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Feasibility of using feedlot manure for biogas production

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Executive summary

Anaerobic digestion has the potential to reduce greenhouse gas (GHG) emissions while also providing biogas as an energy source. With rising energy costs and the introduction of the Emissions Reduction Fund (ERF), there has been an increasing interest in extracting energy from feedlot manure in the form of biogas. While biogas capture has been cost effective in the Australian pig industry, the successful conversion of beef feedlot manure into biogas has not been proven on a similar scale. This is largely because feedlot pen manure in its current form is an unsuitable substrate for biogas production.

There is currently a lack of knowledge within the Australian feedlot industry regarding the biomethane potential (BMP) of beef feedlot manure of differing ages and how harvest techniques impact on BMP values. Consequently there is a need for further analysis and understanding of 1) feedlot manure as a substrate for methane production and 2) the techno-economic feasibility of using this feedstock to produce biogas. Specific project objectives of this study include:

1. A comprehensive review on the application of anaerobic digestion technologies treating agricultural waste for energy recovery including the identification of technically-feasible technologies for beef feedlot manure.
2. An understanding of feedlot feedstock and current manure handling practices at feedlots throughout Australia.
3. A technical and economic assessment of the different anaerobic treatment systems.
4. The results of biomethane potential (BMP) using different aged manures at lab scale.
5. Development of a pre-treatment system(s) to produce optimal influent material from feedlot manure as managed in existing systems.
6. Recommendations for systems worth trialling in a future farm-scale pilot trial.
7. A preliminary economic assessment of the system at a 10,000 head feedlot.

A comprehensive review of the literature has revealed that the economic value of feedlot manure for anaerobic digestion is largely determined by the composition (quality) of the manure. Pen cleaning timing, frequency and method affects the quality of the manure removed. The wide range of organic (volatile solid (VS)) content in material harvested from feedlot pens obtained from literature demonstrates the influence of pen design and management on the quality of manure removed from the pens. Data from these feedlots suggest that the material harvested contains material other than manure. This additional material (e.g. rocks and/or soil) influences the biomethane potential results by increasing the quantity of material harvested and lowering the organic content. The data from the literature highlights the need to be fully aware of the circumstances behind pen manure samples when assessing the substrate as a biogas feedstock. Low VS contents can either be due to prolonged manure breakdown or due to mixing of manure with soil.

This study reported on the BMP and chemical composition of feedlot manure samples from three Australian feedlots. Four types of manure were tested namely, 1) fresh manure (FM): faeces that are freshly dropped; 2) pen surface manure (PSM): faeces and urine that are excreted to the pen and left on the pen surface before pen cleaning; 3) freshly scraped pen manure (FSPM): a mixture of faeces and urine that are excreted and left on the pen over a period of time and includes gravel and soil that is mixed up when the pen is cleaned by machinery and 4) stockpiled manure (SM): scraped pen manure stockpiled over a period of time, usually a few months.

Analysis of the organic matter content in the form of lignin, fat (lipid), volatile fatty acids (VFA), cellulose, hemicellulose, starch and protein were conducted alongside total solids (TS) and VS content for each sample. These were then correlated with corresponding BMP results of each sample. Biomethane potential testing resulted in methane yields of FM (218 L CH_4/kg VS), PSM (173 L CH_4/kg VS), FSPM (135 L CH_4/kg VS) and SM (13 L CH_4/kg VS). SM biogas generation is 7.5% of the amount generated by the clean pen manure (PSM) while the fresh and the pen feedlot manures have shown comparable methane

potential. The results indicate that contamination with soil may be the main factor that affects biogas production therefore highlighting the importance of pre-treatment systems over the time of collection.

Two preliminary pre-treatment experiments of pen surface manure from one feedlot were conducted. The trials examined the effect of stirring on particle size and TS and VS content. The trials demonstrated that there were vast differences between the calculated and tested TS% pen which was attributed to dry crusty nature of the sample. Further testing will need to be completed at increased TS% between the 4-8% range.

To determine the economic feasibility of a feedlot manure biogas system, an engineering firm provided a broad cost estimate for capital expenditure (CAPEX) and an ongoing operational expenditure (OPEX) for the proposed 10,000 SCU manure-biogas development. Working from current market prices, industry knowledge and experience from similar projects, the firm provided costs associated to design and construct a fully engineered, quality control tested and project managed facility. The estimated CAPEX for a biogas development of this nature is expected to range from $8,100,000 - $9,500,000, with an annual OPEX of $350,000/year.

Various measures to increase the economic feasibility of the biogas feasibility include:

- A review of manure harvest management techniques and the modification of existing machinery to improve the quality of the feedstock.
- A review of low cost biogas technology options which could be suitable for feedlots using manure as a single substrate.
- An investigation into the use of various waste streams in addition to feedlot manure (ie co-digestion) and the subsequent exploration into supply chain management.

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List of Abbreviations and Terms

AD	Anaerobic digestion
ADF	Acid detergent fibre
ADG	Average daily gain
ADL	Acid detergent lignin
B_o	Maximum methane producing capacity
BD	Bulk density
BEEFBAL	Feedlot nutrient balance model
BOD	Biochemical oxygen demand
BMP	Biochemical methane potential
C	Carbon
CAP	Covered anaerobic pond
CAPEX	Capital expenditure
CHNOS	Carbon, hydrogen, nitrogen, oxygen, sulphur
CH_4	Methane
COD	Chemical oxygen demand
CO_2	Carbon Dioxide
DM	Dry Matter
DMD	Dry Matter Digestibility
DMDAMP	Dry Matter Digestibility Approximation of Manure Production
DMI	Dry Matter Intake
DOF	Days on Feed
EC	Electrical conductivity
ERF	Emissions Reduction Fund
FCR	Feed conversion ratio
FS	Fixed Solids
GHG	Greenhouse gas
HHV	Higher heating value
HRAD	High rate anaerobic digester
HRT	Hydraulic retention time
LWT	Liveweight
MC	Moisture content
MCF	Methane conversion factor
MLA	Meat & Livestock Australia

M&E	Mass and energy
MJ	Megajoule
MSW	Municipal solid waste
MW	Megawatt
MWh	Megawatt hour
N	Nitrogen
NDF	Neutral detergent fibre
NOx	Oxides of nitrogen
NPV	Net present value
O&M	Operating and maintenance
OPEX	Operational expenditure
P	Phosphorus
PFD	Process flow diagram
REC	Renewable energy credit
SAR	Sodium absorption ratio
SCU	Standard cattle unit (regulatory standard in Queensland)
SOx	Oxides of sulphur
TN	Total nitrogen
TP	Total phosphorus
TS	Total solids
TFLBR	Trickle flow leach bed reactor
VFA	Volatile Fatty Acids
VS	Volatile solids

1. Introduction

1.1 Background

Beef feedlot manure has a relatively high energy content, similar to other organic waste materials. As such, it offers the potential for energy recovery using thermal processes such as combustion, gasification or pyrolysis and biological processes such as anaerobic digestion. Anaerobic digestion has the potential to reduce Green House Gas (GHG) emissions while also providing biogas as an energy source. With rising energy costs and the introduction of the Emissions Reduction Fund (ERF), there has been an increasing interest in extracting energy from feedlot manure in the form of biogas. While biogas capture has been cost effective in the Australian pig industries, the successful conversion of beef feedlot manure into biogas has not been proven on a similar scale. This is largely because feedlot pen manure in its current form is thought to be an unsuitable substrate for biogas production.

Some preliminary Australian manure characterisation has been undertaken by the Advanced Water Management Centre (AWMC), a research centre at the University of Queensland. Additionally, methane emissions from a feedlot holding pond have been measured by the CSIRO. There are significant and confusing differences between these results. The work conducted at the AWMC, reported low methane yields from feedlot manure when compared to piggery waste. However, it also reported less than expected differences in yields between fresh and aged feedlot manure, which is not consistent with the relative volatile solids content of the two substrates. On the other hand, the CSIRO measurements reported much higher methane yields from the effluent than would be expected from first principles. These conflicting results highlight the need for further analysis and understanding of feedlot manure as a substrate for methane production.

1.2 Scope of work

This project investigated the feasibility of anaerobic digestion systems for feedlot manure for optimal biogas production. An initial review of the international research literature on anaerobic digestion of cattle manure and similar waste streams, along with case studies on existing plants was conducted to define the required characteristics of an influent substrate for anaerobic digestion and to identify the current status of energy recovery using anaerobic digestion from feedlot manure, with a particular focus on US practices. Further analysis of manure samples from Australian feedlots were undertaken to provide an understanding of the range of variation of feedstock.

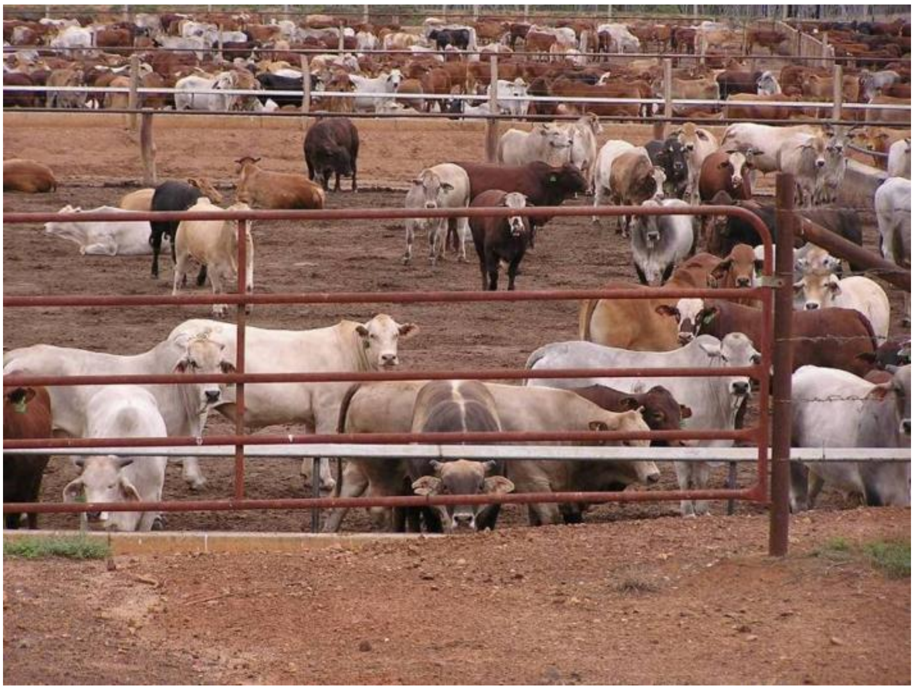
The project utilised laboratory scale studies to determine the optimum solids concentration and pre-treatment of manure prior to anaerobic digestion. This will inform the design of pre-treatment technologies at the medium scale deployed in the field. A preliminary economic assessment was then conducted The results of this work are of particular importance and relevance to feedlots that have committed to investment in anaerobic digesters or are considering such investment.

2. Literature Review

The literature review has been divided into three main sections. The first section describes the Australian lot feeding sector including the provision of data on the quantity and quality of organic wastes produced at feedlots. The second section describes the anaerobic digestion process and its application to the production of biogas from organic wastes. The third section discusses the issues around the production of biogas from feedlot wastes.

2.1 Cattle feedlots

A cattle feedlot is a facility where beef cattle are housed in open pens and fed a prepared diet until they reach a specified weight (See Photograph 1). Only weaned cattle enter the feedlot and no breeding of cattle occurs at the feedlot. The pen surface is typically compacted clay or gravel. Depending on site-specific conditions, feedlot pens are stocked at between 10 and 20 m^2/head. Animal size is sometimes standardised to SCU (standard cattle units) (Skerman 2000).



Photograph 1 - Typical view of cattle in an Australian feedlot

2.1.1 Location of feedlots in Australia

Feedlots are generally located across the grain-growing regions of Australia. The climatic zones in which feedlots are located are of relevance to this study. The amount and annual patterns of rainfall affect the moisture content of manure on the pen surface and the rate at which that manure breaks down. Table 1 below details the distribution of Australian feedlots relative to mean annual rainfall (Watts et al 2013a).

Table 1 – Location of current feedlots with respect to mean annual rainfall

	No. of Feedlots	% of Feedlots	Av. Capacity	Pen Capacity	% Pen Capacity
Summary					
< 750 mm	629	74%	1940	1 185 809	88%
> 750 mm	225	26%	709	159 636	12%
< 600 mm	137	16%	2579	353 256	26%
600-649 mm	77	9%	1748	134 569	10%
650-699 mm	176	21%	1953	343 683	26%
700-750 mm	239	28%	1482	354 301	26%
> 750 mm	225	26%	709	159 636	12%
TOTAL	854	100%	1694	1 345 445	100%

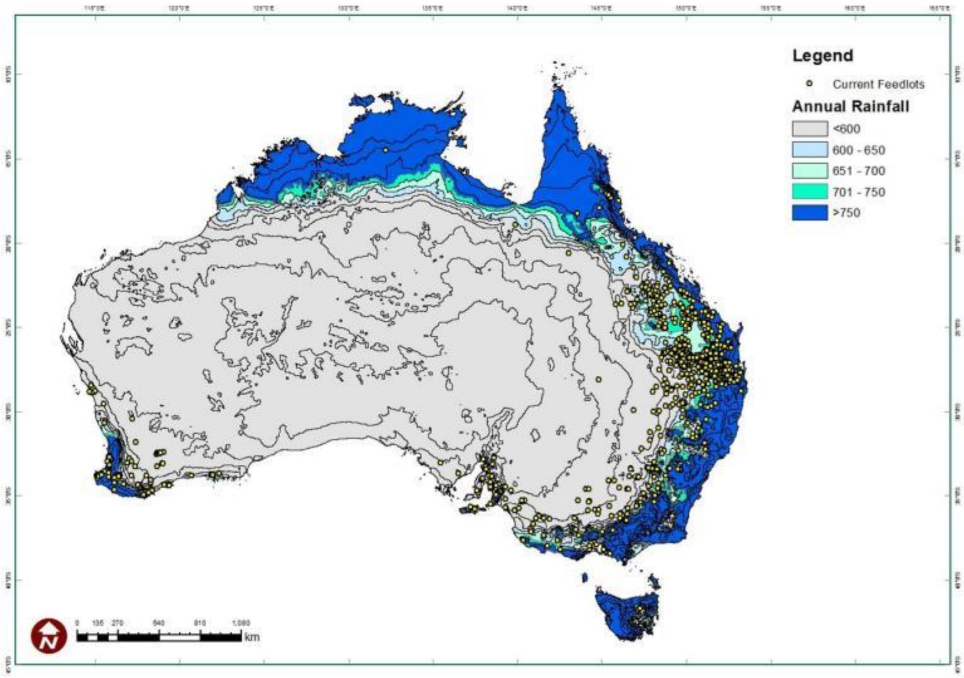


Figure 1 – Location of Australian feedlots vs. annual rainfall

Figure 1 illustrates the current feedlot distribution relative to mean annual rainfall (Watts et al 2013a). Overall, 26% of individual feedlots are in areas that have greater than 750 mm of annual rainfall. While this is a significant number of individual feedlots, it only represents 12% of Australia's current total pen capacity.

The distribution of rainfall throughout the year has a significant bearing on the management of a feedlot (Tucker et al. 1991). Feedlots located in areas with high winter rainfall and low evaporation rates have problems with odour management, as a wet pad is the main cause of odour generation (Tucker et al. 1991). This clearly has a bearing on the viability of anaerobic digestion because water is needed to convert feedlot manure into liquid feedstock. Table 2 and Figure 2 details a summary of Australia's current feedlots in relation to seasonal rainfall (Watts et al 2013a). Currently, 72% of individual feedlots are located in summer dominant rainfall areas. This accounts for 60% of current pen capacity. This also has a bearing on the viability of anaerobic digestion because warm weather is favourable for manure decomposition.

Table 2 – Current distribution of feedlots in seasonal rainfall regions

Climatic Zone	No. of Feedlots	% of Feedlots	Average Capacity	Pen Capacity	% Pen Capacity
Winter Dominant	56	6.6%	1347	75 404	6%
Winter	136	15.9%	2108	286 718	21%
Total Winter	***192***	**22.5%**	**1727**	***362 122***	**27%**
Summer Dominant	34	4.0%	1955	66 472	5%
Summer	580	67.9%	1269	735 932	55%
Total Summer	***614***	***72%***	***1612***	***802 404***	***60%***
Arid	1	0.1%	400	400	<1%
Uniform	47	5.5%	3840	180 499	13%
TOTAL	**854**	**100%**	**1895**	**1 345 425**	**100%**

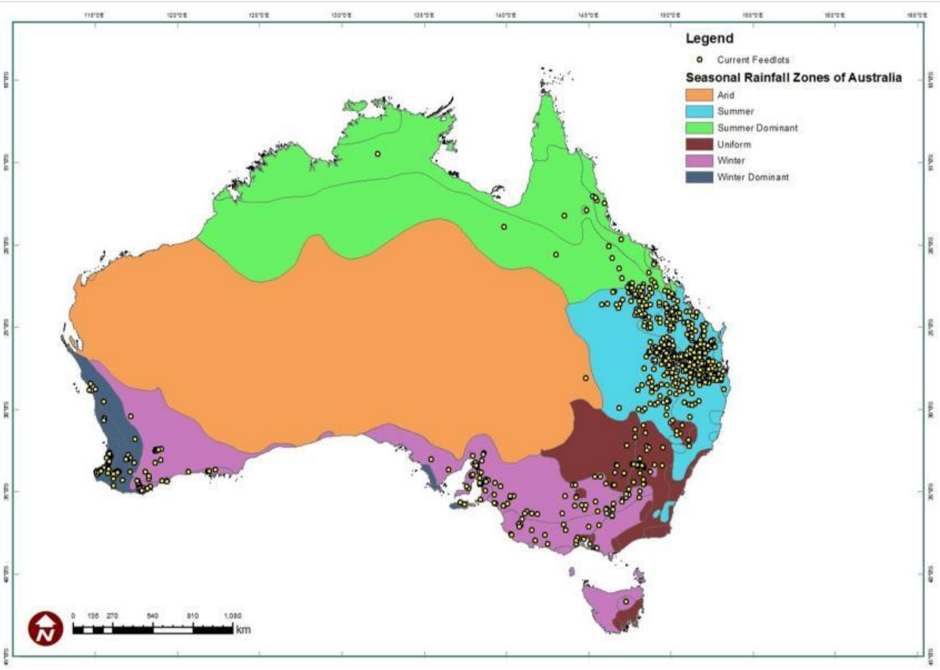


Figure 2 – Location of Australian feedlots vs. seasonal rainfall zones

2.2 Feedlot manure management systems

2.2.1 Manure management overview

Cattle excrete fresh manure (urine plus faeces) onto the pen surface (known as the feedpad) where it immediately begins to breakdown. Ammonia and other volatile components such as Volatile Fatty Acids (VFAs) are lost from the manure. After a period of time, machinery removes the dry manure from the pens (See Photograph 2 - Pen cleaning using a box scraper under dry conditions). The removed manure is typically held in a manure stockpile area where it may be composted prior to sale off-site or spreading as an organic fertiliser on agricultural land. A small percentage of manure is removed from pens by runoff during heavy rainfall events. Dry matter (mainly carbohydrates) is lost from manure to the atmosphere as CO_2 and CH_4 in all phases of manure handling and storage.

