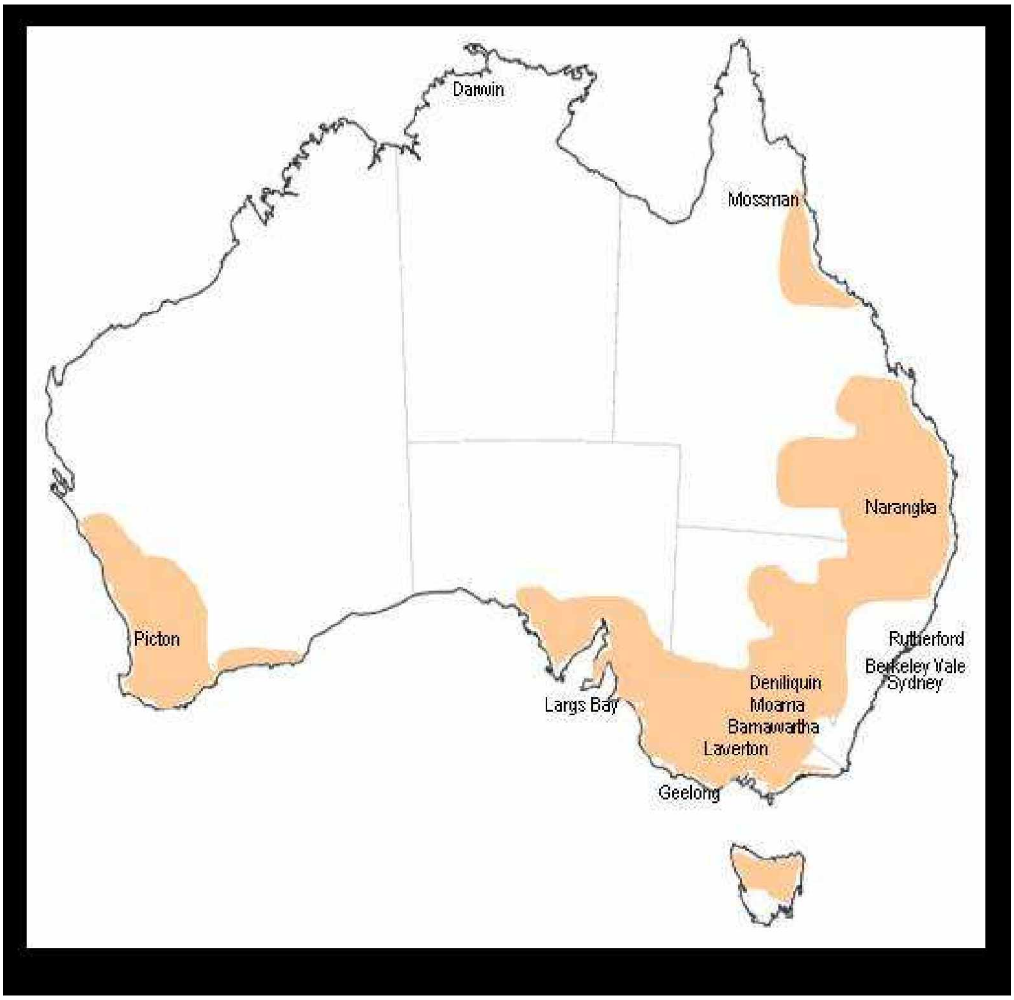
Production facility/location	Capacity ML/yr	Startup	Feedstocks	Feedstock use kt/yr
Biodiesel Industries Australia, Rutherford, NSW	12[2]	Mar 2003	Mostly used cooking oil; canola oil	11
Australian Biodiesel Group, Berkeley Vale, NSW	45	2002	Mostly used cooking oil; tallow; canola oil	40.5
Australian Biodiesel Group, Narangba, Qld (Brisbane)	160	Jul 2006	Mostly tallow; canola oil; cotton seed oil	146.7
Biodiesel Producers Limited, Albury, NSW	60.2	Mid 2007	Tallow; used cooking oil	55
Australian Renewable Fuels, Largs Bay, SA (Adelaide)	45	Mar 2006	Canola oil	40
Australian Renewable Fuels, Picton, WA (Bunbury)	45	Jul 2006	Canola oil	40
Axiom Energy, Geelong, VIC	150	Mid 2007	Used cooking oil; tallow; palm oil	135
Natural Fuel Limited, Darwin, NT	140	End 2006	Palm oil; soybean oil	130
South Australian Farmers Fuel, Millicent, SA	5	End 2006	Canola oil	4.4
Riverina Biofuels, Deniliquin, NSW	44.7	2007	Tallow	40
Eco-Tech Biodiesel, Narangba, Qld (Brisbane)	30[3]	May 2006	Mainly tallow; used cooking oil	28

[1]Based on a review of the projects listed in the Biofuels Taskforce Report and recent announcements. Not all proposed projects may be included
[2]Could be expanded to 40 ML
[3]Could be expanded to 75 ML

Source: (GRDC 2006)

In addition, according to Anon (2006a), Vilo Assets Management has a 50 million litre biodiesel production plant at Laverton in Victoria. Future Fuels at Moama in NSW are producing 30 million litres annually. Evergreen Fuels based at Mossman in Queensland expect to begin production in 2007 as do Biosel in Sydney, NSW (Anon 2006a).

When considering the use of grains as an input for biodiesel production, it is important to consider the availability and price of grain (including the history of fluctuations), potential biofuel yield, potential by-product yield and the competition for feedstock (Paech 2006). In Australia, the production of biodiesel from oilseeds is predominantly limited by environmental conditions and low crop yields (Paech 2006). All of the southern biodiesel plants (Figure 6) are situated in agricultural areas of Australia that produce oilseeds such as canola. The northern plants at Darwin and Mossman may have access to domestically imported vegetable oil or that from overseas such as palm oil. However, as pointed out by Lake (2007), if biodiesel is to become a sustainable industry in Australia, new crops and cropping areas outside of the current food crop areas will need to be developed without displacing crops for food and animal feed, or relying heavily on pesticides and herbicides.