Manure management is site-specific, since it depends on feedlot design, management, labour, climate and seasonality. In Australian feedlots, the components of manure management are:

- Pen cleaning and manure harvesting
- Manure stockpiling and/or composting
- Manure utilisation as fertiliser.

Potentially, manure is a valuable organic fertiliser but the monetary value depends on local circumstances. It is also the source of most odour emitted from a feedlot. Hence, there has been considerable research undertaken over the years into the characteristics of feedlot pen manure.

2.2.2 Pen cleaning systems

As cattle occupy feedlot pens, excreted manure accumulates on the pen surface. It is now well understood that excessive accumulation of manure has an adverse effect on animal performance, animal welfare and environmental impact. Hence, pens should be cleaned of manure at a frequency that prevents adverse effects.

Pens are typically cleaned using box scrapers, front-end loaders or excavators. In some instances, scrapped manure is immediately removed from the pens. In other instances, manure is mounded into a pile in the centre of the pen. The mound is then removed at a later date. Further breakdown of the manure occurs in the mounds so feedlots that mound generally remove a reduced tonnage of manure from the pens.

The frequency at which pens are cleaned (pen cleaning frequency) depends on a range of factors including:

- pen stocking density (head per m^2)
- occupancy (% of time that pen is occupied by cattle)
- feed processing method (feed processing improves feed conversion reducing manure excretion)
- animal live weight and daily feed intake
- pen manure moisture content.

Taking all of the above factors into account, pen cleaning frequency can range from every three weeks to every six months.

A short-term issue that affects pen cleaning frequency is the moisture content of the pen surface. If the pen surface is too dry, pen cleaning causes significant dust. It is difficult to form stable manure mounds (See Photograph 2). Under wet pen conditions (such as are experienced in southern feedlots in the winter), it is difficult to remove the manure as it becomes close to a slurry (See Photograph 3). Most lot feeders agree that the optimum moisture content at which to clean pens is about 35% (which is too wet for all thermal energy options of biogas generation).

On top of the original pen surface, it is typical for what is called the interface layer to form. This is a layer of hard-compacted manure immediately on top of the base gravel or clay (see Photograph 4 - compacted manure interface layer over compacted gravel). Some lot feeders ensure that pen cleaning does not remove this interface layer. This ensures that a soft pen surface is left for the cattle and that excess clay or gravel is not removed from the pens. Photograph 5 below, is an example of a pen surface where about 25 mm of loose dry manure has been removed, but the hard, compacted interface layer is retained. In this case, the removed manure is not contaminated with clay or gravel. In some cases, during pen cleaning the interface layer is completely removed leaving a compacted clay base (See Photograph 6). In this instance, it is inevitable that some clay contaminates the manure, thus reducing its quality as a fertiliser or an energy source. The differences in pen manure quality resulting from different manure management practices will be documented in later sections of this report.

Photograph 2 - Pen cleaning using a box scraper under dry conditions

Photograph 3 - Pen cleaning using a box scraper under wet conditions

Photograph 4 - compacted manure interface layer over compacted gravel

Photograph 5 - Pen cleaning while retaining a compacted manure interface layer

Photograph 6 - Pen cleaning with a front-end loader where the interface is removed exposing the clay base

2.2.3 Quantity of harvested feedlot pen manure

An economic analysis of the energy recovery options for manure requires an estimate of the quantity of manure produced at a feedlot. While there are many studies that report the characteristics (quality) of feedlot pen manure (from a fertiliser perspective), surprisingly few studies have quantified the manure removed from feedlot pens. As the following section shows, when assessing "manure" production, it is important to understand the proportion that is manure and the proportion that is soil, clay or gravel.

Kissinger et al. (2006b) and several others measured manure removal from a number of feedlot pens. Kissinger et al. (2007) reviewed available literature on the characteristics and quantity of manure removed from feedlot pens in the USA. Further details from these two reports can be found in the BEEFBAL model upgrade report (Davis et al. 2012). However, when using this data in Australia, care should be taken in interpreting the results as there are significant variations in:

- Feedlot pen characteristics
- Manure management methods
- Manure sampling and handling protocols
- Manure testing methods
- Climatic conditions

Sweeten et al. (1985) analysed manure harvested from several different feedlots in the USA in 1979 and 1980. Samples were analysed for ash content, moisture content, total-N, sulphur and heat of combustion. Average manure depth is stated to be 115 mm above the original soil layer. For the surface layer, VS is 72.5% but this decreases to only 26.5% in the interface layer. This means that the manure in the interface layer is either well degraded or it is mixed with soil. This would be common at feedlots in the USA at that time when limited feedlot pad preparation was undertaken and soil was often harvested with the manure. Photograph 7 below, documents a US feedlot where virtually no earthworks are undertaken and the pens are simply located on bare uncompacted soil. In this situation, it is common to harvest considerable soil volumes with manure during pen cleaning. Sometimes, earth mounds are constructed in the middle of feedlot pens to provide a dry refuge for cattle during wet conditions (See Photograph 8).

This data highlights the need to be fully aware of the circumstances behind pen manure samples. Low VS contents can either be due to prolonged manure breakdown or due to mixing of manure with soil. For example, Miller (2001) undertook a study looking at the compounds in “feedlot soil” that might contribute to odour emissions (in US studies, “feedlot soil” refers to the combination of soil and manure harvested from pens.). The organic matter (assumed to be VS) of their manure sample taken from the feedlot pens was 32.4% (DM basis) with a total-N of 1.82%. This low VS content clearly indicates that this sample is a combination of manure and soil. Kissinger et al. (2007) reports the results of manure harvesting data from six Nebraska feedlots. The average TS and VS removal were 5.3 and 1.5 kg/head/day respectively. This implies a VS content of the removed material to be 28%, on average, indicating a large proportion of soil in the harvested manure. However, they did report a large range for VS/TS ratio from 19% to 55%. They reported that different management practices resulted in different proportions of soil removed during pen cleaning.

Kissinger et al, (2006a) reported manure removal from 4.7 kg DM/head/day to 8.8 kg DM/head/day (1.7 to 3.2 t DM/head/yr) depending on climatic and pen harvesting conditions. The VS content of the harvested manure ranges from 10% to 55% depending on the amount of VS breakdown and the soil content of the manure. None of these studies provided any data on the amount of soil or gravel that is replaced into pens to restore the level of the original pen surface.

In Australia, for many years, the “standard” amount of manure removed from feedlot pens was assumed to be 1 t DM/head/yr (2.74 kg DM/head/day). In recent years, some lot feeders have indicated that their manure harvesting records indicate the real number could be half of this (0.5 t DM/head/yr or 1.37 kg DM/head/day). It is reasonable to suggest that improved diet formulation and feed processing methods have improved diet digestibility so that less manure is excreted per head.

Photograph 7 - A US feedlot with pen surface of uncompacted soil

Photograph 8 - Feedlot pen with manure mound

Six feedlots across Australia, which are representative of climatic zones, feeding regimes and manure management processes, were selected as study sites by Davis et al. (2012). A methodology to measure manure accumulation rates was developed based on a grid-sampling pattern to provide a feedlot 'manure budget'. The results showed that manure depth was quite variable across the pen due to deposition rates and moisture content at the time of measurement. Under dry conditions (i.e. Feedlot D in Figure 3), on average across the pen, about 20 mm of manure had accumulated after about 25 days. Manure accumulated gradually to about 30 mm after 75 days. With continued dry conditions, the manure pack gradually increases to around 35 mm after a further 50 days. These data indicate that the feedpad compacts very tightly under dry conditions. Further, it is likely that some manure is removed from the pen as dust under these conditions but this loss was not able to be quantified in this study.

Conversely, under wet conditions (i.e. Feedlot F in Figure 3), on average across the pen, a manure depth of 30 mm was measured after about 25 days. After 75 days, a manure depth of 50 mm on average was measured. When the compact manure pack is moistened due to rainfall, it can expand the dry compacted depth two-fold or more. The wetter the pen surface, the greater the variation across the pen. Greater depth measurements indicate areas of higher manure deposition and pugging of the manure due to cattle concentration.

Davis et al. (2012) regularly measured the VS content of the manure on the pen surface. Pen manure samples were obtained directly after pen cleaning, prior to harvest and in between. Over time, the VS in the manure breaks down and is released to the atmosphere as CH_4 or CO_2. The loss of VS from the pen surface was calculated. Davis et al. (2012) concluded from the pen manure decomposition that:

- After 20 days, a reduction of between 60 and 70% in VS in the pad manure compared to fresh manure was measured. Fresh faeces typically have about 80% VS. The greatest rate of VS decomposition occurs in the first 10-20 days (Figure 4).
- After 35 days, a reduction of 70% in VS in the pad manure compared to fresh manure was measured.
- After 80-100 days, a reduction of 75% in VS in the pad manure compared to fresh manure was measured.

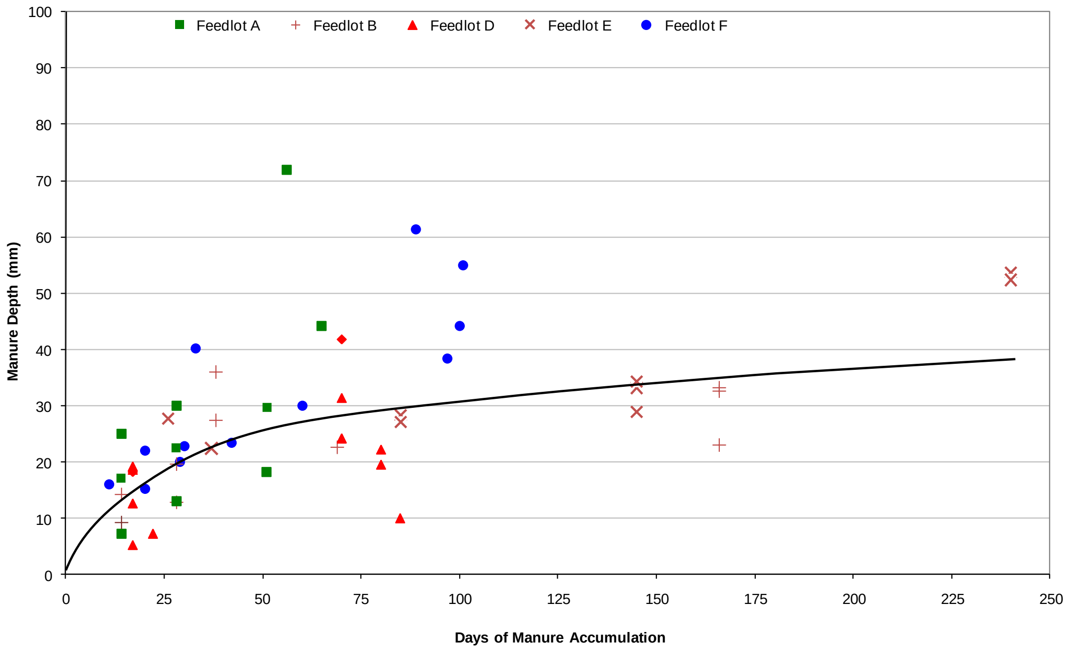


Figure 3 – Manure depth vs. days since cleaning (all pens, Davis et al. (2012))

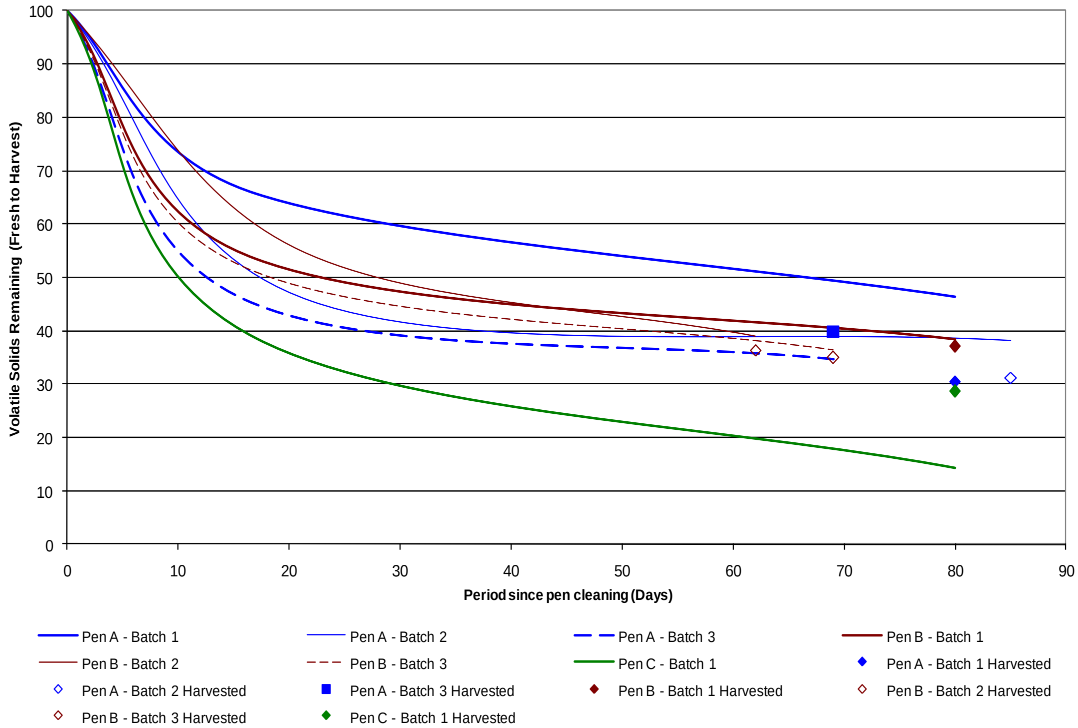


Figure 4 – Volatile solids remaining over time (Feedlot D, Davis et al. (2012))

In addition to manure depth, Davis et al. (2012) compared the estimated TS and VS from four feedlots with that predicted by BEEFBAL (Figure 5). BEEFBAL is a spreadsheet model specifically designed to estimate the quantity and composition of manure produced by cattle feedlots. Estimated data was comparable to predicted data at only one feedlot, where manure excretion ranged between 800 and 1200 kg DM/SCU/year. Dry conditions and maintenance of a manure interface layer ensured that the material harvested was manure only, thus resulting in comparable data. At this site, the data suggests that little soil was harvested, which is consistent with an understanding of the management at that feedlot

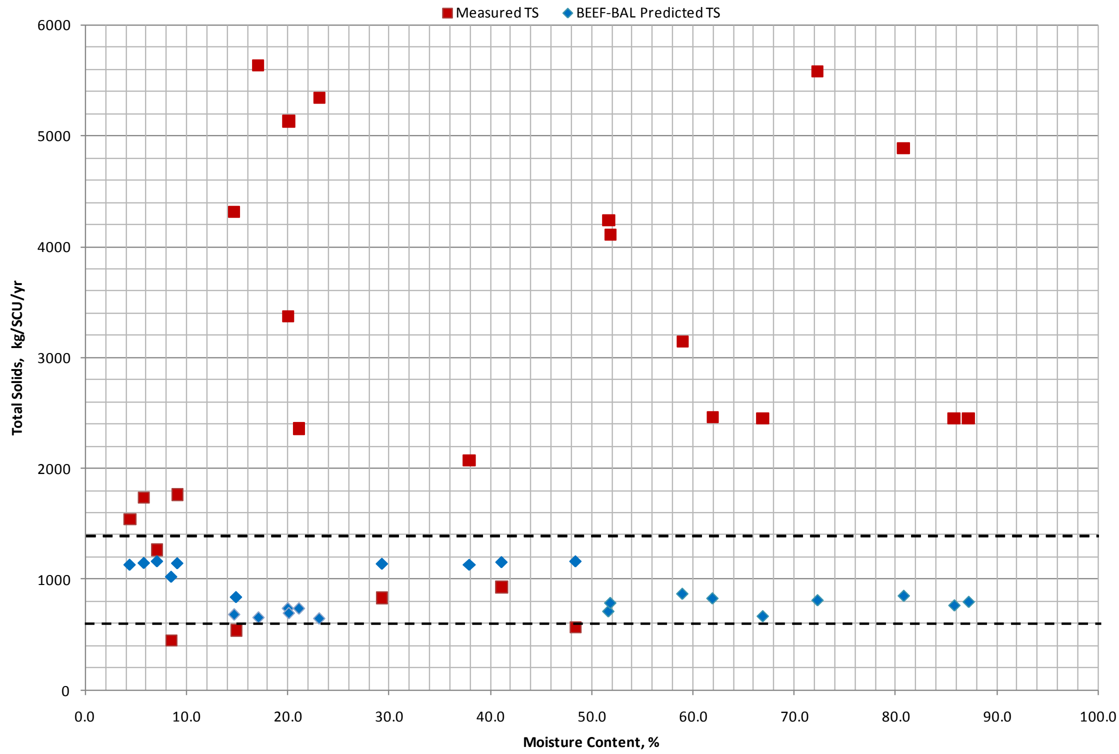


Figure 5 - Comparison of measured versus predicted manure (TS) removed from pens at different moisture contents

At feedlots which cleaned their pens back to the gravel base, the measured TS was up to five times higher than the predicted value using dry matter digestibility approximation of manure production (DMDAMP) in BEEFBAL. In addition, the VS:TS ratio of the excreted manure was about half that of fresh manure. Data from these feedlots suggest that the material harvested contains material other than manure. This additional material (e.g. rocks and/or soil) influences the results by increasing quantity of material harvested and lowering the organic content. This is consistent with US feedlots where "feedlot soil" is harvested.

The data of Davis et al. (2012) suggests that, when only manure is removed from pens, the annual manure harvested is about 1 t DM/head/yr or less as previously quoted. However, as with US experience, if soil is removed with the manure, the annual harvested tonnage is much higher. Fresh faeces mix with the manure on the pen surface and start to degrade. After only 10 to 20 days, 60% to 70% of the VS in the fresh faeces have been lost, and only 10 mm to 15 mm of manure would have accumulated on the pen surface. Pen moisture content is highly variable (10%-90%) depending on local weather conditions.

2.3 Feedlot manure characteristics

2.3.1 Manure moisture, ash, thermal energy and nutrient characteristics

The economic value of feedlot manure for anaerobic digestion is largely determined by the composition (quality) of the manure. Pen cleaning timing, frequency and method affects the quality of the manure removed. Davis et al. (2012) undertook a study of manure accumulation rates in feedlot pens. Watts et al. (2013) undertook a study into the use of manure as a thermal fuel. In both studies, a large number of feedlot manure samples were collected and analysed. The manure samples were divided into three groups: 1. fresh faeces; 2. pen manure; and 3. stockpiled / composted manure.

The fresh faeces samples are fairly closely grouped. All have a moisture content of 75% or more. Most fresh faeces samples have an ash content of 10% - 25% (VS content of 75% - 90%) which is consistent with the data presented below in Figure 6. These samples are too wet to be a thermal fuel but if they could be dried in a cost effective manner without any loss of volatile content, they would be a suitable thermal fuel.

The range in values for both the pen and stockpiled / composted samples is large. On average, the ash content of the stockpiled / composted samples is higher than pen manure samples. This is expected. If the interface layer is removed during pen cleaning (Photograph 6 - Pen cleaning with a front-end loader where the interface is removed exposing the clay base), clay and gravel can be mixed with the manure. This downgrades the manure and increases the ash content. Similarly, as the organic matter in the manure decomposes the relative ash content increases.

Very few stockpiled / compost manure samples lie under the Higher Heating Value (HHV) target curve of 8.1 MJ/kg. HHV is the amount of heat (energy) produced by the complete combustion of a fuel. Hence, they are unsuitable as a thermal energy fuel. While there is a large range in the analyses of the pen manure samples, it is clear that a significant number of the samples lie under the HHV target curve of 8.1 MJ/kg.

Watts, et al. (2013) showed that the ash content of pen manure is highly variable and there are significant differences between feedlots. Ash content can be similar to fresh faeces or similar to highly degraded manure. At each feedlot assessed by Watts, et al. (2013), there was a large range in pen manure characteristics due to management and climate. Hence, it is difficult, but not impossible, to have pen manure that consistently lies under the HHV target curve for thermal combustion of 8.1 MJ/kg.

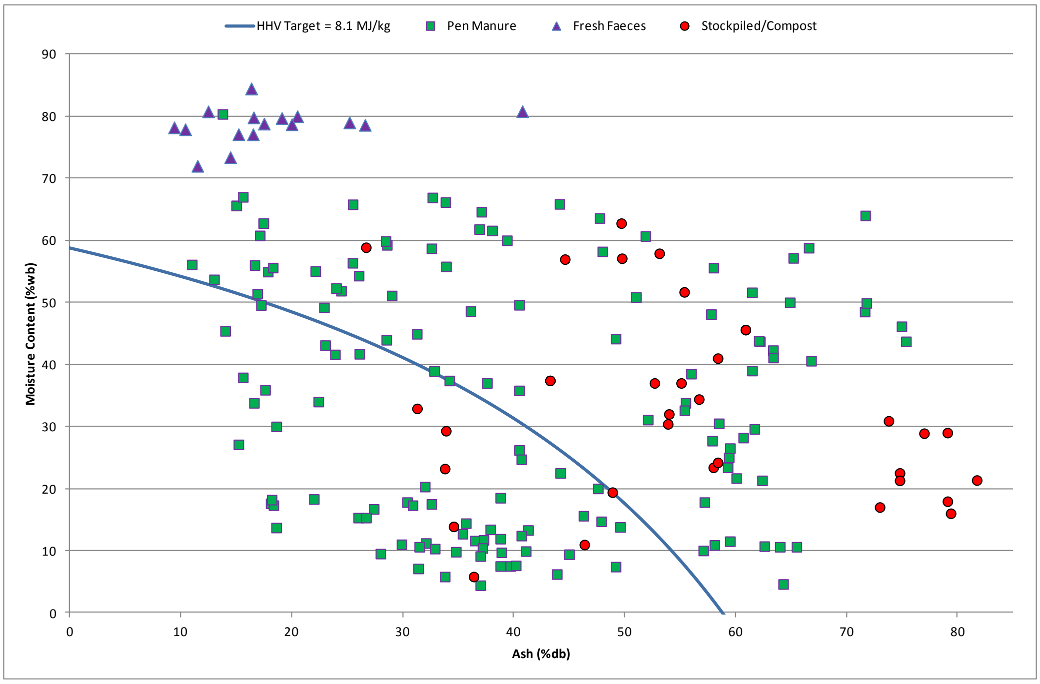


Figure 6 – Relationship between ash content and moisture content for various feedlot manure samples

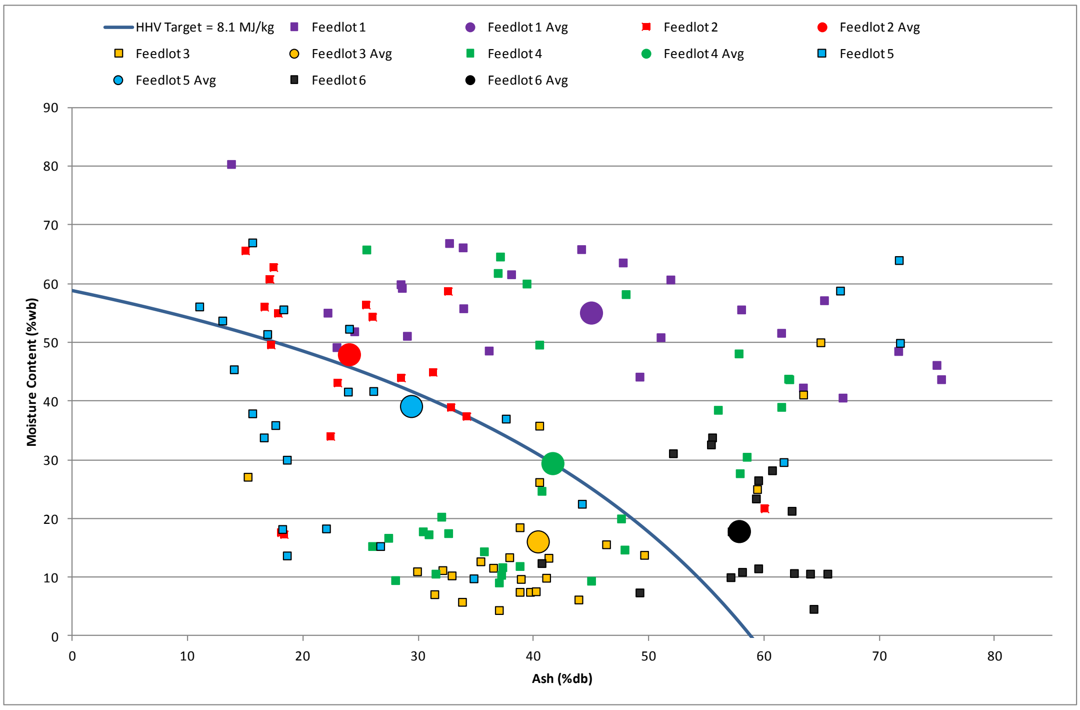


Figure 7 – Relationship between ash content and moisture content for pen surface manure

Similarly, the nutrient content of feedlot manure is highly variable. For each parameter, there is a wide range of results. Given the wide range of manure quality measured across many feedlots, it is concluded that energy recovery plans must be based on site-specific manure analyses rather than generic data such as in these tables.

Gopalan (2013) has analysed manure samples from three different stages of decomposition (fresh, pad, and stockpiled) from three independent feedlots in South East Queensland. This study found that there was considerable loss of both moisture and organic solids as the manure aged, evidenced by an increasing total solids concentration and a decreasing VS fraction.

The settling characteristics of feedlot manure is a key factor in the development of manure effluent strategies, particularly in the design of sedimentation basins (Lott *et al.* 1994). While particle size is important in determining the settling velocity of manure, many other factors including particle density, shape and roughness are key to determining the effective settleabilty of feedlot manure (Graf 1971). A study undertaken by Lott *et al.* (1994) found large remnants of undigested grains and roughage, along with large aggregates in the manure. These aggregates were thought to be comprised of an inner seed husk and wrapped in matted cotton fibre; a process that must have occurred during the digestion of feed.

Analysis on the settling rates of feedlot manure found that 35 to 75% of solids could be removed quickly with a settling velocity of >0.003m/s. Assuming a depth of 1.8m this results in a removal time of 10 minutes (Lott *et al.* 1994). After the initial rapid settling, it was found that a large component (25 to 55%) of the solids could remain in suspension for extended periods of time and efforts to remove this in the sedimentation stage are ineffective. Similarly, Payne (1984) found that 70% solids of pig slurry settled within the first 10 minutes.

Pepple *et al.* (2010) undertook a similar study evaluating the physical and chemical composition of feedlot manure. While comparing the particle density of manure runoff from concrete floored and earthen pens found the densities to be 1.47± 0.18 g/cm^3 and 1.89±0.11g/cm^3, respectively. Interestingly after testing the runoff influent entering and effluent exiting the sedimentation basin there was a 53.5%

reduction in TS concentration, but there was no significant change in the VS/TS ratio. This changed from 51.1% and 50.5% at the entry and exit of the sedimentation basin respectively.

One issue surrounding the digestion of feedlot manure is the apparent build-up of ash and in particular sand (silica) in the bottom of the digester. This is an obvious concern in earth lined pens, but also seems to be a problem on concrete floored pens, as a 'sand' substance was witnessed accumulating at the bottom of a digester tank (Watts pers comms 2014).

2.3.2 Biomethane potential

Biomethane potential (BMP) reflects the anaerobic biodegradability of feedstock, a determining factor of anaerobic digestion (AD). Biomethane potential is commonly quantified by relating the amount of methane produced with the amount of volatile solids (VS) in the substrate, e.g. per unit of VS destroyed or VS loaded (Moller et al. 2004). However, methane productivity does not only depend on total amount of VS. For example, stockpiled feedlot manure typically has 50% VS content while having very low BMP (Gopalan et al. 2013). This raises the question about what constitutes the total VS, i.e. chemical composition of the substrate, and the BMP of different components. A better understanding of the composition of feedlot manure during different stages (e.g. fresh, stockpile) should help explain the overall BMP of feedlot manure. Buswell's formula (Symons and Buswell 1933) can be used to calculate the theoretical methane potential (B_u, L CH_4 / kg VS) of organic materials:

$$C_nH_aO_b + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2 \quad \textbf{Equation 1}$$

$$B_u = \frac{(\frac{n}{2}+\frac{a}{8}-\frac{b}{4})\times 22.4}{12\times n + a + 16\times b} \quad \textbf{Equation 2}$$

Buswell's formula assumes a complete redox reaction and that the only products of AD are water, methane, and carbon dioxide. Theoretical BMP of common substrates can therefore be calculated. For example, the B_u of volatile fatty acids (VFA), carbohydrates, protein and lipids is 370, 415, 496 and 1014 L CH_4 / kg VS, respectively (Moller et al. 2004). Due to the time consuming nature of BMP testing and the relatively simple quantification of chemical composition of manure, there have been some attempts to determine the relationship between BMP of the substrate and chemical constituents. Triolo et al. (2011) found that the lignin content was the strongest predictor for the methane production of pig and cattle manure, whereas Gunaseelan (2007) and Thomsen et al. (2014) found that a combination of four to five chemical constituents can predict the BMP of plant biomass.

2.3.3 Physical contaminants in feedlot manure

Between excretion from cattle and removal from pens, feedlot manure can become contaminated with various physical contaminates. It is clear that the design of biogas units at cattle feedlots has underestimated the degree of physical contamination of the manure (see Section 2.2 Feedlot manure management systems). The physical contaminants include the following.

Soil

Soil can be added to pen manure during pen cleaning (See Photograph 9). This simply adds non-organic matter to the pen manure, thus reducing its value as an energy source. Photograph 10 below, documents correct pen cleaning technique, where a thin surface layer of fresh manure is scraped from the pen surface leaving the compacted interface layer of manure on the soil surface. Photograph 4 above, documents a manure interface layer being peeled off a compacted gravel base that contains rocks and gravel that could potentially contaminate pen manure. The VS content of thinly scraped pen manure can be as high as 75% compared to a VS content of as low as 50% for pen manure containing soil.

Rocks and gravel
Repairs are often made to the surface of feedlot pens by adding rocks or gravel, particularly to high wear areas behind feed bunks and around water troughs (See Photographs 11 & 12). When pens are cleaned, this material can be mixed in with the manure. If pen manure is screened before its final disposal, the rocks can be removed. Photograph 13 below, documents an example of the volume of rocks and gravel that can be screened from manure. Clearly, these types of rocks could cause damage to biogas systems.

Plastic items
Various plastic items, such as ear tags, can contaminate pen manure. Baling twine is of particular concern. This material does not degrade and experience from the USA (see Section 4.7.7 Summary of feedlot biogas in the USA) suggests that bailing twine can wrap around mixing propellers causing them to jam. Photograph 14 below, documents the intake bin for a manure screening plant. There is considerable plastic baling twine caught in the intake screen.

Hair
At the end of winter, cattle shed their winter coats (hair). The hair cannot be easily seen in the pen manure but considerable quantities are present. Hair does not break down easily during the biogas anaerobic process. Photograph 15 below, documents an example of hair, captured in a manure dag, on a pen surface. Feedback from the few feedlot biogas plants in the USA suggested that "hair balls" often form inside the anaerobic digester and these are difficult to remove.

Sundry contaminants
Inevitably, despite attempts to keep pen manure clean, sundry physical contaminants such as lumps of concrete, bones, pieces of steel and other contaminants end up in cleaned pen manure. (See Photograph 16)

Photograph 9 - Pen cleaning where soil is removed with manure

Photograph 10 - Pen cleaning where only manure is removed

Photograph 11 - Example of large rocks being used to repair a high-traffic area in a feedlot pen

Photograph 12 - Placement of gravel to repair a pen surface

Photograph 13 - Stockpile of rocks screened from pen manure

Photograph 14 - Intake bin to manure screening plant showing baling twine

Photograph 15 - Example of hair in a manure dag in pen manure

Photograph 16 - Example of contaminant - wire cable in removed manure

2.4 Feedlot runoff control

2.4.1 Controlled drainage system

A key feature of a feedlot's runoff control system is the formation of a controlled drainage area (Figure 8). It is typically established using:

- a series of catch drains to capture runoff from the feedlot pens and all other surfaces within the feedlot complex and to convey it to a collection system, and
- a series of diversion banks or drains placed immediately upslope of the feedlot complex, which are designed to divert 'clean' or uncontaminated upslope runoff (sometimes termed 'run-on') around the feedlot complex. Where feedlots are built close to the crest of a hill or ridge, there will be minimal runoff from upslope. In these cases, it is possible to have a controlled drainage area without any upslope diversion banks or drains.

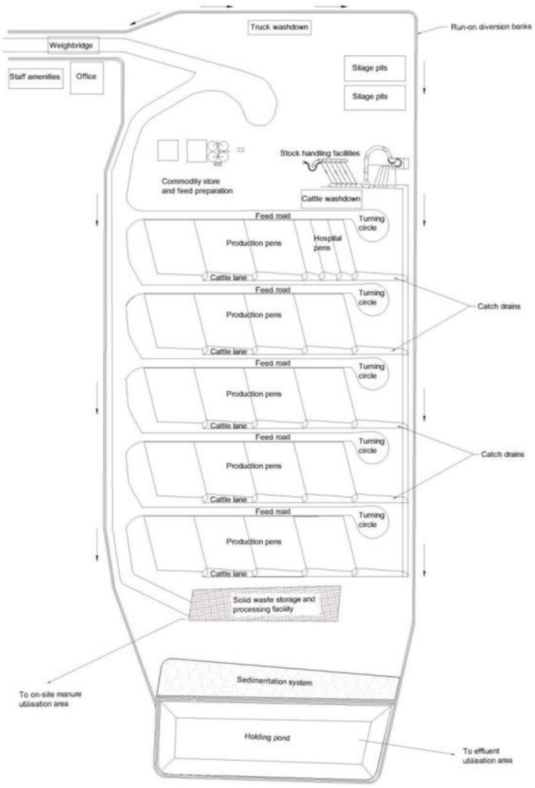


Figure 8 - Controlled drainage area for a feedlot

2.4.2 Sediment removal systems and holding ponds

Sediment removal systems are constructed to trap and detain runoff, allowing entrained sediment to 'settle out' before the runoff enters the feedlot holding pond. Their function is to reduce siltation of the holding pond. Holding ponds are designed to capture and store the runoff from the controlled drainage area. The application of holding pond wastewater to land, where it is sustainably utilised by crops and soil, is generally the preferred form of wastewater management.

2.4.3 Feedlot effluent quality

Feedlot runoff can contain high levels of nutrients. It might be expected that as the nitrogen content of effluent increases so would other major nutrients such as P and K. However, Watts, et al. (2013) showed that there is no relationship between Total N and Total P content of feedlot effluent, probably due to variable atmospheric losses of nitrogen from holding ponds and phosphorus settling in pond sediment. Given the wide range of effluent quality measured across many feedlots, it is concluded that effluent management plans must be based on site-specific effluent analyses rather than generic data.

2.4.4 Biogas from feedlot effluent

Unlike other intensive livestock systems such as piggeries, feedlot holding ponds and the effluent that is captured are poor candidates for biogas production. The reasons are:

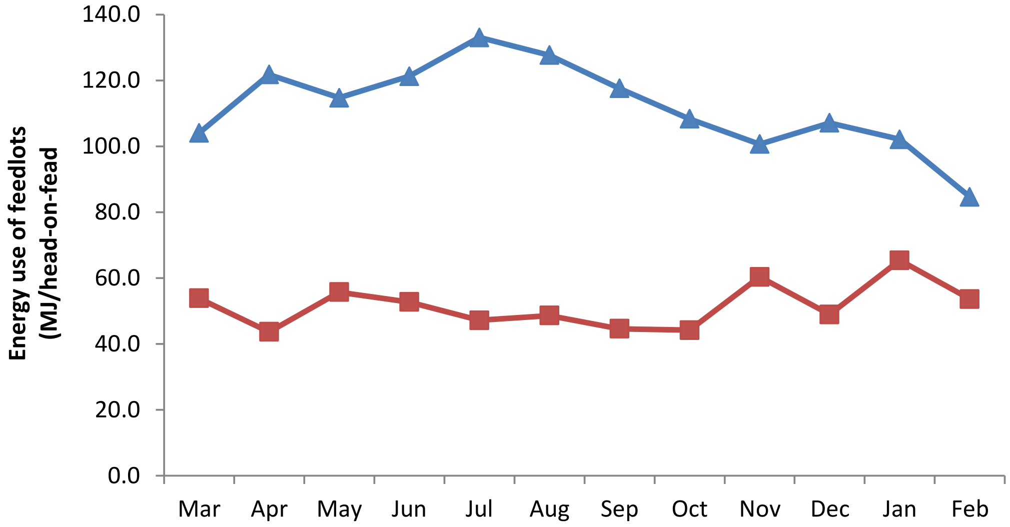
1. As much of the manure as possible is removed from the effluent prior to storage in the holding pond by the use of sediment removal system. The vast majority of the organic matter produced in feedlot manure is retained on the feedlot pens and is not transferred to the holding pond. For example, Bierman et al. (1999) found that only 2-4% of organic matter excreted on the feedlot pen surface in their experiment was removed in runoff.

2. The inflow of effluent is highly variable as it is driven mainly by rainfall. Extended periods can occur where there is no fresh effluent inflow.
3. Feedlot holding ponds are usually configured to maximise evaporation loss. Hence, they are shallow with a large surface area. This makes them unsuitable to retrofit to become a covered anaerobic pond.