Representation based on information from: (Anon 2006a and APL 2005); map supplied by: (Geoscience Australia 2005)

Figure 6 A map of Australia showing the approximate locations of towns with functioning or planned biodiesel plants and an estimated distribution of pig producers in 2005.

Pig production in Australia occurs in the south western, southern, and eastern agricultural regions and in limited capacity in northern Tasmania (Figure 6). As almost all of the biodiesel plants are located within this region, pig producers should be able to take advantage of any suitable glycerine production. Furthermore, most of the country's pigs are produced in the eastern part of the country (Table 7) where most of the biodiesel plants are already located or where there are plans to locate them.

Table 7 The number of sows, as of June 2004, in each of the States of Australia and the percentage of the total in each State.

State	Number of sows	% of total
New South Wales	89, 111	28
Queensland	74,619	23
Victoria	65,098	20
South Australia	50,210	16
Western Australia	37,044	12
Tasmania	2,137	1

Source: (APL 2005)

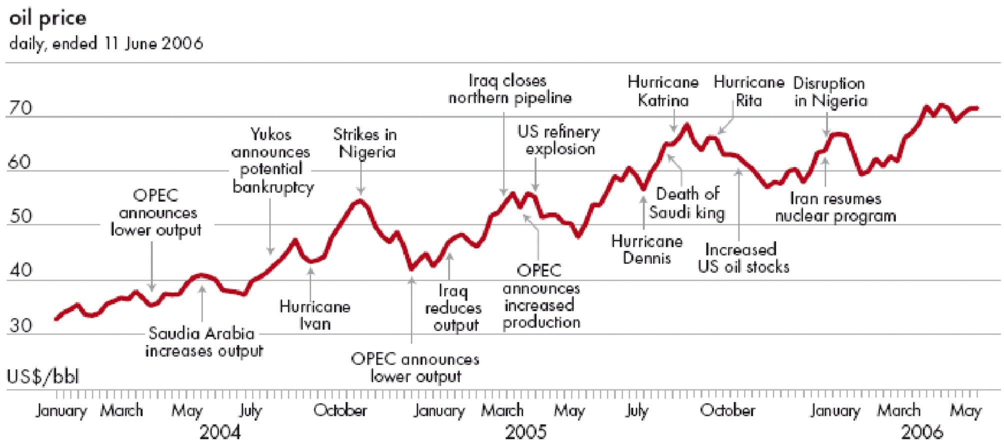
It should be noted though that most plants rely on used vegetable oils and animal tallow and hence the resulting glycerine will be suitable for pig feed. Vegetable oils such as canola will vary in nutritional value as suggested in Tables 1 and 2 and hence feed analyses for glycerine sourced from different vegetable crops will be required when diets are formulated. This notion is supported by Campbell (2006) who believes that improving diet formulation will reduce feed costs and the variability in animal performance.

8. Likely cost of glycerine for pig feed

When considering the economics of biodiesel production, the sale of glycerine is an important revenue stream (Hamilton 2004), although it is often over-looked. Supply for glycerine produced as a co-product of biodiesel depends largely on supply of biodiesel. Hence glycerine prices are highly variable and are affected by changes in biodiesel production (Toohey *et al.* 2003). Moreover, there are many uses for glycerine, all with varying market supply and demand schedules and hence price of glycerine may be difficult to predict.

8.1. Market supply for biodiesel and glycerine

High mineral oil prices and taxes and other financial incentives to encourage the production of biofuels have made biodiesel production costs comparable with those for conventional diesel (Milmo 2005). World oil prices were trading around US$63 a barrel in West Texas Intermediate terms in March 2006 (ABARE 2006), up by around $30 a barrel since the beginning of 2004 (Figure 7). Given similar events to those of the past three years are still occurring around the globe and fears of oil production declining, it is not expected that price of oil will decline significantly. Hence the expansion into production of alternative fuels is likely to continue.



Source: (ABARE 2006)

Figure 7 Changing oil prices over the years 2004 to 2006 and reasons for those changes.
Tyson *et al.* (2004) explained that the expansion of biodiesel in Europe in recent years has had a major impact on glycerine prices. They also point out that if the US displaced 2% of the on-road diesel with biodiesel in a B2 (2% biodiesel, 98% conventional diesel fuel) policy by 2012, almost 1.1 billion gallons of B100 (pure biodiesel, 100% long chain mono alkyl esters of fatty acids) would be used and 800 million pounds of new glycerine supplies would be produced. That is, the policy could potentially quadruple domestic glycerine production adding to world production of biodiesel that is likely to increase in South America, Australia, Southeast Asia, Asia, the former USSR and Africa (Tyson *et al.* 2004). It is likely that any excess glycerine will be exported and hence it will impact on world prices. Should the increase in quantity supplied be greater than the increase in demand, as Doppenberg and Van Der Aar (2007) expect, then prices for glycerine will fall so potentially making it an attractive energy-rich feedstuff for the feed manufacturing industry.

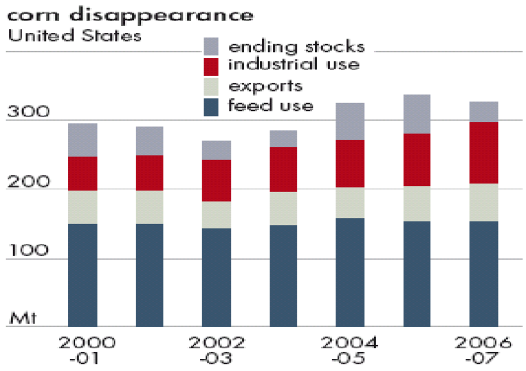
Australia can also consider export of biodiesel to, for example, the European Community, where future demand is expected to outstrip supply (Hamilton 2004). If this proved to be a viable export industry then biodiesel production could increase in Australia and with it, an increase in glycerine production. However, as pointed out by ABARE (2006), the growing use of vegetable oil for biodiesel production is increasing and global vegetable oil consumption is forecast to increase by 2% in 2006-07. If supply of vegetable oil does not also increase then under this scenario its price would also increase and in the longer term biodiesel production could contract.