2.5 Energy consumption at cattle feedlots

Davis et al. (2009) undertook a study of energy usage at Australian feedlots. Eight feedlots were selected such that the feedlots represent a cross section of geographical, climatic and feeding regime diversity within the Australian feedlot industry. A number of energy sources are used in a feedlot. Electricity is principally used for grain movement, feed processing, and administration, to pump water from bores and to wash cattle. Gas (Natural, LPG - Propane, LPG - Butane) is the predominant energy source for boiler equipment used in heat/steam generation. Diesel predominantly and to a lesser extent petrol is used in mobile plant and equipment. Energy usage is largely driven by the feed management and the processing system employed by the feedlot. Among them, feed management is the largest single consumer of energy in the feedlot.

The average monthly total energy usage across all feedlots for March 2007 to February 2009 ranged from 49 MJ/head-on-feed/month to 160 MJ/head-on-feed/month. Feedlots with steam flaking feed processing systems had an average usage in the order of 120 MJ/head-on-feed/month, compared with an average of about 45 MJ/head-on-feed for feedlots that process grain by other means. It appears that energy usage at feedlots with steam flaking tends to be higher in winter and lower in summer, although this is not clear for feedlots without steam flaking. Considering that biogas production in winter, as influenced by ambient temperature and production, can be lower than in summer, the mismatch between energy consumption and production needs to be considered for biogas production in feedlots.



■ **feedlots -no steam flaking** ▲ **feedlots - steam flaking**

Figure 9 – Average monthly total energy usage at eight feedlots (MJ/head-on-feed/month) during March 2007 to February 2008

For steam flaking systems, the average monthly gas energy usage measured in 2007-2008 ranged from 240 to 380 MJ/t grain processed. Slightly higher levels were measured in 2008-2009 (260-430 MJ/t grain processed). There were three types of gases used within the four feedlots with steam flaking systems. These were LPG, butane and natural gas. All of these gas sources have different calorific values (heating content) and pricing structures and therefore impact on energy consumption. Some of the variation in gas usage can be attributed to heating efficiency during winter months. However, mill management also impacts on energy consumption.

2.6 Anaerobic digestion operating parameters

2.6.1 The anaerobic digestion process

Anaerobic digestion is a biological mechanism that converts organic material into methane and carbon dioxide in the absence of oxygen. The energy in the material being digested is retained in the produced gas as methane. Anaerobic digestion is a natural process that takes place in the absence of oxygen. The digestion process occurs in several steps. Figure 10 shows an overview of the process (Pavlostathis & Giraldo-Gomez 1991).

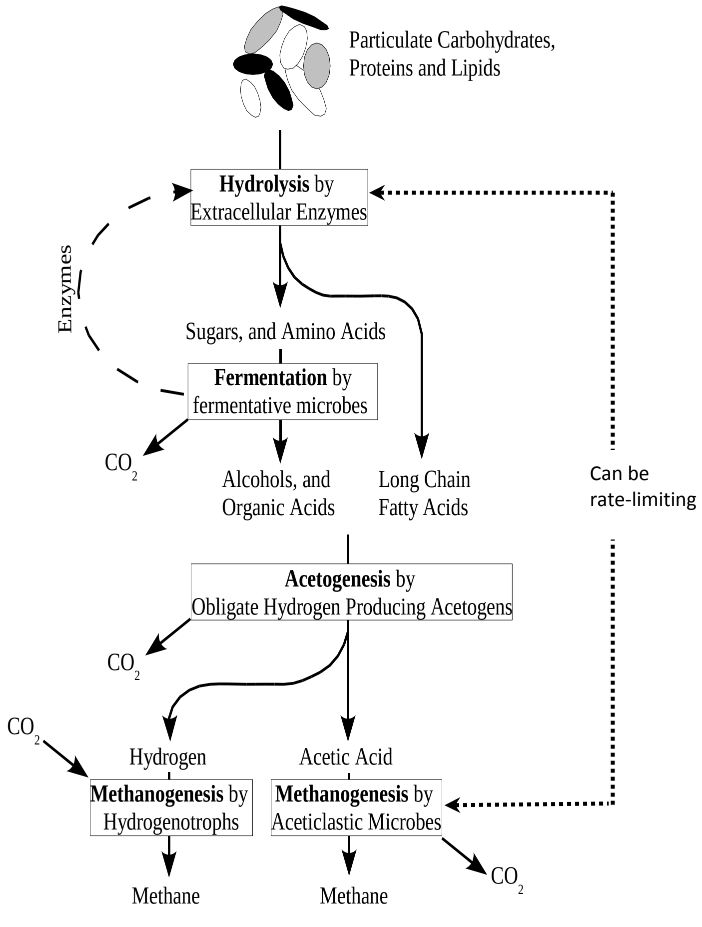


Figure 10 – Anaerobic digestion process

Source: Pavlostathis & Giraldo-Gomez (1991)

The key steps involved in anaerobic digestion include (Monnet 2003, Pavlostathis & Giraldo-Gomez 1991):

a. Hydrolysis – This is a chemical process where hydroxyl groups break down complex organic molecules into sugars, amino acids and fatty acids. This step can often limit the rate of the digestion process due to the nature of the feedstock. To reduce the possibility of rate limitation, the feedstock should be reduced to small particulate size. Significant rate limitation in this step will lead to an overall poor digester performance. This would be evident with undegraded material being washed out.
b. Acidogenesis / Fermentation – This is a biological process in which sugars and amino acids a converted into volatile fatty acids, alcohols, and carbon dioxide. It is almost never rate-limiting, but will decrease pH, and may inhibit other steps.
c. Acetogenesis – Organic acids and alcohols are converted to acetic acid, and hydrogen in this biological process. It is generally only rate-limiting in very high rate processes.
d. Methanogenesis – The final stage in anaerobic digestion, methanogenesis involves the action of two groups of methanogenic bacteria. The first group (aceticlastic methanogens) splits acetate into methane and carbon dioxide, and the second group (hydrogenotrophic methanogens) combines hydrogen and carbon dioxide to produce methane.

2.6.2 Digester temperatures

Typically, most digesters are designed for either mesophilic or thermophilic conditions. Mesophilic digestion takes place optimally around 30 to 38 °C, or at ambient temperatures between 20 and 45 °C, where mesophiles are the primary microorganism present; while thermophilic digestion takes place optimally around 49 to 57 °C, or at elevated temperatures up to 70 °C, where thermophiles are the primary microorganisms present. In general, with increasing temperature, the digester performance improves, comparable digester size is reduced due to higher loading rates but the thermophilic digesters are regarded as being less stable (Batstone 2006). There appears to be an upper temperature limit of around 60°C above which there is a rapid reduction in microbial activity (Chynoweth et al. 1998). Sudden changes in reactor temperature of (± 2°C) can lead to the last stage of digestion (methanogenesis) to fail. Sufficient energy is normally available from the gas engine system to heat the digester to at least mesophilic temperatures without an external heat source (Batstone 2006).

2.6.3 Ammonia content

Ammonia inhibition is caused by the free form of ammonia (i.e., NH_3, not the ammonium ion NH_4^+). Inhibition by ammonia is strongly influenced by pH and is also temperature dependent, as demonstrated in Figure 11 (Batstone et al. 2002, Siegrist et al. 2002).

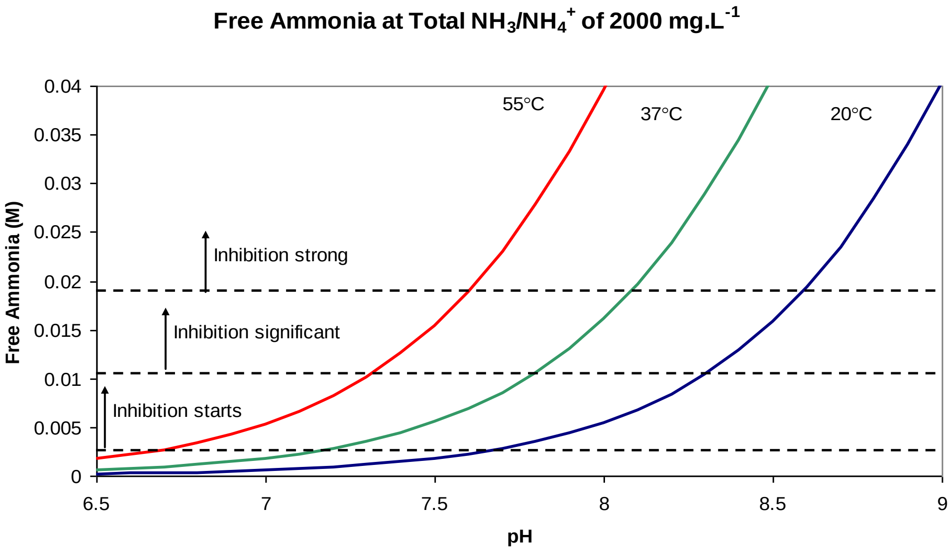


Figure 11 – Free ammonia levels, and ammonia inhibition

Ammonia inhibition has a strong impact on the final step of aceticlastic methanogenesis and in the short term, will cause inhibition. In the long term, it will cause a fundamental change in microbiology that causes the system to operate in a sub-standard way (Karakashev et al. 2006).

Despite its negative impacts, ammonia can also have a positive impact in that its presence maintains a pH of >7, which is vitally important for anaerobic digesters. The fermentation step produces acids, which lowers the pH and the presence of ammonia helps maintain the pH at a higher level. At a pH of below approx. 6.5-7.0, methanogenesis stops (Batstone et al. 2002), fermentation continues and the system enters an acid overload from which it is very difficult to recover (caustic dosing is required). Ammonia acts as a base, and keeps the pH at a high level.

Most of the ammonia-nitrogen in feedlot manure is produced from urine. Due to the nature of feedlot manure management, pen manure contains little ammonia-nitrogen. Considering the positive impact of ammonia in AD, however, the buffer capacity of feedlot manure may be smaller than other manure (e.g. pig manure) that contains higher amount of ammonia-nitrogen.

2.6.4 pH and VFAs

Eghball et al. (1997) found that pH of feedlot manure collected from unpaved pen varied from 7.4 to 8.9. The amount of VFAs and ammonia that are volatilised from manure mainly depends on manure pH and concentrations of VFA's and ammonium nitrogen. As the pH is reduced, the proportion of VFA's in the volatile form increases. At higher pH levels, the ammonium nitrogen equilibrium moves towards ammonia, which is more readily volatilised.

In general, the optimum pH for anaerobic digestion is 6.5-7.5. The conversion rate of organic compounds to VFAs is faster than the conversion rate of VFAs to methane. At concentrations above 1,000 mg/L VFAs can be toxic to methanogenic bacteria. Significant toxic problems are unlikely to occur if the digestion process is operated in the pH range 6.5-7.5 with VFA concentrations below 1,000 mg/L (Svoboda 2003).

2.6.5 Antibiotics and feed additives

A wide range of antibiotic agents are registered for therapeutic use on cattle in Australia. Some of the most important antibiotic agents include benzathine penicillin, procaine penicillin, ampicillin, amoxycillin, cloxacillin, cefuroxime, cephalonium dihydrate, cefuroxime, ceftiofur, erythromycin, oxytetracycline, sulfadiazine, sulfadimidine, sulfadoxine, dihydrostreptomycin, novobiocin, trimethoprim, florfenicol, neomycin, tylosin and flunixin (Khan *et al.* 2008). In addition, there are more than 30 antibiotic products registered for 'enteric' uses in Australia, including polyether ionophores (monensin, lasalocid, narasin, salinomycin), macrolide (tylosin), oxytetracycline, and neomycin (Khan *et al.* 2008). Among these, monensin is the most common active ingredient of feed additives registered for enteric uses in Australia (Khan *et al.* 2008). Very few of the individual chemical contaminants have been thoroughly investigated in Australian feedlot manure and effluent. Enteric feed additives are likely to be significantly more prohibitive to biogas production than the agents used only intermittently to treat illness (Roser *et al.* 2011). For example, polyether ionophores such as salinomycin, lasalocid and monensin are used to improve feed conversion efficiency in feedlot beef cattle. However, polyether ionophores are toxic to many bacteria, protozoa, fungi and higher organisms.

Not all of the antibiotics in livestock feed are metabolised during the digestion process. This incomplete digestion results in a significant percentage of the antibiotics, passing through the animal and being excreted in the parent form. For example, studies have found that approximately 40-50% of the monensin added to cattle feed was excreted (Hilpert et al. 1984; Elanco 1989), and at least 75% of monensin administered orally to steers was excreted within three days of intake (Herberg et al. 1978). Through the use of ^{14}C (Carbon 14) radioactive marking, it has been determined that all of the excreted monensin is found in faeces and none in the urine (Herberg et al. 1978). Residual monensin levels as high as 1 to 5 mg/kg have been found in the manure of cattle provided with feed that contains the monensin additive (wet basis) (Donoho 1984; Elanco 1989).

Studies have documented that monensin metabolites have a decreased biological activity (as compared to monensin) (Donoho 1984), while metabolites of other antibiotics still comprise antibiotic potency (Thiele-Bruhn 2003). Once excreted by the animals, metabolites are subjected to various biotic and abiotic degradation processes. Photodegredation and hydroxylation are the most important abiotic degradation and inactivation processes, however, the effects of these processes are thought to be limited when antibiotics fix to soil particle surfaces or get "sheltered" from pores within the soil matrix.

The increased opportunity for biotic degradation, through microbial biotransformation in soil and manure is considered a more important degradation path (Thiele-Bruhn 2003). For this reason, monensin has been found to degrade faster in soil and manure. Research has illustrated the effectiveness of biotic degradation by comparing the half-life of monensin under different conditions. Under photolysis degradation the half-life of monensin was found to be 43.9 days (Elanco 2010), 13.5 days in soil (controlled laboratory), 3.8 days in the field without manure, and 3.3 days in the field with manure (Carlson and Mabury 2006). In another study, the half-lives of monensin and lasalocid in soils were found to be less than 4 days, while fresh liquid manure amendments did not significantly alter degradation (Sassman and Lee 2007).

From the time of manure excretion, to final land application, various physical processes including leaching, runoff, and direct handling by staff provide opportunities for the antibiotics to be lost into the surrounding environment. Manure management therefore acts as an important "buffer" process to reduce the biological activity of antibiotics. Aerobic manure management (composting) has been found to result in similar or greater attenuation than anoxic or anaerobic management. Dolliver *et al.* (2008) found that stockpiling manure had a comparable effectiveness in reducing some antibiotics, when compared to manure managed by composting and vessel composting. At the end of the composting period (22–35 days), chlortetracycline reduced by 99%, monensin and tylosin reduction ranged from 54 to 76%, whereas sulfamethazine did not degrade (Dolliver *et al.* 2008). Kuhne *et al.* (2000) found that degradation of tetracycline was faster in ventilated liquid manure than in unventilated conditions.

Antibiotics have been found to inhibit the activity of anaerobic microbes and therefore, depending on dose rates may negatively affect biogas production (Dennis and Burke 2001). The inhibitive effects of antibiotics on anaerobic methane production vary significantly between different antibiotics. For example, the effective concentration (EC) that inhibited anaerobically digested methane production by 10% (EC_{10}) was 130 mg/L for tylosin, but only 0.7 mg/L for imipenem (Figure 12). Data of open bars was from experiments with municipal sewage (Gartiser et al. 2007), data of filled bars was from experiments with fresh and screened cattle manure (Mitchell *et al.* 2013)

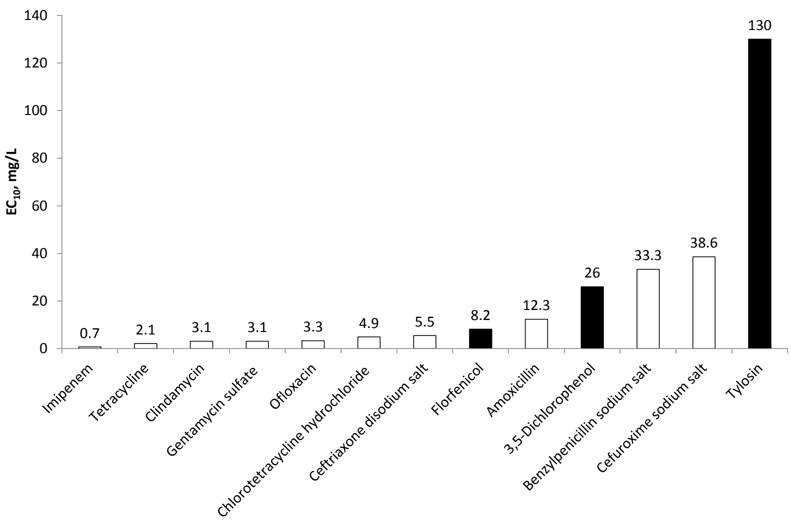


Figure 12 – Effective concentration of some antibiotics when 10% inhibition was found on methane production from anaerobic digestion (EC10).

Despite its wide use as a feed additive, very few studies have investigated the effect of monensin on anaerobic methane production. Gartiser et al. (2007)) found that adding monensin to municipal sewage, at a concentration between 25 and 100 mg/L reduced methane production by 77%. The study did not identify a dose response relationship however, it is important to note that different substrates have different microbial communities and thus, degradation of antibiotics varies from one substrate to another. Varel and Hashimoto (1982) found complete inhibition of methane production when manure from steers fed monensin at 29 mg per kg of feed was added to a biologically active 3L anaerobic digester. The study witnessed a six month period of microbe acclimation, before the system methane production returned to expected levels. Experience from dealing with covered anaerobic ponds at a piggery also suggest that trace amounts of monensin can kill a whole pond within a few days, leaving little chance of recovery (Jenkins S, per comm).

In another study, Varel et al. (2012) found that anaerobic digestion at 38°C or 55°C may be an effective treatment to reduce chlortetracycline (CTC) in swine manure, but not monensin in cattle manure. After 28 days of anaerobic digestion, manure from cattle fed with monensin at 22 mg/kg dry feed matter and manure from swine fed CTC at 55 mg/kg dry feed matter, the concentration of CTC in the 22°C, 38°C and 55°C swine digester slurries decreased 70, 80 and 98%, whereas monensin decreased 3, 8 and 27%, respectively. Methane production was higher from the slurries in the 38°C than in the 22°C digesters, but fell to intermediate level in the 55°C slurries (Varel and Hashimoto 1982). At a commercial scale, use of monensin in a dairy farm was found to have no discernible effect on biogas production from the covered anaerobic lagoon (Martin 2008). However, without knowing the historical usage of monensin (and potentially other antibiotics) in animals and the resulting concentration in the slurry, it's difficult to understand why inhibition was not observed.

2.7 Types of anaerobic digesters

The design of the anaerobic digester needs to provide sufficient retention time to allow for hydrolysis of particulate substrates, and provide beneficial conditions for methanogenesis where acetate is converted to methane. This also includes maintaining the digester pH above 7.0.

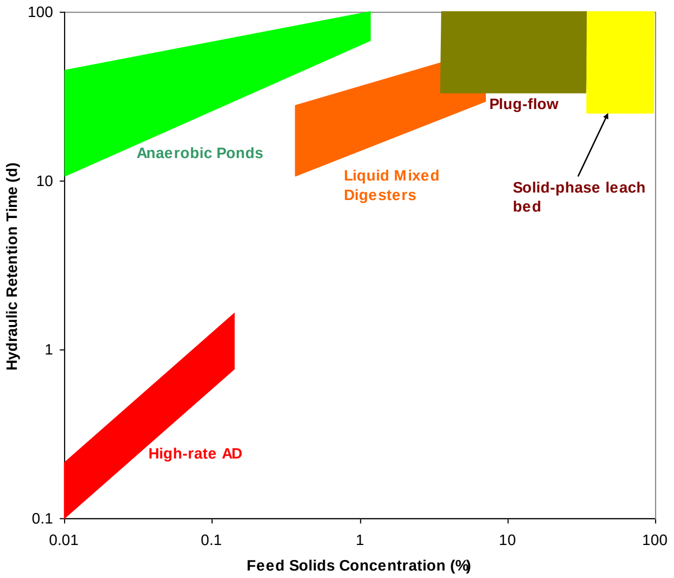
Anaerobic digestion (AD) technologies have developed into two broad areas as shown in Figure 13. The split between the two groups should be read as the four upper technologies in a group and the single technology in the lower group.

Methods that provide the ability for a long hydraulic retention times (HRT) with extended sludge retention, providing beneficial conditions for the methanogenesis step where acetate is converted to methane, include:

- anaerobic lagoons
- liquid mixed digesters
- plug flow digesters
- leach bed digesters.

Short HRT time, with extended solids retention to promote hydrolysis of the feed stream is a feature of high-rate AD.

AD systems can have only one stage, that is, all the biochemical reactions take place in the same digester. However, two or multi-stage systems are also used to optimize environmental conditions for the different stages of AD. Typically, two stages are used where the first one harbours the hydrolysis-acidification reactions, and the second one harbours the acetogenesis and methanogenesis (Vandevivere et al. 2002). The most common AD systems used by the intensive animal industry utilise one stage design due to lower cost and easier operation (Vandevivere et al. 2002).



Source: Batstone D (2009) Pers-Coms. and Jensen, 2014)

Figure 13 – Operating conditions (HRT and feed solids concentration) of different types of anaerobic digestion

2.7.1 Anaerobic Ponds

Ponds provide a long HRT and are perceived as a low capital cost option. Large ponds tie up land, can be a source of odour problems and require desludging approximately every 10 years. Desludging can be expensive and may require a pond shut down or an alternative waste handling system in operation while desludging occurs. Methane capture requires an impermeable cover and collection system (See Photograph 17). Methane capture from covered anaerobic ponds (CAPs) has generally been reported as relatively poor. However, recent work by the New Zealand National Institute of Water and Atmospheric Research (NIWA) demonstrates that biogas availability from a well-designed CAP is similar to the biogas availability from heated tank reactors (NIWA 2008). Solids loading heavily drive overall costs. The concentration of the waste stream to the pond is relatively low at around 1% for piggery effluent. Because of the large pond volumes, correction under failure can be extremely expensive or impractical.

Photograph 17 – Covered anaerobic pond for biogas production

2.7.2 Liquid mixed digester

The mixed digester operates at an inflow concentration range of 3-6% total solids. The digester is operated as a fully mixed system, with either gas recirculation, or mechanical mixers incorporated in the design. The feedstock can be continuous or batch fed with retention times of approximately 20 days. This is established technology and is used across many industries. The costs are relatively high to establish the plant and the tanks provide poor volumetric loading. The mixed digester produces a liquid digestate.

2.7.3 Liquid plug flow

Material is loaded at the front of the digester, and passes through the digester to become a product at the end. As the materials are not mixed, intimate contact between the bacteria and the biomass is poor. The liquid plug flow digester operates at semi-solid liquid (10-20% total solids) conditions in a long polyethylene tube. The plug flow digester has a very high loading rate.

2.7.4 Solid phase (leach bed)

This is similar to an engineered, high-rate landfill where material is loaded into a digester, tumbler, or baskets, and leachate or inoculum liquid is circulated through the solids in the digester. Very high loading rates are possible with very high feed solids concentrations of 20% or more total solids. Good gas conversion is possible due to retention of the active biomass. The digesters can be difficult to effectively seal. The digesters can operate in either batch or continuous form. The batch solid phase digester is operated until methane production stops and the digester is unloaded and reloaded. The biogas quality and quantity is variable. However, the batch plant can be relatively inexpensive. For the continuous solid phase digester, material is continually added and spent material removed. The digester produces a continuous biogas supply but is considerably more expensive than the batch process. The continuous process is only practical at a very large scale and is extremely expensive.

2.7.5 High-rate anaerobic digesters

High-rate anaerobic digesters normally operate with extended solids retention time, and short HRT by integrating solids retention within the main digester. They require a low solids feed, with relatively high amounts of soluble feed material, and are most often used for domestic sewage treatment, as well as industrial wastewaters (van Lier 2008). HRTs are normally short, typically less than 48 hours, while solids retention times can be very long. (See Photograph 18 – Anaerobic Digester – Denmark farm facility).

Photograph 18 – Anaerobic Digester – Denmark farm facility

2.8 AD process outputs

2.8.1 Biogas yield

Biogas produced anaerobically is primarily composed of methane (CH_4) and carbon dioxide (CO_2). The gas may also contain smaller amounts hydrogen sulphide, ammonia and trace elements of hydrogen, nitrogen and carbon monoxide. The gas is usually saturated with water vapour and can also contain dust particles.

Table 3 shows the typical range of biogas components. The actual content of a particular component will depend upon the feedstock mix.

Table 3 - Typical range of biogas components

Component	Content range[a]	Content range[b]
Methane	55 – 80%	63.2%
Carbon dioxide	15 – 45%	18.8%
Hydrogen Sulphide	0 – 5000 mg	
Ammonia	0 – 450 mg/m^3	
Humidity	Saturated	
Calorific Value	20 – 25 MJ/m^3	

Source: a) Navickas (2007).

b) Birchall (2010). NOTE Methane content ranged from 54% to 70.4%

To determine the CH_4 production from manure, it is necessary to convert VS content to CH_4 generation by applying the B_o factor (maximum biomethane potential) and the Methane Conversion Factor (MCF). The methane emissions (kg CH_4/yr) can be calculated using the following equation:

$$Q_b = VS \times B_o \times MCF \times \rho CH_4$$ **Equation 3**

Where:

Q = methane production from the waste (kg/yr)
VS = volatile solids production (kg)
B_o = maximum methane-producing capacity
MCF = methane conversion factor
ρCH4 = density of methane (0.662 kg/m^3)

B_o factor

Due to differences in digestive efficiency and feed type, B_o varies with animal type across the world. IPCC (2003) provides typical B_o values for different livestock species and locations (Table 4).

Table 4 – Maximum methane-producing capacity of the manure (B_o)

Animal	B_o (m^3 CH4/ kg VS)
Swine	0.45
Dairy cattle	0.24
Feedlot beef cattle	0.17

Source: (IPCC 2006)

Moller et al. (2004) note that "methane productivity" from manure can be measured in terms of VS destroyed, VS loaded, volume, or animal production. Methane productivity measured in terms of VS destroyed (m^3 CH_4/kg VS_{DES}) corresponds to the theoretical methane yield (B_o) if there is complete degradation of all organic components of the manure. The theoretical methane potential can be calculated from Buswell's formula. Methane productivity in terms of VS loaded (m^3 CH_4/kg VS_{load}) as residence time approaches infinity is referred to as the ultimate B_o. The ultimate methane yield will always be lower than the theoretical methane yield because a fraction of the substrate is used to synthesise bacterial mass, a fraction of the organic material will be lost in the effluent, and lignin-containing compounds will only be degraded to a limited degree (Moller et al. 2004). Inhibition of the biological process by inhibitors such as ammonia and VFA is another factor contributing to the actual methane yield being lower than the potential yield which would be obtained if inhibition was not present. It has been observed that both the B_o and the volumetric methane production (L CH_4/ m^3 manure) of manure from different origins can be very variable. Moller et al. (2004) notes that the ultimate methane yield (m^3 CH_4/kg VS) is affected by various factors, including:

- Incubation temperature (varies from 35°C to 55°C).
- Source and amount of inocula added.
- Timing and amount of mixing of the sample.
- Amount of dilution of the sample.
- Incubation time (50 to 157 days).

Not surprisingly, both Vedrenne et al. (2008) and Karim et al. (2002) have found that variation of any of these parameters affects maximum methane yield. Hence, apart from variations between species and feed type, B_o data will vary depending on experimental protocol and should be evaluated with knowledge of the experimental procedures adopted. For example, ICF Consulting (1999) provides B_o values for beef, dairy and swine for various diets as collated from a range of researchers (see Table 5, Table 6). This table shows the variability of the data.

Angelidaki et al. (2009) pointed out that despite a mass of data having been generated; comparison of biodegradability data in the literature is very difficult. This is not only due to the variety of equipment, but also to the many different environmental conditions and protocols that are used. For example, the inoculum-nutrients mix, liquid and headspace volumes, pH, headspace pressure and the detection system can all differ from on test to another (Angelidaki et al. 2009). Recently, a guideline has been defined on components (e.g. substrates, inoculum, medium.) and also the procedure (e.g. how to report results) of the BMP test (Angelidaki et al. 2009).

Biogas yield from anaerobic digestion of organic material is determined by the feedstock composition. Table 5 shows the wide range of biogas yields for different feedstocks. The quantity of VS in the wet biomass is not specified and this introduces a degree of uncertainty in the actual biogas yield from each biomass source. However, the intention of Table 5 is to show the range of biogas yields possible from different feedstocks. Table 6 also shows the B_o reported in literature.

Gopalan (2013) demonstrated that, at beef feedlots, over 40% of initial methane potential from manure is lost in 2-3 weeks of drying on pads and this loss is over 70% in stockpiles (Table 8). There is significant reduction (up to 70%) in the non-degradable organic fraction of solids along with the expected reduction in the degradable fraction through the practice of stockpiling. Fresh manure degrades faster, as shown by first order coefficient (k_{hyd}) fitted using model analysis (Gopalan, 2013).

Table 5 - Biogas yield from different feedstocks

Biomass	IEA Bioenergy[a] (m^3 biogas/ wet t biomass)	Bioplin Technology[b] (m^3 biogas/ t biomass)	B_o Maximum methane producing capacity[c] (m^3 CH_4/kg VS)
Pig Manure	18	25	0.45
Fattening Cattle Manure	34	30	0.17
Dairy Manure	20	55	0.24
Poultry Manure	93	35	0.36-0.39
Distillery Waste	35 (Potato)	80	
Vegetable Processing	35		
Rape Seed Cake	612		
Canteen Waste (high fat)	90		
Canteen Waste (low fat)	44		
Fat	108 (flotation fat)	800 (used fats)	
Fatty Waste		400	
Vegetable Oil		350	
Sewage Waste		80	
Meadow Grass	98		
Maize Silage	190	200	
Grass Silage	183	110	
Milled Grain	597		
Corn Crop Mix (5.3% fibre)	391		
Total Plant Grain Silage	195		

Source: a) IEA Bioenergy 15th European Biomass Conference & Exhibition; b) Navickas (2007); c) IPCC (2006), the Oceania region

Table 6 – Methane yields from various types of animal waste

Type of animal waste	B_0 (L CH_4/kg VS)	References
Cattle manure (wheat straw bedding)	85	(Buendía et al., 2008)
Cattle manure	95	(Qiao et al., 2011)
Dairy cattle manure	148	(Møller et al., 2004)
Pigs-weaner	150	(Vedrenne et al., 2008)
Piggery waste-solid fraction	165-175	(Rodriguez & Lomas, 1999)
Pig manure	170	(Qiao et al., 2011)
Cattle manure	200	(Ahring et al., 2001)
Cattle manure(readily biodegradable industrial by-products added)	200-260	(Kaparaju et al. 2008)
Pigs-grower/finisher	200-450	(Massé et al., 2000)
Cattle manure (6-8 weeks)	210	(Hashimoto et al., 1981)
Cattle manure	220	(Hill, 1984)
Cattle manure (fresh)	260	(Hashimoto et al., 1981)
Pigs-sow	270	(Møller et al., 2004)
Pig-dry sow	280	(Vedrenne et al., 2008)
Pig	320	(Hill, 1984)
Pigs-grower/finisher	320	(Vedrenne et al., 2008)
Pigs-farrowing	340	(Vedrenne et al., 2008)
Pigs-grower/finisher	350	(Møller et al., 2004)
Poultry manure	360	(Hill, 1984)
Cattle manure	420	(Karim et al., 2007)
Pigs- faeces	420-470	(Feng et al., 2008)
Pigs-grower, faeces	480	(Hashimoto et al., 1981)
Pigs-faeces and urine	580	(Feng et al., 2008)

Source: Gopalan (2013)

Table 7 – Maximum methane producing capacity for US livestock fresh manure

Animal Type	Diet	Converted B_o (L CH_4/kg VS)	References cited
Beef	7% corn silage, 87.6% corn	290	(Hashimoto et al. 1981)
	Corn-based high energy	330	(Hashimoto et al. 1981))
	91.5% corn silage, 0% corn	170	(Hashimoto et al. 1981)
		230	(Hill 1984)
		330	(Chen et al. 1980)
Dairy	58-68% silage	240	(Morris 1976)
	72% roughage	170	(Bryant et al. 1976)
		140	(Hill 1984)
	Roughage, poor quality	100	(Chen et al. 1988)
Pigs	Barley-based ration	360	(Summers & Bousfield 1980)
	Corn-based high energy	480	(Hashimoto 1984)
		320	(Hill 1984)
	Corn-based high energy	520	(Kroeker et al. 1979)
	Corn-based high energy	480	(Stevens & Schulte 1979)
	Corn-based high energy	470	(Chen 1983)
	Corn-based high energy	440	(Iannotti et al. 1979)
	Corn-based high energy	450	(Fischer et al. 1975)

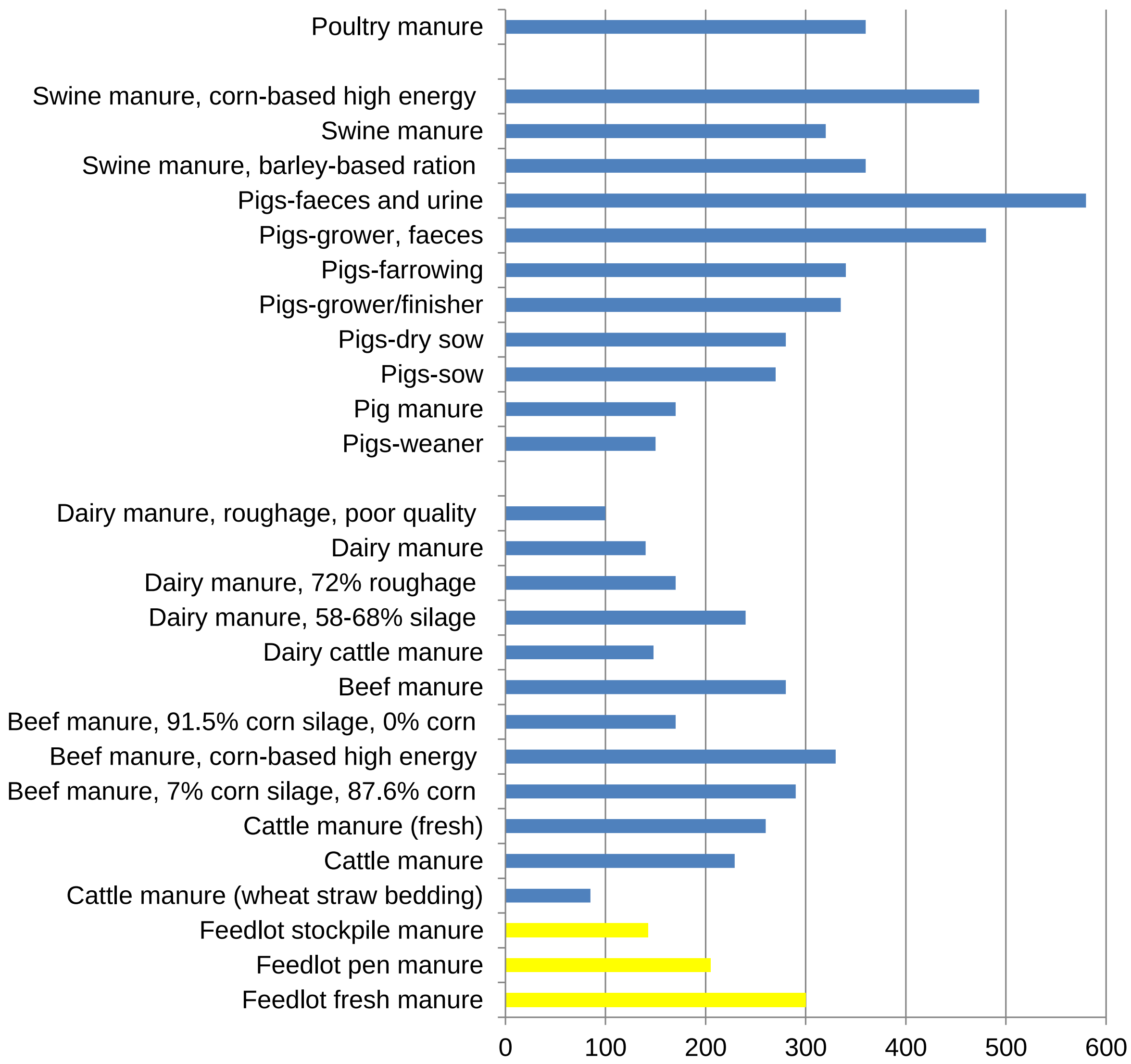


Figure 14 – Reported BMP (L CH_4 / kg VS) in literature

(Data for feedlot stockpile, pen and fresh manure sourced Table 8 – Biochemical methane potential (B0) of manure samples collected at three Australian feedlots)

Table 8 – Biochemical methane potential (B_0) of manure samples collected at three Australian feedlots

Manure source	FA1	FB	FA2	FC
		B_o (L CH_4/kg VS)		
Fresh	260±20	360±10	350±10	230±10
Pad	200±20	280±10	270±10	70±10
Stockpiled	160±30	200±20	150±10	60±10

Notes: Results presented as value ± 95%error for assays performed in replicates of three; FA, FB, FC represents different feedlots from Queensland, Australia. FA1 and FA2 are the same feedlot sampled in summer and winter to check for seasonal variability. Source: Gopalan (2013)

Methane conversion factor (MCF)

The MCF reflects the portion of B_o that is achieved (IPCC 2006). The system MCF varies with the manner in which the manure is managed and the climate, and can theoretically range from 0 to 100%. Both temperature and retention time play an important role in the calculation of the MCF. Manure that is managed as a liquid under warm conditions for an extended period of time promotes methane formation. These manure management conditions can have high MCFs, of 65 to 80%.

2.8.2 Cogeneration and combined heat sand power (CHP) plant

Biogas can be used in a number of ways. Disposal through a flare stack burner is the least favourable option for energy recovery. Powering a conventional boiler to generate steam, or powering a gas engine or gas turbine in a cogeneration plant are the main pathways of energy recovery.