8.2. Market demand for biodiesel and glycerine

Tyson *et al*. (2004) recognized that biodiesel expansion could flood markets with glycerine and hence they suggested that US Federal investments in new uses for glycerine and new products produced from glycerine will be required if the industry is to continue expanding. According to Lemke (2006), organizations such as the American Oil Chemists Society are also looking for more uses for glycerine to ensure demand increases. Moreover, the US Federal investment in biodiesel research and development has the potential to improve glycerine product quality and reduce glycerine-refining costs so leading to increased values for their glycerine streams (Tyson *et al*. 2004). Tyson *et al*. (2004) suggested areas of research may include: generating products from crude glycerine *in situ* followed by product separation; improving biodiesel technology to produce higher quality glycerine; developing glycerine-refining technology suitable for small biodiesel producers. Hence the price of glycerine will depend somewhat on the products developed and the demand for them.

Demand for glycerine by the pig industry will largely be driven by availability and price of alternative energy sources, the number of pigs produced and producers' expectations about demand for pork products. The main drivers of change within the Australian pig industry are fluctuating world grain prices, the changing Australian sow herd size, herd productivity and increased domestic consumption of fresh pork (Dowling 2006). According to research undertaken by APL, grain prices account for 60 to 65% of total cost of production but during Australian droughts or when world grain prices are abnormally high, grain can move to 65 to 70% of the total cost of production for growing and marketing pigs (Dowling 2006). Cereal and coarse grain prices are below the highs reached during late 2002 but increased throughout the first half of 2006. Sorghum prices increased by 38% from January 2006 to July 2006, while GP wheat prices increased by 28% (Dowling 2006). Consequently, pig producers will continue to seek alternative feed sources.

This need is becoming more urgent due to the rapid growth in ethanol production. For example, currently in the USA demand for corn for ethanol production is likely to limit pig producers' access to corn (Lammers *et al*. 2007a), (Figure 8). This expansion in demand for biofuels could therefore put upward pressure on corn prices resulting in reduced competitiveness in livestock production (Informa 2005).



Source: ABARE (2006)

Figure 8 Industrial use of corn in the USA is increasing compared to other uses for corn.

Furthermore, CIE (2005) used a Global Meat Industries model (see Appendix for details) and suggested that should 700 million litres[5] of ethanol be used in Australia the impact on feed grain prices could result in annual pork production decreasing by around 1kilo tonne carcass weight equivalent (cwe) in 2008 and 2009 and approximately 3 kilo tonnes cwe by 2015. Should the Government introduce mandatory additions of Australian manufactured ethanol to fuel then by 2015, pork production may decrease by around 26 kilo tonnes cwe annually. This model does not account for producers becoming more efficient in terms of using alternative feed sources or inefficient producers leaving the industry. In addition, CIE (2005) noted that if feed prices rise sufficiently in Australia due to greater ethanol production, then intensive animal producers in metropolitan areas could import grain but that would be contingent upon reasonable overseas feed grain prices and biosecurity restrictions on imports.

While feed prices could be driven up by events such as increased ethanol production and drought, CIE (2005) expect that in Australia through to 2015 there will be strong performance in the intensive livestock industries (mainly pig, poultry and dairy) resulting in an increase in demand for feed grains of around 2.4% per year. However, as reiterated by Campbell (2006), Australia is seriously disadvantaged in intensive animal agriculture by high grain prices and hence he proposed a solution may be to reduce the use of grains in pig diets. Such a reduction can only be contemplated if there is a cost-effective substitute for any grain left out of the diet. Crude glycerine resulting from an expansion of biodiesel production may be such a component and hence demand for it may increase.

8.3. Global glycerine pricing

In 2004/2005 there was a slide in glycerine prices largely due to a large surge in output of biodiesel, particularly in Europe where over two million tonnes were produced (Milmo 2005). Should increases in the quantity of glycerine supplied be greater than the increase in quantity demanded by producers then price could drop. Furthermore, the Australian pig industry is highly concentrated with 3% of piggeries in control of 54% of the total sow herd, while smaller piggeries (with less than 50 sows) account for 65% of total piggeries but only for 5% of the total sow herd (Dowling 2006). It is expected that these larger piggeries will have sufficient buying power to possibly negotiate a reduced price. However, biodiesel producers will still need to be convinced that the price is high enough to produce animal-feed standard glycerine. Pig producers also have some capacity to substitute energy sources and biodiesel producers need to be aware of this cross-price elasticity of demand for glycerine. Conversely, there are many uses for glycerine and hence demand for these other uses may to some extent keep the price of glycerine stable.

There is a difference in price between refined and crude glycerine (Toohey *et al.* 2003). Most (97%) of the glycerine used today is a highly refined product (97%+ purity) with purification costs being high (US$400 per ton) while crude glycerine (50% to 90% glycerol by weight)

[5] According to CIE (2005), the ‘Biofuels for Cleaner Transport’ policy established a target level of consumption for all biofuels of 350 million litres by 2010 mainly to be met by ethanol and biodiesel, with ethanol accounting for over 80% of the target level. In the perspective of the total fuel market in 2010, this is a relatively modest target with biofuels accounting for 0.9% of total petrol and diesel consumption. CIE (2005) have suggested another option of a volumetric target that is twice that of the Coalition’s policy at 700 million litres by 2010.

sells at a discount to USP prices, depending on the glycerol content of the product, the amount and type of contaminants present, and supply and demand balances (Tyson *et al.* 2004). Hence when looking at glycerine prices care must be taken in ensuring that the price for crude glycerine (at an approved feed quality) is considered for pig feed and not just a 'standard' glycerine price.