Cogeneration is also known as a combined heat and power (CHP) plant. Biogas is burnt with oxygen in a reciprocating gas engine to produce mechanical energy. A variety of reciprocating gas engines have been used, including spark ignition and compression ignition. The gas engine drives an alternator, which generates electrical energy. To enable heat recovery, the radiator on a standard engine is replaced with a heat exchanger. Additional heat can be recovered from the engine exhaust gas.

The conversion of biogas energy into electrical energy is approximately 30-35%. An additional 57% of biogas energy can be converted into heat energy if the gas engine is fitted with an efficient heat exchanger and heat from the flue gas is recovered (Navickas 2007). Approximately 8% of the energy contained in biogas is lost through system losses. The efficient conversion of the energy available in biogas will depend largely on the CHP plant design. In the larger European biogas plants, the generated electricity is sold at a premium price and the generated heat is supplied to a local residential community scheme. Recent development of biogas usage include supplying biogas to a microturbine for the generation of small electrical and heat loads, and also supplying biogas to a fuel cell where electricity is directly generated through an electrochemical process. These approaches may not be relevant to feedlots that don't require mobile electrical energy.

2.8.3 Digestate and sludge handling and disposal

Anaerobic digestion produces digestate, which is a mixture of liquid and solid residue. The quality of the digestate will vary according to the feedstock processed. As the organic material passes through the anaerobic digestion process, the digested material becomes stable, with the majority of the organic material decomposed. This will produce higher concentrations of nutrients. The availability of the nutrients is higher in digestate than in untreated organic waste. The nutrients are mineralised to allow for improved plant uptake. Digestate has approximately 25% more available NH_4-N and a higher pH than untreated liquid manure (Danish Biogas Association 2010).

Digestate originating from agricultural manure may contain antibiotics, pesticide residues and metals, which originate from animal feed additives. The European Commission is in the process of establishing policy in a "Green Paper" which is expected to regulate the level of contaminates in composts and digestate.

2.9 Biogas regulations and safety

2.9.1 Biogas regulations

The biogas plant is treated the same as an industrial gas installation and the installation of a biogas plant must comply with the local and state gas safety and environmental regulations. State gas safety agencies and environmental authorities are summarized in Davidson et al. (2013). Currently there are no existing biogas guidelines in Australia. In response, APL has recently developed a risk based Code of Practice for biogas production and usage at piggeries (Davidson et al. 2013) . The Code incorporates international best practice from Germany, Canada, US and New Zealand, and Australian regulations and standards relevant to on-farm biogas and Australian climatic conditions. The Code covers the life cycles of a biogas plant project, from planning, construction, on to operations and maintenance. It also covers health and safety and environmental protection throughout the biogas plant project. This has recently been published (see http://australianpork.com.au/wp-content/uploads/2013/10/2011_1013.423-FINAL-REPORT-CONSULTATION.pdf)

2.9.2 Biogas safety

Davidson et al. (2013) have reported on the properties of biogas production related to present health and safety issues. These include risk of fire and explosion, intoxication, asphyxiation and disease. These biogas-specific risks can be minimised through proper design, management practices, protective equipment and training. For example, to minimize explosion hazards, open flames should never be used near a digester. Also, large engines and electric generators must be carefully managed to avoid sparks that may ignite the gas. No smoking is allowed near the digester or related biogas pipes and equipment. To avoid diseases, personal protective equipment must be used to avoid contact with manure. Washing after working near the digester is also recommended. Keeping the digester facility clean will reduce disease hazards as well as the spread of odours and fly populations in the digester facility.

2.9.3 Environmental protection

Agricultural biogas production complements the existing manure handling and treatment, and thus can enhance the environmental protection aspects of modern agriculture. For example, digestate odour is significantly reduced compared to untreated liquid manure. The VFAs and mercaptans that are largely responsible for odour generation from animal manure are consumed during anaerobic digestion.

However, biogas plants may require imported waste materials which present biosecurity risks. Also, emissions and discharges from biogas plants need to be carefully managed. For example, the operation of the digester at mesophilic temperatures is not regarded in Europe as providing enough sterilisation treatment to remove pathogens. The centralised AD plants include a pasteurisation stage in the process and this enables the safe distribution of digestate from the centralised plant to any of the feed stock supply farms, without the risk of spreading disease. A Danish monitoring programme reports that maintaining a thermophilic processing temperature for 53.5°C for eight hours has the same effect as pasteurising the mixture at 70°C for one hour (Danish Biogas Association 2010).

2.10 Agricultural Biogas plants in Australia

The majority of Australia's AD industries are associated with municipal waste water treatment plants

(WWTP) with most sites employing cogeneration (CHP) units. Numbers for industry and agricultural AD facilities are difficult to obtain, however, an estimate has been provided in Table 9 – Australian biogas plants operating and proposed (2010). Renewable energy provided 14.8% of Australian electricity generation during 2013. Bioenergy totalled 6.9% of this, with biogas contributing to about 2% of the share of total renewable electricity capacity (CEC 2013). However, electricity generation from AD installations has shown most growth over the past five years. Goals of 2,413 and 55,815 GWh for bioelectricity were set for 2020 and 2050 respectively, to which on-farm AD and AD using biowaste and industrial organics are key contributors (CEC, 2008). The number of biogas facilities in Australia is currently being updated (see http://biogas.nceastg.usq.edu.au/biogas/) through the International Energy Agencies Bioenergy Subprogram Task 37 *Energy from Biogas* (see http://www.iea-biogas.net/).

Table 9 details a survey of the Australian biogas installations and proposed projects, which produce energy from anaerobic-digested feedstock. The location of the existing and proposed biogas plants in Australia is shown in Table 9 (Source: Geoscience Australia (2010).

Table 9 – Australian biogas plants operating and proposed (2010)

Company	State	Waste Stream Feedstock	Electrical energy Capacity (kW)	Installation Date
QAF Meat Industries - Corowa	NSW	Piggery waste	240	Proposed
AJ Bush & Sons	NSW	Rendering plant	85	Proposed
Charles IFE Pty Ltd - Berrybank	VIC	Piggery waste	180	1990
Burrangong Meat Processors	NSW	Abattoir	600	Reopening
AJ Bush & Sons	QLD	Rendering plant	1000	Developing
Rockdale Beef	NSW	Abattoir	920	Unknown
Westside Meat Works	VIC	Abattoir	100	Unknown
EarthPower Technologies	NSW	Food waste	3500	2003
McCain's Foods	VIC	Food waste	3000	Unknown
Werribee AGL	VIC	Sewage methane	10000	1996
Werribee Melbourne Water	VIC	Sewage methane	1300	1995
Werribee 2 Melbourne Water	VIC	Sewage methane	7000	1998
Diamond Energy - Shepparton	VIC	Sewage methane	1100	2007
Diamond Energy - Tatura	VIC	Sewage methane	1100	2009
Carrum Downs 1 & 2	VIC	Sewage methane	17000	1975
WA Water Woodman Point	WA	Sewage methane	1200	1998
Water Corp WA	WA	Sewage methane	1200	1999
Brisbane City Council – Luggage Point	QLD	Sewage methane	3200	1979
Stanwell Corp - Townsville	QLD	Sewage methane	270	2000
Brisbane City Council – Oxley Creek	QLD	Sewage methane	1030	2003
Gold Coast City Council - Elanora	QLD	Sewage methane	230	2005
Veolia Water - Ti Tree	QLD	Biomass	2200	2008
Sydney Water – North Harbour	NSW	Sewage methane	1400	2008
Sydney Water – Malabar	NSW	Sewage methane	3000	1999
Sydney Water – Cronulla	NSW	Sewage methane	497	2001
Sydney Water – Bondi	NSW	Sewage methane	970	2008
Sydney Water – Glenfield	NSW	Sewage methane	400	2008
Sydney Water – Liverpool	NSW	Sewage methane	230	2008
Sydney Water – Warriewood	NSW	Sewage methane	150	2008
Sydney Water – Wollongong	NSW	Sewage methane	400	2008
Carbon Partners - Scencorp Group	VIC	Greenwaste and food waste	6800	Proposed
Victorian Farmers Federation / Bio-cogen	VIC	Agricultural waste	2000	Proposed

Although biogas technology can be deployed with feedstock from any organic waste streams, it appears that, in Australia, a major area of potential deployment is within the agriculture and food processing industry. The CEC Australian Bioenergy Roadmap (2008) noted significant potential for increased use of agricultural wastes in Australia, from an estimated 791 GWh per year in 2020 to 50,566 GWh in 2050. This translates to an increase from a 1% bioenergy contribution from agricultural-related wastes in 2011 to 7% in 2020 and 69% by 2050. Currently 1.3 million tonnes of waste is produced from abattoirs. This industry has a projected potential to produce 33.7GWh/yr by 2020 and 1773 GWh/yr by 2050.

There is clearly a growing interest in biogas production from organic wastes in Australia. However, there are few examples in the intensive livestock sector. In the past few years, due to the introduction of the Carbon Farming Initiative (CFI), there has been strong interest in covering anaerobic treatment ponds at piggeries. Some examples of these developments will be discussed in following sections. However, there are currently no known biogas facilities at any Australian feedlot. Some examples of intensive livestock and processing industries which have adopted biogas capture from wastewater include:

- Piggery waste
  - Berrybank piggery (Australian Centre for Cleaner Production, 2001)
  - Blantyre Farms (http://blantyrefarms.com.au/quality-sustainability)
  - Bears Lagoon piggery (RIRDC, 2010).
- Red meat processing
  - King Island beef processing plant (Johns & Butler 2012) (decommissioned)
  - NH Foods, Oakey Beef Exports (http://www.mla.com.au/globalassets/mla-corporate/generic/about-mla/covered-anaerobic-lagoons.pdf)
- Poultry Farms
  - Darling Downs Fresh Eggs (http://www.cleanenergyfinancecorp.com.au/media/63281/20130731-cefc-pdf-factsheet-darlingdownsfresheggs_lr.pdf)

2.11 Experiences with biogas production at US feedlots

2.11.1 Overview of feedlot biogas projects in USA

During the project, an opportunity arose to undertake a study tour of feedlot biogas developments in the USA. A search was undertaken to find operational biogas units that were using dry-lot feedlot manure. The Agstar site (http://www.epa.gov/agstar/projects/) was searched. While there are 39 pig and 199 dairy projects listed, only one relevant feedlot project (Hampton Feedlot) was found (See Table 10). Further searching located Western Plains Energy, which is a feedlot manure biogas unit based on the existing Hi-Mark Feeders unit in Canada. In addition, it was found that experimental work was being undertaken at Colorado State University.

The lack of operational feedlot biogas projects in the USA indicates the considerable difficulties in getting a biogas system to work functionally and economically with the current state of knowledge.

Table 10 – Beef anaerobic digester operational projects – 2014 (Agstar)

Farm/Project Name	City	State	Digester Type	Year Operational	Animal Type	Population Feeding Digester	Co-Digestion	Biogas End Use(s)
Suwannee Farms	O'Brien	FL	Mixed Plug Flow	2009	Beef			
Amana Farms, Inc.	Amana	IA	Mixed Plug Flow	2008	Beef	4000	Sludge (Paper sludge substrate)	Cogeneration
Linkenmeyer Family Feeders / Link Energy, LLC	Riceville	IA	Mixed Plug Flow	2012	Swine and Cattle	4000; 5000	Additional substrates	Electricity
Sievers Family Farms	New Liberty	IA	Complete Mix	2011	Beef	4890	Agricultural substrates (corncobs, cornhusks, soybean stubble, hog manure)	Electricity
Bio Town Ag, Inc.	Reynolds	IN	Mixed Plug Flow	2011	Swine and Cattle	800; 4500	Wastes from surrounding community	Cogeneration
Waste No Energy	Monticello	IN	Complete Mix	2013	Swine and Cattle	4000; 300	Food waste, fats, oil, grease, organic waste	Cogeneration
Hampton Feed Lot	Triplet	MO	Induced Blanket Reactor	2012	Cattle	2500		Electricity
Oak Hill Farm	Nottingham	PA	Complete Mix	2011	Swine and Cattle	4400; 130	Food wastes	Electricity

2.11.2 Hampton Feedlot Inc.

Hampton Feedlot is located near Triplett, Missouri. It can hold about 4000 beef cattle, of which 2400 head are in covered barns. Photograph 19 – Aerial photograph of Hampton Feedlot shows an aerial view of the site with conventional open feedlot pens and four covered barns. The incentive to develop a biogas plant on-site was not driven by the desire to generate energy but as a response to EPA compliance issues around the holding pond system, which was full of solids.

In December 2009, the members of the Hampton Feed Lot organized Hampton Alternative Energy Products, LLC as an "eligible new generation processing entity" in order to build, operate and own a development facility and a renewable fuel production facility for its producer members, consisting primarily of the members of the Hampton Feed Lot. In 2010, Hampton Feedlot had undertaken a feasibility study and obtained a grant of $450,000 from the Missouri Department of Natural Resources towards the $4M project. The facility was built in 2011 and is now operational.

Manure is scraped three to four times a day into pits beneath the four confinement barns. No manure from open feedlot pen is used as this is contaminated with soil. The manure is agitated in deep pits and then pumped to a mixing tank (See Photograph 20 – Mixing tank close to confinement barns). No screening of the manure occurs. The mixing tanks have these larger propeller agitators in them. The influent seems to come into the tank via a jet. The tanks are completely agitated so that nothing settles.

Effluent from the holding pond system is added until the effluent has a solids content of 7-8%. It is then pumped, via a macerator (See Photograph 21 - Macerator on influent line) and heat exchanger (See Photograph 22 – Heat exchanger on influent line), into the base of one of six upflow anaerobic sludge blanket (UASB) reactors. The macerator is necessary to break up ear tags, hooves and other debris that gets through the mixing tanks. It also breaks the manure down into finer particles to improve digestion. The heat exchanger heats the influent prior to entering the digester. The heat comes from the exhaust of the methane-fuelled engine that runs a generator. Positive displacement slurry pumps are used to move all effluent (See Photograph 24 – Two of the six digester tanks).

Photograph 24, documents two of the digester tanks. They can be seen under construction in the centre of Photograph 19 – Aerial photograph of Hampton Feedlot. Each tank is 130,000 L capacity and is operated at about 39°C. The system does not use any mechanical or hydraulic mixing in the tanks. The hydraulic retention time is 3-5 days. The Operator commented that sand” accumulates in the digester tanks and this is very difficult to remove. The Operator seemed to believe that this was silica derived from the feed as the manure is from concrete floors and is not contaminated with soil.

Biogas is used to fuel an electricity generator (See Photograph 25 – Electricity generator using biogas) which provides all of the electricity requirements of the feedlot. A second generator could be installed to supply electricity to the local grid. They generate enough electricity to supply the “parasitic” load of the digester and the feedlot as well as selling some to the grid. There is a complex control system for the facility (See Photograph 26). The effluent from the top of the digester tanks goes through a solids separator (See Photograph 27). The liquid component is recycled and excess liquid is sent to the feedlot's holding pond where it has apparently caused the pond to become active and to breakdown much of the accumulated solids. The solids in the effluent are dried and are being sold as a soil conditioner.

Photograph 19 – Aerial photograph of Hampton Feedlot

Photograph 20 – Mixing tank close to confinement barns

Photograph 21 - Macerator on influent line

Photograph 22 – Heat exchanger on influent line

Photograph 23 – Positive displacement pumps on influent line

Photograph 24 – Two of the six digester tanks

Photograph 25 – Electricity generator using biogas

Photograph 26 – Control system for anaerobic digester and generator

Photograph 27 – Separated solids from digester effluent

2.11.3 E3 Biofuels

E3 Biofuels is an integrated facility near Mead, Nebraska that includes a 28,000 head covered feedlot, an anaerobic digester and an ethanol plant (See Photograph 28). Figure 15 details the connections in the system. The facility was built in 2006 but shutdown in 2007 after a boiler explosion and poor performance of the system. The facility has recently re-opened.

Cattle are housed in confinement barns with slatted floors (See Photograph 29). Manure falls into under-floor channels from which it is pumped to a manure holding pond (See Photograph 30). Periodically, a slurry pump (See Photograph 31) pumps manure from the holding pond into a mixing tank (See Photograph 32). After the slurry is thoroughly mixed, it is transferred into one of the anaerobic digesters (See Photograph 33 & 34). Biogas from the digester is pumped to the ethanol plant to fuel boilers (See Photograph 35). Excess biogas is flared (See Photograph 36).

The facility includes a complex system for dewatering the effluent from the digesters. This includes a belt press (See Photograph 37) which was meant to use polymers. There is also a sand filtration system. This system has never worked properly.

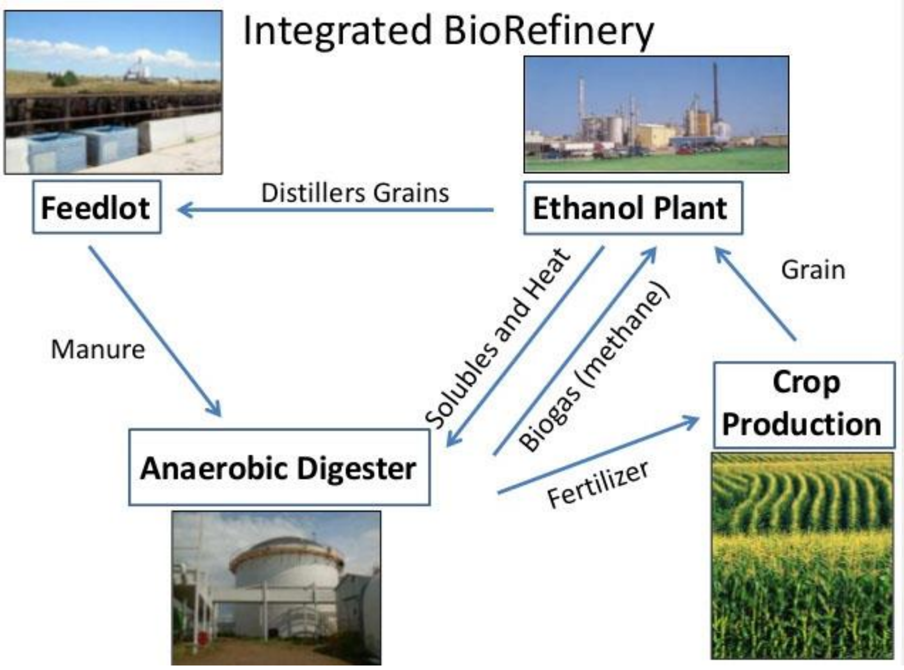


Figure 15- Schematic outline of E3 Biofuels

Photograph 28 – Google Earth image of E3 Biofuels

Photograph 29 – Cattle on slatted flooring in confinement barn

Photograph 30 – Manure slurry holding pond

Photograph 31 – Slurry pump with confinement barns in background

Photograph 32 – Manure mixing tank

Photograph 33 – Anaerobic digester tank

Photograph 34 – Detail of anaerobic digester tank

Photograph 35 – Biogas pump from digester to ethanol plant

Photograph 36 – Excess biogas flare

Photograph 37 – Belt press for effluent dewatering (not operating)

2.11.4 Hi-Mark Feeders/Biogas

Highland Feeders is a large cattle feedlot about 25 km north of Vegreville in Alberta, Canada. Highland Feeders was founded in 1983 when Mike and Bern Kotelko diversified their grain operation with 50 feeder cattle. Now the company operates the sixth largest feedlot in Canada with a standing capacity of 36,000 head. Some years ago, Highland Feeders decided to develop a biogas unit at the feedlot (http://himarkbiogas.com/). The first pilot plant was developed in 2003 and the company has continued to develop integrated biogas technologies in the intervening years. In 2005, the Growing Power Hairy Hill was commissioned (http://www.growingpower.com/). This site apparently uses feedlot manure as well as residential organic waste and is operating successfully.