Do to the lack of data on glycerine prices for varying grades, the following information provides an indication of prices. Since the first quarter of 2005, depending on the grade, the price of glycerine has fallen from the price of the 1970's through to early 2005 of between US$0.60 and US$0.80/¢lb to a range between US$0.30 to US$0.55/lb (UCAP 2006). Refined glycerine in the USA averaged $0.36/lb in 2006, and is forecast to be around $0.35/lb in 2007 to 2008 (NAPM 2006). It is possible that the price of glycerine suitable for pig feed may be as low as AUS$0.14/L in Western Australia however there is no data to confirm this price.

Biodiesel producers receive between US$0.05 and US$0.15/lb for crude glycerine (50% glycerol) and 80 to 88% refined glycerine sells for between US$0.30 and US$0.40/lb (Tyson *et al.* 2004). Therefore if biodiesel producers want to dispose of glycerine then they may be happy to sell it at little or no profit. For conversions into litres, kilograms and tones as well as Australian dollars, see Table 8.

Table 8 The equivalent quantity of glycerine in USA and Australian dollars.

US$/lbs	US$/L	AUS$/L	US$/kg	AUS$/kg	AUS$/tonne
0.05	0.11	0.14	0.11	0.14	141
0.15	0.32	0.41	0.33	0.42	423
0.30	0.65	0.83	0.66	0.85	846
0.34	0.73	0.94	0.75	0.96	959
0.35	0.75	0.96	0.77	0.99	987
0.36	0.78	0.99	0.79	1.02	1016
0.40	0.86	1.10	0.88	1.13	1129
0.55	1.18	1.52	1.21	1.55	1552
0.60	1.29	1.65	1.32	1.69	1693
0.80	1.72	2.20	1.76	2.26	2257

1AUD = 0.7814 USD (RBA 2007)

1pound = 0.453592kg

Glycerine = 23.0lbs/9.79lbs/gal=2.35gal (Shifflett 2006).

8.4. The cost of glycerine in Australian pig diets

To determine the highest cost that glycerine would be included in pig diets, Dr Bruce Mullan (Royston Consulting Australia Pty Ltd) completed a least-cost feed formulation analysis[6] for weaner, grower and finisher pigs (Table 9). The diets were formulated to represent typical

[6] This analysis was derived from the *Agridata - Concept5* Feed Formulation Package.

diets fed to pigs across Australia. Milling and transport costs were included in the analysis at $60/tonne. For a base case analysis the cost per tonne of the major components were:

- Barley at $240;
- Wheat at $220;
- Lupins: $310
- Tallow at $600;

Based on approximate costs incurred by feed mills, the cost of molasses was assumed to be $1,000 per tonne. Glycerine was set at $1000 per tonne given the perception in the literature that it could act as a substitute for molasses.

Based on these costs a least-cost diet was formulated to provide adequate energy and lysine levels in the diets of weaner, grower and finisher pigs (Table 9). In addition, given the base case grain prices the maximum cost at which glycerine would be included in the diet was calculated. To determine how sensitive the cost of glycerine was to a change in grain prices, the price of wheat was increased from $220 to $300 per tonne and the price of barley was increased from $240 to $320 per tonne (designated as "high grain prices" in Table 9). The percentage tallow, price sensitivity for tallow and maximum cost of molasses was also calculated within the model.

Table 9 Least-cost diet information for weaner, grower and finisher pigs and the maximum acceptable costs for glycerine, tallow and molasses in pig diets.

Item	Weaner	Grower	Finisher
Energy (MJ DE/kg)	14.5	13.5	12.8
g avail. Lysine/MJ DE	0.80	0.65	0.55
Least cost of diet ($/t)	635	380	355
Base case grain prices			
Maximum cost glycerine ($/t)	**44**	**149**	**174**
High grain prices			
Maximum cost glycerine ($/t)	**125**	**267**	**260**
% tallow included in diet	1.4	0.9	1.6
Price sensitivity for tallow ($/t)	345 to 820	365 to 645	to 647
Maximum cost molasses ($/t)	No max price	61	124

These results are preliminary with assumptions about the composition and cost of the feed components. However, given the base case grain prices they indicate that glycerine would need to cost less than AUS$174 per tonne (Table 9) before producers would consider it as a component of pig diets, bearing in mind that they have access to competing sources of energy. As discussed in Section 8.3 above, glycerine may be available in Western Australia at a price of $141/tonne. Given this price, producers may be happy to incorporate glycerine into their diets at least for growers and finisher pigs.

Given an increase in wheat and barley prices of around 35%, the maximum cost of glycerine that would be acceptable, based on the least-cost diet formulation would also increase. Producers may then consider glycerine, priced up to approximately $260 per tonne, as a feed component in their pig diets (Table 9).

The use of glycerine may become more attractive in the future if research shows how glycerine can benefit growth performance and (or) meat quality. This being the case, then the maximum cost that producers would be willing to pay for glycerine may increase.

Producers also feed tallow to pigs and hence it was included in the diet formulated for this example. For all pig classes it was cost effective to include it in the diet at between 1 and 2% (Table 9).

Glycerine may be a substitute for molasses (depending on its availability throughout the country) and hence its price and nutritional qualities may influence demand for glycerine. Demand for molasses close to the sugar-producing centres in Queensland is increasing as more cattle feedlots and farmers in drought affected areas are looking to molasses as an energy source, and hence prices increased by $20 a tonne during the year up to June 2006 (Cogo 2006). Molasses is a cost-effective and convenient source of ME (11.0 MJ/kg DM) and minerals with ration inclusion rates for cattle being in the range of 3 to 8% (MLA 2000). Although a 15% inclusion rate is feasible and there are indications that rates of 25% or higher are possible and practical (MLA 2000). Nevertheless, it was noted in the early 1970's by Connor *et al.* (1972) that molasses has been less widely accepted as an ingredient in poultry and pig diets. This is generally still the case today even though they found that it can be included into the diet in quite high levels without being detrimental to performance. Nevertheless, in all cases glycerine would be preferred to molasses in the feed formulation exercise completed as part of this study (Table 9).