2.11.5 Western Plains Energy

Western Plains Energy is an integrated ethanol / feedlot manure biogas plant near Oakley, Kansas. Photograph 38 documents the site with the biogas plant on the left and the ethanol plant on the right of the image. The biogas plant consists of four large anaerobic digesters and two covered lagoons. Photograph 39 documents a general view of the anaerobic digesters. The design of the facility was provided by Himark Biogas.

Unfortunately, by the time of the visit, the site was subject to legal action between Himark BioGas and Western Plains Energy due to poor performance of the biogas plant. Hence, no detailed inspection of the plant was possible and details of the plant can be discussed. A press article about the project (Manure Manager – March/April 2013) can be accessed at http://magazine.agannex.com/publication/?i=150214&ver=html5&p=8

Photograph 38 - Google Earth image of Western Plains Energy

Photograph 39 – General view of Western Plains anaerobic digesters

2.11.6 Colorado State University Leach bed system

Dr Sybil Sharvelle at Colorado State University (CSU) is leading a project investigating biogas production from feedlot manure using a leach bed system. The system includes three stages. Hydrolysis is carried out in a trickle flow leach bed reactor (TFLBR) and methanogenesis can be carried out in a high rate anaerobic digester (HRAD) such as an upflow anaerobic sludge blanket reactor (as per Hampton Feedlot) or a fixed film reactor (Figure 16). Most of the work has focussed on optimising the performance of the TFLBR. The unit is housed in a mobile demonstration unit (See Photograph 40). Photograph 41 documents the control panel within the demonstration unit.

Since leach bed reactors (LBRs) are high solids reactors, studies have indicated clogging issues in LBRs handling 26% TS. Since TFLBRs are subjected to hydrolyze up to 90% TS, obtaining hydraulic flow through the reactor is a challenge. The objective of this research at Colorado State University is to (a) ensure good hydraulic flow through the TFLBRs and (b) evaluate and optimize the performance of the TFLBR to effectively hydrolyze the HSCM. The system is operated as a batch process with a hydraulic retention time (HRT) of 42 days without leachate recirculation. A layer of sand is added as dispersion media on top of the manure bed in the TFLBRs. This promotes good hydraulic flow through the reactor eliminating clogging issues.

Organic leaching potential of a single pass (without leachate recirculation) TFLBR configuration was evaluated in terms of chemical oxygen demand (COD). Manure is naturally rich in nutrients essential for microbial growth in AD. In a typical MSLBR system, the TFLBRs are subjected to leachate recirculation, conserving the essential nutrients in the system. However, in this single pass system, the leachate removal flushes out the nutrients in the TFLBRs over time. So, nutrient solution is added to the TFLBRs to provide a constant supply of essential nutrients in the reactors for the purpose of this study and would not be necessary in a leachate recirculated TFLBR.

A comparison between nutrient dosed and non-nutrient dosed TFLBRs was performed. The non-nutrient dosed and nutrient dosed TFLBRs indicated a COD reduction of approximately 66.3% and 73.5% respectively, in total in terms of dry mass. A total reduction in volatile solids (VS) of approximately 46.3% and 44.7% was observed in the non-nutrient dosed and nutrient dosed TFLBRs, respectively. Biochemical methane potential (BCMP) tests indicated a CH_4 potential of approximately 0.17 L CH_4/g COD leached and 0.13 L CH_4/g COD leached from the non-nutrient dosed and nutrient dosed TFLBRs, respectively. Concentration of inorganics leached from the TFLBR was monitored periodically.

To date, this is a demonstration unit only. No work has been done in preparation of manure removed from pens for placement in the TFLBR. Photograph 42 documents the pre-screened manure that is loaded into the TFLBR.

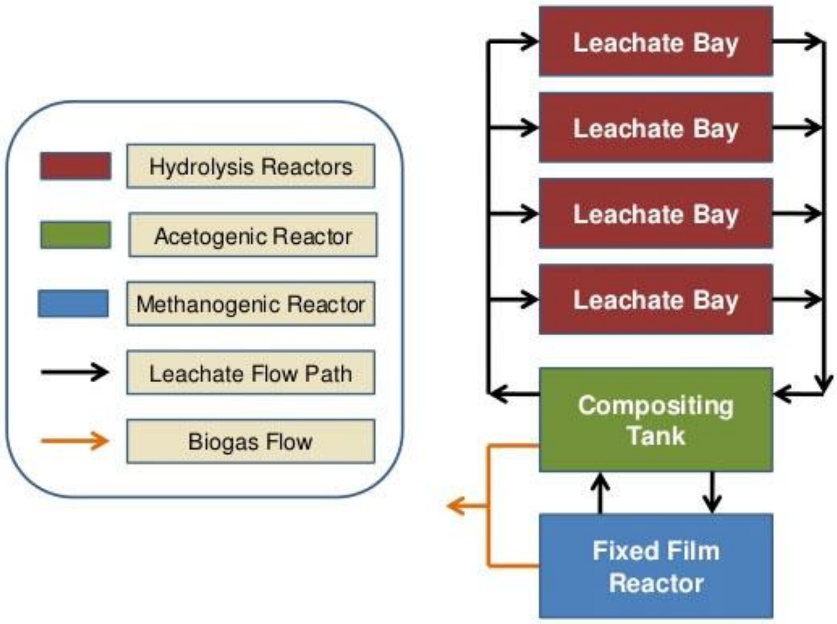


Figure 16 – CSU leach bed system

Photograph 40 – CSU mobile leach bed system

Photograph 41 – Control panel at CSU leach bed system

Photograph 42 – Screened manure for leach bed trials

2.11.7 Summary of feedlot biogas in the USA

Following investigations into feedlot biogas in the USA and site inspections of most of the currently operational sites, the following conclusions can be drawn.

1. There are very few (3-4) operational facilities for cattle feedlots.
2. Two of the operating facilities used manure from cattle housed in barns with concrete floors, thus eliminating the issue of soil contamination in pen manure.
3. All operating facilities are based on the high capital cost option of in-tank anaerobic digesters.
4. No facility seemed to have successfully dealt with the issue of removing contaminants from pen manure (although the facility in Canada was not visited).
5. All sites commented on rapid sludge / solids accumulation rates inside the digesters (greater than anticipated in the design stage). This seems to indicate that the significance of pen manure contamination was under-estimated.
6. Most facilities had invested heavily in systems to dewater effluent coming out of the digesters and there were technical difficulties with these as well as high capital cost.

2.12 Improving biogas yield of feedlot manure

It is possible to propose actions that can be taken to improve the viability of generating biogas from feedlot manure through a clear understanding of the issues presented by feedlots. The following is a list of possible actions that could be taken to improve the biogas yield of feedlot manure.

2.12.1 Change manure harvesting techniques

Gopalan (2013) found that the degradability of feedlot manure decreased from fresh manure to pen manure to stockpiled manure, as shown by decreasing VS from 83 to 60% (See Figure 17). This suggests that easily degradable components such as VFAs, sugar and starch – rich carbohydrates have decomposed rapidly in the pen and further degraded during the storage of manure. Figure 4 details the reduction of VS on the feedlot pen surface over time.

Manure with low VS content is not going to be a good feedstock for AD because, although there may still be significant amount of VS left (e.g. 60%), it mainly contains lignocellulosic matter that can only be partly degraded during AD (Angelidaki & Ahring 2000). Triolo et al. (2011) found that lignin concentration in VS was the strongest predictor of BMP for both energy crops and animal manure – low lignin content indicates higher BMP.

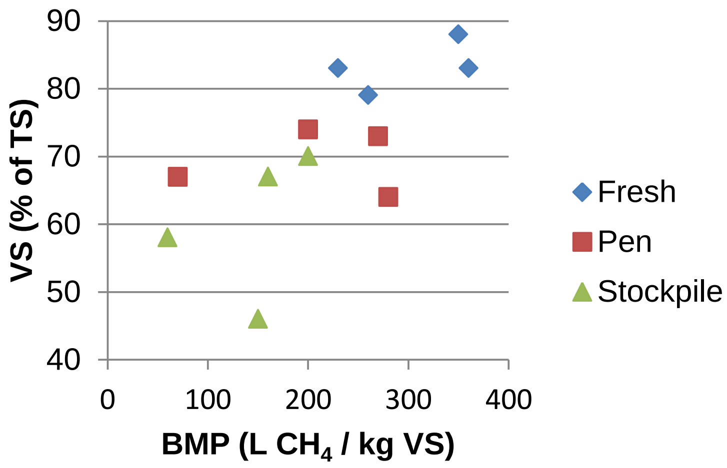


Figure 17 – Relationship between Biochemical methane potential (BMP) and VS content of feedlot manure samples

Data source: Gopalan (2013)

2.12.2 Pre-treatment of feedlot manure

Pre-treatment of manure may be helpful to improve the biogas yield. Biological treatment such as incubating with hemicellulose degrading bacteria at 70°C has been found to increase biogas production by 30% (Angelidaki & Ahring 2000). Thermo-chemical treatment such as wet explosion (a steam explosion process) at 180°C for 10 minutes has been found to increase biogas production by 136% (Biswas et al. 2012). These approaches, although effective at laboratory scale, may be too complicated for implementation at feedlots.

To maximise the degradation of organic materials, feedlot manure needs to be pre-treated so that particle sizes are reduced and foreign materials are removed. Common practice in manure composting can be directly used to treat manure for AD. Firstly, a windrow turner for manure composting may be used to break the clogs into smaller sizes. Secondly, common screening techniques such as rotating screen, brush roller, vibrating screen, and run-down screen can be used to remove gravel and other foreign materials.

To enhance the AD of manure, techniques such as ultra-sonic treatment have been developed. Wu-haan et al. (2010) evaluated the effect of ultrasonication as a pre-treatment to AD of beef feedlot manure. Ultrasonic pretreatment was applied at two amplitudes (μm_{pp}, peak-to-peak amplitudes in µm) and at two time settings (in seconds). Ultrasonic pretreatment increased the average soluble COD up to 92%, and the average methane yield up to 43%. Increasing the ultrasonic amplitude and treatment time resulted in an increase in manure soluble COD and methane production. The greatest methane production was obtained at the highest power and longest treatment time (160 μm_{pp}, 30 seconds) and was found to be 230 mL CH_4 g/VS for beef feedlot manure.

Thermal (up to 190 °C) and thermo-chemical treatment (with acid or alkaline) have been found to increase biogas production from pig, chicken and cattle manure (Carrère et al. 2009). For example, Carrère et al. (2009) found that methane yield (mL CH_4/g COD) was increased by 64% with thermal treatment at 190 °C, and by 78% with a combination of 190 °C and pH = 10.0. However, few studies have evaluated the energy efficiency of these treatments. When Wu-haan et al. (2010) took into account the energy input for ultrasonication, the lowest ultrasonic amplitude combined with the shortest treatment time (80 μm_{pp}, 15 seconds) achieved the greatest energy efficiency, i.e. increased methane yield providing 63% more energy than what was required to operate the ultrasonic process.

2.12.3 Dilution and mixing of feedlot manure

The following section provides some detail around dilution and mixing of feedlot manure. For one kg of pen manure with an initial solids content of 55%, about 3.6 kg of water must be added to achieve a slurry with TS of 12%.

55/(100+x) solids content =12/100 TS =>x=358 g water

Considering a medium sized feedlot (10,000 head capacity) that generates manure of 1 t DM/head/yr, this would require 65.5 ML water annually.

10,000 t DM => 10,000/0.55 t "wet" manure =>10,000/0.55*3.6 t water

A feedlot with 10,000 SCU has been predicted to generate effluent at 115 kL/d (Bridle, 2011), which amounts to 4.2 ML effluent annually. Considering that effluent contains solids as well, relying on effluent to dilute feedlot pen manure may not achieve a feasible TS content for plug flow digester. To utilise pen manure for AD would thus require either additional water, or solid phase digester. To utilise fresh manure (TS about 20%) would require much less dilution water. However, significant management practice has to be implemented which may not be cost effective.

2.12.4 Co-digestion of manure with other products

Co-digestion of animal manure with other easily degradable materials may be another way to improve biogas production. For example, Labatut et al. (2011) demonstrated that mixing raw dairy manure with used vegetable oil can increase BMP by 49% compared to raw dairy manure, and mixing with dog food and ice cream can increase BMP by 93% (See Figure 18). Synergistic activity has also been found in some co-digestion mixtures.

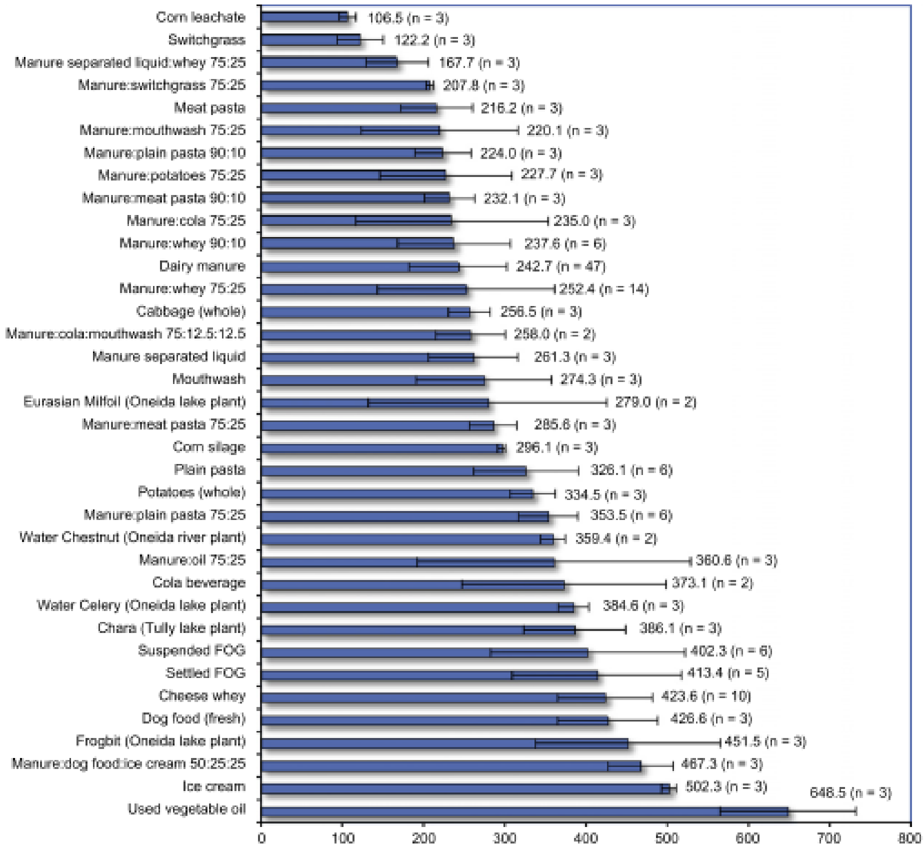


Figure 18 – BMP (L CH_4 / kg VS) of mono- and co-digested substrates

Note: The value outside the bars is the average B_o with the sample number in parenthesis. Error bars represent the standard deviation of B_o for each substrate. Adopted from (Labatut et al. 2011).

2.12.5 Improvement of C:N ratio in manure feedstock

The production of methane from organic carbon depends upon the availability of carbon in the feedstock. The ideal C:N ratio range for optimum anaerobic digestion is 16:1–25:1 (Zhu 2010). A lower C:N ratio can lead to ammonia accumulation and pH values exceeding 8.5, which is detrimental to the methanogenic bacteria (Monnet 2003). Zhu (2010) suggests that increasing the C:N content of the piggery waste stream by the addition of waste streams with a high C:N ratio will increase the volume of biogas produced. It is suggested that it is also possible to increase the methane content of the biogas by the addition of certain feedstocks to the piggery waste stream, for example oat straw and corn stalks. This will have a significant impact on the economic viability of the plant. However, further research would be required to determine the biodegradability of potential additional organic materials available in Australia.

3. Methodology

3.1 Feedlot manure sampling

3.1.1 Biomethane potential testing and chemical composition

Three feedlots in Southeast Queensland with different feed processing technology and pen capacities were selected for this experiment. One pen per feedlot was used for all samples with multiple samples within the pen taken and further processed as described below. Details about manure sample types and measurements performed are presented in Table 11.

Table 11 – Feedlot manure sampling information

	F1	F2	F3
Steam flaking	Yes	No	Yes
Manure collection date	Jan 31st 2014	Feb 5th 2014	Jun 18th 2014
Weeks elapsed since last pen cleaning	25	n.r. [a]	6 [b]

[a] not reported by feedlot manager; [b] estimated by feedlot manager

Fresh manure (FM) samples were collected by walking along the pens and manually picked up using a small garden spade and then transferred into a plastic bag and sealed (See Photograph 43). At least three random scoops were taken for each bag and a total of three bags were collected. Freshly dropped piles were carefully taken to prevent contamination of other materials. When a hard surface exists on the manure pile, the hard surface was scraped out and only the fresh manure inside was collected. Samples were kept in eskies with ice packs to reduce the degradation of waste before transported to the lab.

Photograph 43 – Fresh manure sampling at feedlot 1

Pen surface manure (PSM) samples were also collected by walking along the pens and manually picked up using a small garden spade and then transferred into a plastic bag and sealed (See Photograph 44). PSM sampling was performed to mimic as close as possible manure harvesting depicted in photograph 5. At least three random scoops were taken for each bag and a total of three bags were collected. Three PSM samples were kept in eskies with ice packs to reduce the degradation of waste before transported to the lab. Another bulk PSM sample of about 40 kg were collected and kept in a 100 L wheelie bin in a cool place before the pre-treatment trial. Age of pad manure was calculated with reference to the last pad scraping event and therefore represents the maximum age (in weeks).

Photograph 44 – Pen surface manure sampling at feedlot 1

Freshly scraped pen manure (FSPM) samples were manually taken by hand on the same day when pen is cleaned by machinery, e.g. box scraper (Photograph 45 – Manure from freshly scraped pen at feedlot 3). About 40 kg of FSPM were sampled and kept in a 100 L wheelie bin in a cool place before the pre-treatment trial. Another three FSPM samples were kept in eskies with ice packs to reduce the degradation of waste before transported to the lab.]

Photograph 45 – Manure from freshly scraped pen at feedlot 3

Stockpiled manure (SM) samples were taken by hand from a minimal depth of 10 cm at about ten different locations around the stockpile (Photograph 46 – Stockpile manure sampling at feedlot 1).

Samples were kept in eskies with ice packs to reduce the degradation of waste before transported to the lab.