9. Conclusion

Glycerine, as a co-product from biodiesel production, is available in Australia and is likely to increase in availability over time due to increases in local production and the prospects of importing glycerine from regions such as Asia. Depending on the feedstock, it can be used as a feed component in animal diets and a least-cost formulation has indicated that glycerine can be an efficient alternative in pig diets. There are few anti-nutritional properties in glycerine derived from feedstocks suitable for animal feeds but due to the lack of research concerning its use in pig production it is not certain how it will influence pig growth or meat quality at least under Australian conditions. Furthermore, glycerine derived from palm oil is expected to be a significant product in Australia and while it is expected that a large proportion of this research will need to be done to determine its value as a feed component in pig diets.

Production costs for biodiesel appear to be lower in the USA than Australia and with economies of scale it is likely that costs will decrease. This fall in costs may lead to an increase in production and it is expected that consumers will increase demand for biodiesel. Hence it is expected that glycerine production will increase and together with potential increases in imports of glycerine, the price may fall. In response to price, demand for glycerine should increase until the market stabilizes.

10. Limitations

This study relies on research done to date on the area of biodiesel and glycerine. Due to the industry as it is currently defined being in its infancy there is little information to draw on. This is especially so for use of glycerine in pig diets.

11. Recommendations

Given the high price of animal feed, potentially cost-effective prices of glycerine and preliminary research indicating that glycerine may be suitable for animal diets, there is potential to introduce glycerine into pig diets in Australia. As a result of the findings in this study the following recommendations have been made:

1. The chemical properties of crude glycerine will vary depending on the feedstock source and the manufacturing process. Currently there is little knowledge concerning the variation in glycerine attributes and how it affects quality of animal feed. It is recommend that attempts be made to contact all known Australian biodiesel/glycerine producers to request representative glycerine samples that will be subsequently analysed, particularly for GE, oil, methanol, ash and minerals, including Na;

2. Currently there appears to be limited dialogue between glycerine producers and the pig industry regarding product quality and requirements. In addition to requesting glycerine samples from producers, information pertaining to feed-grade glycerine availability (quantity, quality and possible minimum price) should also be requested.

3. It is recommended that feeding trials measuring growth performance, carcass specification and meat quality at different levels of glycerine inclusion in the diet should be conducted contingent upon the findings in recommendations 1 and 2. These studies should focus initially on grower and finisher pigs, but studies with weaner pigs could also be considered given the energy deficit encountered after weaning and glycerine's gluconeogenic capacity.

12. Acknowledgements

John Spragg provided useful guidance in the early stages of this review and his help is gratefully appreciated. The work on feed formulation conducted for this project by Bruce Mullan is gratefully acknowledged.

13. References

ABARE (2006). Australian Commodities, 06.2 June Quarter, Commonwealth of Australia. Retrieved 21st February 2007 from http://www.abareconomics.com/publications_html/ac/ac_06/AC_June06_FULL_BOOK.pdf

Alberta Gov (2007). Biodiesel overview. Agriculture and Food, Alberta Government. Retrieved 12th February 2007 from: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/afi11174

ABC (2006). Pig industry faces further challenges: ABARE's Outlook conference for 2006. ABC Rural National Unit, 28th February. Retrieved 22 March 2007 from: http://www.abc.net.au/rural/content/2006/s1579990.htm

Anon. (2005). Biodiesel from Alternative Feedstocks. Retrieved 22nd February 2007 from http://www.biodiesel.org.au/forums/testing2005detai.htm

Anon. (2006a). Biodiesel Production. Retrieved 22nd February 2007 from: http://www.biodiesel.org.au/Biodiesel%20Production/biodieselproduction.html

Anon. (2006b). Biodiesel player in the red, downsizes operations. Biofuels News 22 December. Retrieved from 22nd March from: http://www.agric.wa.gov.au/pls/portal30/docs/FOLDER/IKMP/SUST/BIOFUEL/020107BiofuelsNews.pdf

APL (2005). Australian Pig Annual 2005. An Australian Pork Limited Report, Deakin West ACT, Australia. 80pp.

Bantz, S.G. and Deaton, M.L. (2006). Understanding U.S. Biodiesel Industry Growth using System Dynamics Modeling Systems and information engineering design symposium, April. pp 156-161.

Bender M. (1999). Economic feasibility review for community-scale farmer cooperatives for biodiesel. Bioresource Technology 70: 81-87.

Best, P. (2006) Increased biofuel production will grow supplies of by-products: Glycerine gives an energy option. Feed International, December, pp20-21.

Biofuels Taskforce (2005). Report of the biofuels taskforce to the Prime Minister. The Australian Commonwealth Government. Retrieved 21st February 2007 from: http://www.pmc.gov.au/biofuels

Biodiesel TechNote (2006). Characterization of Crude Glycerol from Biodiesel Production from Multiple Feedstocks. Biodiesel TechNote, Fall, Vol. 3, The Department of Biological and Agricultural Engineering, University of Idaho. Retrieved 21st February from http://www.uidaho.edu/bioenergy/NewsReleases/Technote06.pdf

Bonnardeaux, J. (2006). Glycerine overview. A report for the Department of Agriculture and Food, Government of Western Australia, November.

Campbell, R.G. (2006). Global Pork Meat Trade and Customer Demands on Feed Supply. Paper presented to the 2006 Australasian Milling Conference, 28-30 March 2006. Flour Millers Council of Australia and the Stockfeed Manufacturers of Australia. Retrieved 13 March 2007 from: http://www.porkcrc.com.au/publications/

Cargill (2007). Biofuels. Cargill Incorporated. Retrieved 13 March 2007 from: http://www.cargill.com/products/industrial/ps_ethanol.htm

Cerrate, S., Yan, F., Wang, Z., Coto, C., Sacakli, P. and Waldroup, P.W. (2006). Evaluation of Glycerine from Biodiesel Production as a Feed Ingredient for Broilers. International Journal of Poultry Science 5(11): 1001-1007.

CIE (2005). Impact of ethanol policies on feedgrain users in Australia. A report prepared by the Centre for International Economics for the MLA on behalf of the Australian Beef Industry. Canberra and Sydney. 57pp. Retrieved 13 March 2007 from http://www.thecie.com.au/publications/CIE-Ethanol_report.pdf

Cogo, K. (2006). Molasses demand and price on the rise. ABC Rural Queensland, 29th May. Retrieved 6th March 2007 from: http://www.abc.net.au/rural/qld/content/2006/s1649963.htm

Conaghan, E. (2006) Biofuels: Farm-grown diesel fuels timely venture. GRDC Groundcover issue 62 June-July. Retrieved 12th February 2007 from: http://www.grdc.com.au/growers/gc/gc62/biofuels.htm

Connor, J. K., Burton, H. W. and Fuelling D. E. (1972). Molasses in broiler and layer diets. Australian Journal of Experimental Agriculture and Animal Husbandry, 12: 262-268.

Cook, L. (2007). Feed controls – stopping BSE (mad cow disease). New South Wales Department of Primary Industries, Primefact 313, 2nd ed., January. Retrieved 27th March 2007 from: http://www.dpi.nsw.gov.au/__data/assets/pdf_file/101185/feed-controls-stopping-bse-mad-cow-disease.pdf

DAF (2006). Biofuels. A Background Paper. Department of Agriculture and Food, Western Australia. Retrieved 21st February 2007 from: http://www.agric.wa.gov.au/pls/portal30/docs/FOLDER/IKMP/SUST/BIOFUEL/200602_BFTASKFORCEBACKGROUND.PDF

DeFrain, J.M., Hippen, A.R., Kalscheur, K.F. and Jardon, P.W. (2004). Feeding glycerol to transition dairy cows: effects on blood metabolites and lactation performance. Journal of Dairy Science 87(12): 4195-206.

Doppenberg, J. and Van Der Aar, P. (2007). The nutritional value of biodiesel by-products (Part2: Glycerine). Feed Business Asia Mar/Apr: 42- 43.

Dow (1999a). Discover the origins of some of the world's most consistently pure products: Synthetic glycerine products general storage considerations. The Dow Chemical Company, Michigan USA. Retrieved 13th March 2007 from: http://www.pgchemicals.com/resources/statements/Glycerine_Handling_Storage.pdf

Dow (1999b). Discover the origins of some of the world's most consistently pure products: Synthetic glycerine products safety and handling. The Dow Chemical Company, Michigan USA. Retrieved 13th March 2007 from: http://www.dow.com/PublishedLiterature/dh_003d/09002f138003df28.pdf?filepath=glycerine/pdfs/noreg/115-00650.pdf&fromPage=GetDoc

Dowling, D. (2006). A snapshot of the Australian pig industry during 2005/06. *Connections*, On-line Journal at http://www.agrifood.info/connections/

DPI (2007). Ruminant Feed Ban. Department of Primary Industries, Victoria. Retrieved 13th May 2007 from: http://www.dpi.vic.gov.au/dpi/nrenfa.nsf/LinkView/870F9BBC569953C34A256ACB002384F3CCCB356A6EA3B5FECA256EDD008183EA

Ferguson, K. (2007). Biodiesel byproducts ups animals' energy. Iowa State Daily, 17th April, University of Phoenix. Retrieved 13th May from: http://media.www.iowastatedaily.com/media/storage/paper818/news/2007/04/17/Fyi/Biodiesel.Byproduct.Ups.Animals.Energy-2845411.shtml

Francis, A. (2006). Australia's largest biodiesel refinery. ABC Rural 29th November. Retrieved 8th February 2007 from: http://www.abc.net.au/rural/content/2006/s1800099.htm

Frost and Sullivan (2006). R&D Creating New Avenues for Glycerine. Published on-line 4th August. Retrieved 21st February 2007 from: http://www.frost.com/prod/servlet/market-insight-print.pag?docid=77264824

Geoscience Australia (2005). Maps of Australia. Commonwealth of Australia. Retrieved 3rd March 2007 from: http://www.ga.gov.au/map/

Goold, A. T., Taverner M.R. and Hodge R. W. (1976). The effect of rapeseed meal in the diet of young pigs on digestibility of diets and pig performance. Australian Journal of Experimental Agriculture and Animal Husbandry 16: 372-375.

GRDC (2006). Biofuels. Ground Cover, Issue 65 November – December. Retrieved 20th March 2007 from: http://www.grdc.com.au/growers/gc/gc65/biofuels.htm

Hamilton, C. (2004). Biofuels Made Easy. Presentation to the AIE Melbourne Branch, 18th March. Retrieved 21st February 2007 from http://www.aie.org.au/melb/material/hamilton/Biofuels.pdf

Hancock, N (2005). Biodiesel Overview on Global production and policy. A Department of Agriculture and Food report, Government of Western Australia, November. Retrieved 21st February from http://www.agric.wa.gov.au/pls/portal30/docs/FOLDER/IKMP/SUST/BIOFUEL/200511_B_DWorldOverview.pdf

Hargreaves, J. (1999). Supply chain alliances vital. Pigpen No. 19 March. Retrieved 13 March 2007 from: http://www2.dpi.qld.gov.au/pigs/5206.html

Hobbs, S. (2003) Bio-diesel, farming for the future, In. "Solutions for a better environment". Proceedings of the 11th Australian Agronomy Conference, 2-6 Feb. 2003, Geelong, Victoria. Australian Society of Agronomy. Retrieved 8th February from: http://www.bebioenergy.com/agronomy_conference.htm

Informa (2005). The Structure and Outlook for the US Biofuels Industry. A report prepared by Informa Economics, Inc for The Indiana State Department of Agriculture. Retrieved 12th February 2007 from: http://www.in.gov/isda/pubs/biofuelsstudy.pdf

ISU (2007) Biodiesel Byproduct Effective in Swine and Poultry Feed. News Release 11th April, College of Agriculture, Iowa State University of Science and Technology. Retrieved 13th May 2007 from: http://www.ag.iastate.edu/aginfo/news_detail.php?var1=313

Kato, T., Hayashi, Y., Inoue, K. and Yuasa, H. (2005). Glycerol Absorption by Na^+-Dependent Carrier-Mediated Transport in the Closed Loop of the Rat Small Intestine. Biol. Pharm. Bull. 28: 553-555.

Kijora, C., Kupsch, R.D., Bergner, H., Wenk, C. and Prabucki, A.L. (1997). Comparative investigation on the utilization of glycerol, free fatty acids, free fatty acids in combination with glycerol and vegetable oil in fattening of pigs. Journal of Animal Physiology and Animal Nutrition 77(3): 127-138.

Kijora, C. and Kupsch, S-D. (1996). Evaluation of technical glycerols from "Biodiesel" production as a feed component in fattening of pigs. Research Paper, Wiley InterScience 98(7-8): 240-245. Published Online: 24 October 2006: http://www3.interscience.wiley.com
Kijora, C., Bergner, H., Kupsch, R.D. and Hagemann, L. (1995). Glycerol as a feed component in fattening pigs. [German] Arch Tierernahr 47(4):345-60

Kingwell, R. and Plunkett, B. (2006). Economics of On-Farm Biofuel Production. Paper presented as an invited paper at the conference *Bioenergy and Biofuels*, 10 Feb, Perth, Western Australia.

Kotrba, R. (2006). Everything Under the Sun. Biodiesel Magazine February. Retrieved 21st February 2007 from http://www.biodieselmagazine.com/article.jsp?article_id=710

Lake, A. (2007). Response to Inquiry into Australia's future oil supply and alternative transport fuels. In Chapter 7 - Supply side responses - Alternative fuels – Biofuels. Parliament of Australia Senate. Retrieved 8th February 2007 from: http://www.aph.gov.au/senate/Committee/rrat_ctte/oil_supply/submissions/sub68.pdf

Lammers, P., Honeyman, M., Bregendahl, K., Kerr, B. Weber, T., Dozier (III), W. and Kidd, M. (2007a). Energy Value of Crude Glycerol Fed to Pigs. Research A.S. Leaflet R2225 Iowa State University Animal Industry Report. Retrieved 12th February 2007 from: http://www.ans.iastate.edu/report/air/2007pdf/R2225.pdf

Lammers, P., Honeyman, M., Kerr, B. and Weber, T. (2007b). Growth and Performance of Nursery Pigs Fed Crude Glycerol. Research A.S. Leaflet R2224 Iowa State University Animal Industry Report. Retrieved 12th February 2007 from: http://www.ans.iastate.edu/report/air/2007pdf/R2224.pdf

Lawrance, L. (2006). Crops: oilseeds. Australian Bureau of Agricultural and Resource Economics. Retrieved 21st February 2007 from: http://www.abareconomics.com/interactive/ac_sept06/htm/oilseeds.htm

Lemke, D. (2006). Volumes of versatility. Auri Ag Innovation News Jan- Mar 15(1): 8. Retrieved 8th February 2007 from: http://www.auri.org

McCoy, M. (2006) Glycerine Surplus: Plants are closing, and new uses for the chemical are being found**.** Chemical & Engineering News, February, 84(6): 7. Retrieved 21st February 2007 from: http://pubs.acs.org/cen/news/84/i06/8406notw3.html

McGraw-Hill (2005). Glycerol. McGraw-Hill Encyclopedia of Science and Technology McGraw-Hill Encyclopedia of Science and Technolog[redacted]. The McGraw-Hill Companies, Inc. Retrieved 15th March 2007 from: http://www.answers.com/topic/glycerol

Millar, H.W.C. (2005). Agriculture and Veterinary Chemicals (Control of Use) (Ruminant Feed) Regulations (2005): Specification and method of measurement for tallow and used cooking oil for the ruminant feed ban. Retrieved 13th May 2007 from: http://www.dpi.vic.gov.au/dpi/nrenfa.nsf/93a98744f6ec41bd4a256c8e00013aa9/52c2d64da00b1816ca2572bf0020bd27/$FILE/Specs.pdf

Miller, F. (2006). Two for One Deal: Biodiesel byproduct fuels growth in broilers. A University of Arkansas, Division of Agriculture media release, 2nd August. Retrieved 21st February 2007 from http://www.uark.edu/depts/agripub/Publications/Agnews/agnews06-42.html

Milmo, S. (2005). A changing landscape. Chemistry World, November. Retrieved 12th February 2007 from http://www.rsc.org/chemistryworld/Issues/2005/November/landscape.asp

MLA (2000). High-energy feed alternatives for the feedlot industry. On tips and tools Feedlot:FL04. Meat and Livestock Australia, November. Retrieved 15th February from: http://www.mla.com.au/

Mourot, J., Aumaitre, A., Mounier, A., Peiniau, P. and François, A.C. (1994). Nutritional and physiological effects of dietary glycerol in the growing pig. Consequences on fatty tissues and post mortem muscular parameters. Livestock Production Science 38: 237-244

NAPM (2006). Glycerine: New York Commodity Corner, November Edition. Retrieved 8th February from http://www.napm-ny.org/resources/commodity.html

Paech, A. (2006). The Australian biofuels industry and the Wimmera district: scoping study. A Victorian Government Department of Primary Industries report, September. Retrieved 21st February from http://www.dpi.vic.gov.au/dpi/nrenti.nsf/93a98744f6ec41bd4a256c8e00013aa9/807b97be2848cfbeca257263007bafbf/$FILE/BioFuels06.pdf

Passey, R. (2002). Biodiesel: A Fuel for the Future. A Case Study to inform the State Sustainability Strategy, June. Retrieved 8th February 2007 from http://www.sustainability.dpc.wa.gov.au/CaseStudies/biodiesel/biodieselprint.htm

Pethick, D.W., Cummins, L., Gardner, G.E., Knee, B.W., McDowell, M., McIntyre, B. L., Tudor, G., Walker, P.J. and Warner, R.D. (1999). The regulation of glycogen level in the muscle of ruminants by nutrition. Retrieved 28th February 2007 from: http://msa.une.edu.au/msa/public/5a59985.htm

Pond, W.G., Church, D.C., Pond, K.R. and Schoknecht, A. (2005). *Basic animal nutrition and feeding (5th Edition).* John Wiley & Sons Inc., Hoboken, USA.

Potter, T. and McCaffery, D. (2006). Grain Research Update GDRC for Irrigation Croppers Biodiesel in Australia – Small scale production. Retrieved 8th February from: http://www.irec.org.au/reser_f/06_pdf/Biodiesel%20in%20australia%20-%20small%20scaleproduction.pdf

RBA (2007). Daily Statistical Release: Exchange Rates. Reserve Bank of Australia, Release date: 12 March. Retrieved 13th March from: http://www.rba.gov.au/Statistics/exchange_rates.html

Rola-Rubzen, M.F., Pringle, M., Storer, C. and Ariyaratnam, A. (2005). Analysis of supply chain of agricultural commodities in the North Eastern Agricultural Region (NEAR). Consultancy Report, October, Muresk Institute, Curtin University of Technology, Northam.

Schröder, A. and Südekum, K-H. (1999). Glycerol as a by-product of biodiesel production in Diets for ruminants. Paper presented at the 10th International Rapeseed Conference, Canberra, Australia.

Selwood, R.N. (2006). Submission to the Senate Rural and Regional Affairs and Transport Committee Inquiry into Australia's Future Oil Supply and Alternative Transport Fuels by Natural Fuels Australia LTD (NFAL). February. Retrieved 8th February from http://wopared.parl.net/Senate/committee/rrat_ctte/oil_supply/submissions/sub95.pdf

Shifflett, J. (2006). Preparing formulas for submission to the Nonbeverage Product Laboratory: A Presentation. Alcohol Tobacco Tax and Trade Bureau US Department of Treasury. Retrieved 20th March from: http://www.ttb.gov/ssd/presentations/PreparingFormulasForSubmission_12-06-06.ppt

Shokes, F., Bhardwaj, H., Starner, D. and Roberts, M. (2006). Canola – an alternative oilseed crop for Virginia with good biofuel potential. Poster presented at the October 16, 2006 Deans' Forum on Energy Security and Sustainability. Retrieved 22 March 2007 from: http://www.research.vt.edu/energy/EnergyEcon_Poster_Abstracts.html

Smith, T. (2006). New Picton biodiesel plant WA's biggest. Media Release, Australian Minister for the Environment and Heritage, 26th July. Retrieved 13th March 2007 from: http://www.environment.gov.au/minister/env/2006/mr26july06.html

Thompson, J. C. and He, B. B. (2006). Characterization of crude glycerol from biodiesel production from multiple feedstocks. Applied Engineering in Agriculture 22(2): 261-265.

Toohey, D.E., Jayanath, A. and Crase, L. (2003). Pre feasibility study into biodiesel opportunity. A study conducted for the Pratt Water Murrumbidgee Valley Water Efficiency Feasibility Project. 31 December. Retrieved 8th February from: http://www.napswq.gov.au/publications/pratt-water/working-papers/pubs/biodiesel.pdf

Tyson, K. S., Bozell, J., Wallace, R., Petersen, E. and Moens, L. (2004). Biomass Oil Analysis: Research Needs and Recommendations. Technical Report National Renewable Energy Laboratory Golden, Colorado USA, June. Rretrieved 22nd March 2007 from: http://www.nrel.gov/docs/fy04osti/34796.pdf

UCAP (2006). Glycerine glut drags prices downward. News Brief for week ending 6 July. Retrieved 8th February 2007 from: http://www.ucap.org.ph/070606.htm

WA Gov (2005). Biofuels Industry Task Force Motion. ASSEMBLY - Wednesday, 14 September 2005. Retrieved 28th February from: http://www.parliament.wa.gov.au/hansard/hans35.nsf/(ATT)/1D269DA865AB61064825709 0001D1077/$file/A37+S1+20050914+p5337b-5351a.pdf

Weiss, M.J., Knodel, J.J. and Olson D. (2006). Insect Pests of Canola. Radcliffe's IPM World Textbook, University of Minnesota. Retrieved 22 March 2007 from: http://ipmworld.umn.edu/chapters/Weiss_et_al_canola.htm

Whittington, T. (2006). Biodiesel production and use by farmers: is it worth considering? A report for the Department of Agriculture and Food, Government of Western Australia. June. Retrieved 15th February from: http://www.agric.wa.gov.au/pls/portal30/docs/FOLDER/IKMP/SUST/BIOFUEL/Onfarmbio dieselprod.pdf

Zijlstra R.T., Hickling D.R., and Patience J.F. (2005). Comparison of voluntary feed intake and growth performance between grower pigs fed diets containing either mustard meal or canola meal. *Council ResearchNews* Prairie Swine Centre Inc., Saskatoon, Canada. Retrieved 13 March 2007 from: http://www.manitobapork.com/admin/docs/05febres.pdf

Appendix: Description of the GMI model

The following description is taken from CIE (2005)

The GMI model is a detailed representation of global meat production, consumption and trade. The model managed and run by the CIE on behalf of MLA. It identifies and accounts for:

- 26 regions including Australia and its major trading partners and competitors; and
- 10 commodities including grass and grain fed beef, live cattle, lamb and mutton, pigmeat and poultry and seafood.

The model traces the value chain for each meat type from farm level through to retail level and includes trade and transport margins after accounting for trade barriers.

Economic features of the model include:

- imperfect substitution in consumption between meats in response to relative prices;
- imperfect substitution between sources of each meat – domestic and imported sources and between countries at the import level; and
- all barriers that distort world trade including tariffs, quotas and non-tariff barriers. The

model is comparative dynamic — it makes projections of global meat outcomes given a set of assumptions and trends concerning:

- population, income growth and changes in exchange rates;
- underlying productivity growth for each type of meats; and
- changes in trade barriers.

The projection provides a 'baseline' from which the model can be used in comparative static model to evaluate 'what-if' policy questions.