Photograph 46 – Stockpile manure sampling at feedlot 1

3.1.2 Physical characterisation

Testing of secondary parameters such as turbidity, bulk density and settling velocity of solids was carried out on 3 types of manure (fresh, pen and stockpile manure) from two feedlots (F4 and F5) located in Southeast Queensland. F4 uses steam flaking for grain processing while F5 uses a dry process. Details are given below:

1. F4 FM (Freshly cleaned manure from pen)
2. F4 PSM (Fresh surface pen manure)
3. F4 SM (Stockpile manure)
4. F5 PSM (Thinly scraped pen manure)
5. F5 SM (Old stockpile manure)

Details of the age of pen surface manure (weeks elapsed since last pen cleaning) were not provided.

3.2 Biomethane potential batch tests

3.2.1 Sample Preparation

A single composite sample was created from the three bags collected from each feedlot pen in the laboratory and immediately processed. Large components of the manure were broken into smaller sizes and large stones and gravel, if present, were removed. The manure was then placed into a domestic food processer (Kambrook KFP400) and processed for 60 seconds to break the manure into smaller, more uniform particle sizes. This resulted in particle sizes of ≅ 1cm. The samples were then placed in a coffee grinder (Sunbeam EM0415) for 45 seconds to decrease particle size to ≅ 2mm. One kilogram of the collected samples were processed each time and distributed in 200 g lots in snap-lock plastic bags. The samples were then stored at 4°C in a refrigerator until ready to be analysed for chemical composition and biomethane potential.

3.2.2 Chemical characterisation

TS, VS and MC measurement

The solid content of the samples was determined according to Standard methods (APHA, 2005). For the determination of total solid (TS), samples of 2 to 4 grams were placed in a ceramic crucible and weighed. The crucibles were placed in a muffle furnace for 30 min to remove any contamination and then cooled in a desiccator before use. The samples were then dried in an oven at 105 ± 2 °C for 18-20 hours (recommended between 15-20 hours) until they reach constant weight. After cooling in a desiccator, the samples were weighed again for TS measurement. The samples were then oxidized at 550 °C for 2 hours for volatile solid (VS) determination. The volatile solids (VS) were determined by subtraction of the minerals content of the sample (residual ash after oxidation) from the total solids content. The following equations were used:

$$TS(\%)=(W1-Wc)/(Ws-Wc)\times100$$

$$VS(\%)=(W1-W2)/(W1-Wc)\times100$$

Where:

Wc : Clean crucible weight

Ws : Sample plus crucible weight

W1 : Crucible weight after drying at 105°C and cooling in a desiccator

W2 : Crucible weight after drying at 550°C and cooling in a desiccator

The total solid content is a measure of the amount of material remaining after all the water has been evaporated, so moisture content of the sample can be calculated as:

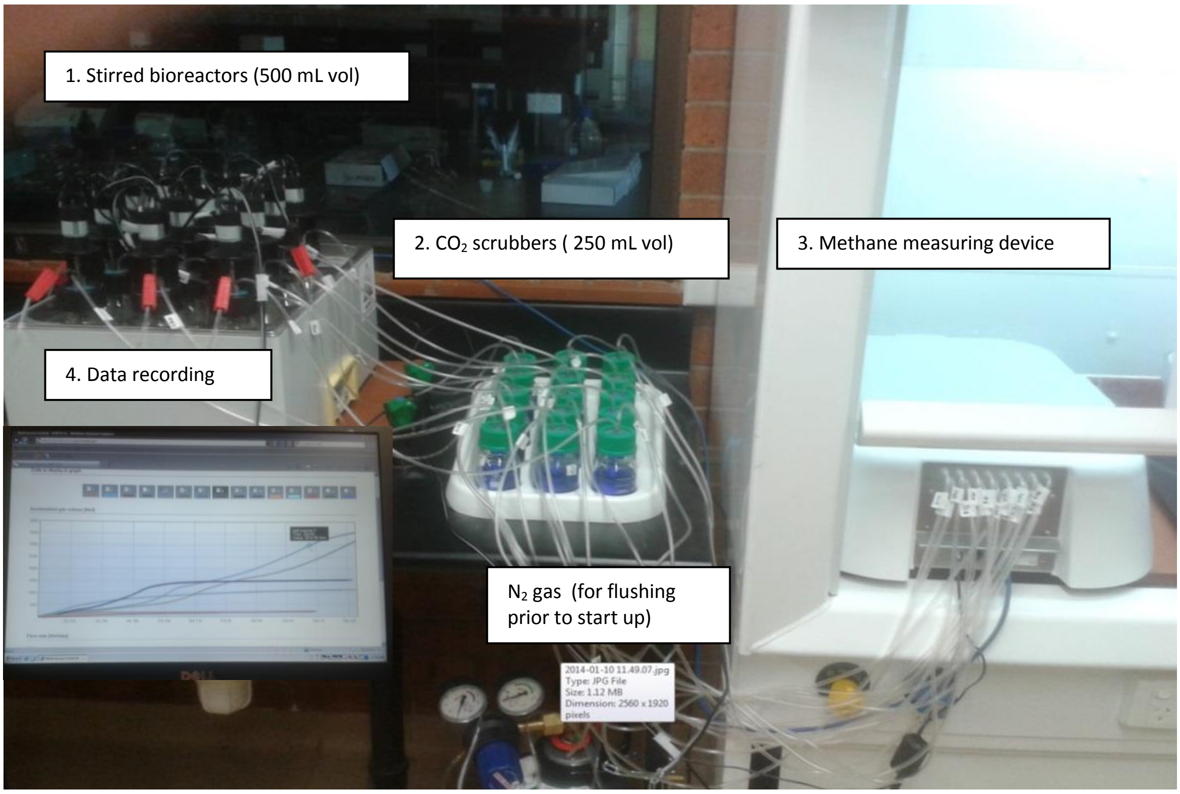
$$MC\ (\%)=100-TS(\%)$$

Organic matter composition

Further analysis of the organic matter content in the form of lignin, fat, volatile fatty acids (VFA), cellulose, hemicellulose, starch and protein was performed by SGS Food and Agriculture (Brisbane, QLD).

3.2.3 BMP set up and operation

A multi-channel analyser - the automatic methane potential test system (AMPTSII, bioprocess control, Sweden) - was used to perform BMP testing of manure samples. The AMPTS consists of fifteen parallel reactors and the same number of gas flow meters attached to a data acquisition system (See Photograph 62). A schematic representation is illustrated below in Figure 19. (Modified from Badshah, Liu and Mattiasson (ND). Biogas, a mixture of methane and carbon dioxide, that is produced in temperature controlled reactors (fifteen sets) each with an overhead stirrer (1) passes through one-way valves and enters into scrubbing solution units (fifteen sets) where carbon dioxide is fixed (2) and methane passes to the sensor chamber (fifteen sets) (3) where the volume is quantified and recorded by the software (4). Arrow shows the direction of gas flow.



Photograph 47 – Laboratory set up of the Automatic Methane Potential Test System (AMPTS)

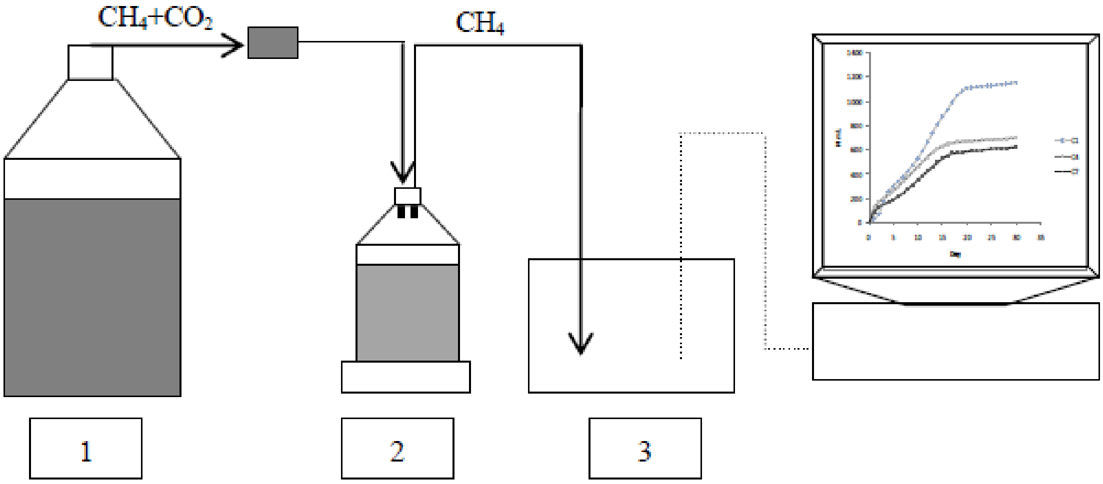


Figure 19 - Schematic presentation of AMPTS

AMPTS was developed for automatic real-time measurement of the biomethane production during anaerobic digestion of any organic biomass. The system consists of a water-bath having capacity of 15 bioreactors of 500 mL each. Each bioreactor is fitted with a mechanical agitator to provide gentle mixing for the bioreactor contents. Mixing is performed intermittently (30s on 120s off) during the whole experiment. The biogas produced in each bioreactor passes through Tygon® tubing (3 mm ID) to individual Schott bottles containing an alkaline solution (3M NaOH - 120 g NaOH mixed with 1 L distilled water). Several acid gas fractions, such as CO_2 and H_2S, are retained by chemical interaction with NaOH, only allowing CH_4 to pass through to the biomethane gas monitoring unit. A pH indicator is added into each Schott bottle for controlling the acid binding capacity (thymolphthalein pH-indicator (4%, 40 mg in 9 ml ethanol (99.5%) followed by addition of 1 ml distilled water is added to the NaOH solution and mixed at a ratio of 5:1000 ml, 80 ml of the mixture then placed in 250 ml Schott bottles). The volume of CH_4 gas released from the CO_2 scrubbing bottles is measured using a wet gas flow measuring device with a multi-flow cell arrangement (15 cells). This measuring device works according to the principle of liquid displacement and buoyancy and can monitor ultra-low gas flows. A digital pulse is generated when a defined volume of gas flows through the device. An integrated embedded data acquisition system is used to record, display and analyse the results.

3.2.4 Inoculum (sludge) source

Inoculum used for every batch test was collected from the anaerobic digestion unit at Pittsworth, QLD wastewater treatment plant. The plant consists of overflow settling tank, anaerobic digester and a trickling filter. The anaerobic tank is an over ground concrete tank with semi-continuous stirring (dimensions: 3m diameter; 8m height; approximately 57 m^3 volume).

After collection the sludge was directly sieved (1.7 mm mesh) and mixed well for 60 seconds. In order to minimize the amount of biogas that is produced by the sludge itself, pre-incubation of the inoculum under anaerobic conditions by applying N_2 was carried out for 7 days at 37°C in order to deplete the residual biodegradable organic material present. When no significant gas production is observed, the sludge is ready to be used. After the pre-incubation step, the pH, TS, VS, COD and MC of the sludge was measured.

3.2.5 Inoculum: substrate ratios (ISR)

Manure samples collected from the different feedlots as outlined in Section 6.1 were used as substrates in the biomethane batch tests. When preparing the experiment, a certain inoculum to substrate ratio (ISR) needs to be chosen. The appropriate ratio depends on the method chosen or the properties of the substrate. An inoculum to substrate ratio of 2:1 (on a VS basis) was used in this study. A total amount of 400 g liquid per reactor (for 500 mL bottle) including 300 ml inoculum and the solid substrate mixed in 100 ml distilled water was used for each batch reaction. An ISR was calculated according to the following equation:

Ratio 2:1 = $(M_{inoculum} \times VS\%_{inoculum}) / (M_{substrate} \times VS\%_{substrate})$

$M_{total} = M_{inoculum} + M_{substrate} = 400$ g

Where M = amount in grams

3.2.6 Blanks and controls

Blank assays containing only sludge (inoculum) and distilled water (1:1) were used to compensate for the amount of biogas produced by the inocula itself (i.e. correct for background methane production from the inoculum. Positive control assays were also set up for every batch using pure cellulose powder (Fluka, Avicel PH-101, ~50µm particle size). Cellulose correlates well with volatile solids and provides an excellent estimate of the readily degradable organic content.

The following details are specific for cellulose:
TS: 95.5%
VS (TS): 99.999%
VS (total): 95.534%
MC: 4.24%

The average methane yield for cellulose at an ISR of 2: 1 is approximately 350 L methane/kg VS. All blanks and controls were set up in triplicate and maintained at 37°C ± 1°C and run at the same time the sample assays were performed.

3.2.7 Preparation of bioreactors and start-up procedure

Triplicates of each combination inoculum-substrate were used:

- 3 reactors as blanks containing only sludge (inoculum) + distilled water.
- 3 reactors as positive controls containing only sludge (inoculum) + cellulose in distilled water.
- 3 x 3 reactors with sludge (inoculum) + manure sample (substrate)

All bottles were filled with the same amount of inoculum. For each manure sample, the calculated amount in grams (based on VS) was added to each one of the three replicate reactors.

The bioreactors were flushed continuously with N_2 for approximately 60 seconds to achieve anaerobic conditions before commencing each batch run. A single batch run was conducted for each manure sample and incubated for 30 to 35 days until methane production plateaued. The data for methane generation rate and accumulation was recorded by a data acquisition system and displayed graphically using computer software.

3.3 Physical characterisation: turbidity, bulk density and settling velocity

Slurries for each of the 5 manure samples from Feedlots 4 & 5 were firstly prepared by mixing a specific amount of manure and distilled water to create slurries with differing total solids content. The samples were placed in a 1L bottle and shaken for 30 seconds before being stored at 4°C for 60 hours to saturate the solid with moisture.

The turbidity of the manure slurries were measured at 3 different time intervals; 10 seconds, 5 minutes and 36 hours (Holliday et al 2003). A 2100N turbidimeter (Hach) was used to measure turbidity for triplicate samples. Samples were brought to room temperature before being poured into a 1 litre measuring cylinder. They were then shaken for 10 seconds and then let to settle for 10 seconds before separating the liquid from the settled solids. The turbidity of the water and the weight of the solids were then measured. The separated liquid was again shaken for 10 seconds and then let to settle for 36 hours before separating the liquid from the settled solid. The turbidity of the water and the weight of the solid were similarly measured.

Bulk density was determined by weighing the manure samples after being shaken in a 500mL measuring cylinder.

Settling velocities were determined based on the method of Lott et al 1994. Settling velocities of different size particles were measured using a 1 L graduated cylinder. The slurry was shaken for 30 seconds and then left to settle for 10 seconds. The solid was separated and then weighed. This process was further repeated using settling times of 5 minutes and 36 hours.

3.4 Pre-treatment systems

Various pre-treatment approaches have been used in the literature, ranging from biological treatment such as incubating with hemicellulose degrading bacterium at 70°C, to thermal (up to 190°C) and thermo-chemical treatment (with acid or alkaline). These approaches, although effective at the laboratory scale, seem too complicated for implementation at a larger scale or commercial feedlots. Two pre-treatment options have been tested. The first option was a simple container with a stirrer and the second involved rolling/crushing the manure before washing it through a sieve with a pressurized water jet. Each of the approaches was trialled on pen surface manure and freshly scraped pen manure. The hypothesis was that mixing manure with water can produce stratified fractions of different VS and TS contents and the fraction of high VS content can be a suitable feedstock for the AD.

3.4.1 Pre-treatment trial

Approximately 40 kg of freshly scraped pen manure (FSPM) and pen surface manure (PSM) from Feedlot 3 were collected and sub samples were taken by mixing and quartering the larger manure sample. This involved manual disaggregation of the manure clods before it was mixed, divided into quarters and sub samples were taken from one of the quarters.

A simple pre-treatment system was developed using a 100 L wheelie bin (See Figure 2).Two valves were attached via bulk heads at a diameter of 25mm. Centres of the two outlets were 50 mm and 250 mm from the bottom of the bin, drawing the manure mixture from the mid and bottom layers. Manure samples were mixed with water to a total of 50 L to achieve estimated TS contents from 1% to 6%. A paint stirrer (1050 W, 500 rpm) was used to mix the contents for approximately 3 min at a depth of about 50-mm from the bottom of the bin. Two sampling approaches were tested: the first was to immediately sample from the outlets after stirring, the second was to leave the mixture settle for about 40 min after stirring and then sample from the outlets. For each approach, a small sample (approximately 1 L) was taken from each of the outlets and sent to lab within about two hours.

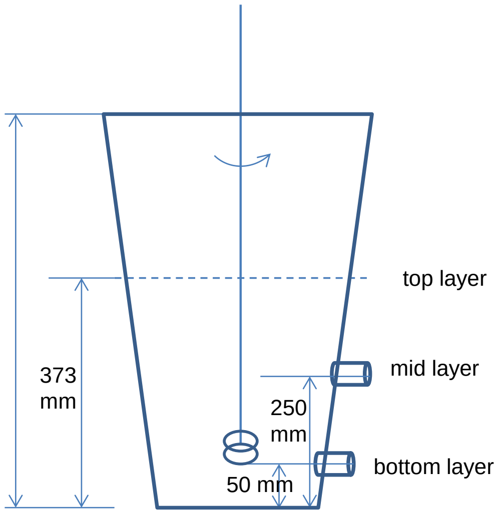


Figure 20 - Pre-treatment trial 1. Left: illustration of pre-treatment system; right: mixing manure with water by stirrer

Initial visual and handling inspections of the solids residue remaining at the bottom of the bin during the initial scoping (Trial 1) illustrated the need for an alternate approach to disaggregating and mixing the manure substrates. A revised approach was theorised involving two additional physical processes: crushing; and water pressure. The revised approach (Trial 2) used approximately 5 kg of the mixed sample. This was spread evenly onto a wooden sheet. The large clods were initially crushed with the broad side of a sledge hammer to provide a more consistent thickness across the sample. The sample was then spread across the board and a secondary board was placed on top before mass was applied. Approximately 75 kg was applied to further 'roll' the manure into a thin 'cake' with a uniform thickness between 20-30mm.

After rolling, the manure was added to a 10mm sieve for further processing. A rotating water jet from a Karcher® pressure cleaner was applied to the manure to break up manure clods (See Photograph 48).

Photograph 48 – Operation of the pressure cleaner to break up manure clods

A minor revision was applied in Trial 3, where manure was soaked in water for about 30 min before washed through the sieve. Enough solids to produce a theoretical 6.1% (for PSM samples) and 6.7% (for FSPM samples) TS content inside the 50L bin were prepared. The treated slurry from the sieving procedure was added to the bin used in the initial trial. Where required additional water was added to ensure the TS contents were closer to the values of initial mixer experiments. Detailed in Photograph 49 is the only alteration made to the bin during Trial 2 and 3, which was the installation of a third sample point directly in the centre of the bin bottom. This valve was included to allow sampling of the very bottom sludge layer. The electric stirrer was again used to suspend the manure and check the evenness of mixing throughout the water column. After three minutes of mixing, samples (<1 L) from each port were taken while the mixer was still operational.

Photograph 49 – Positioning of the three sample valves

4. Results and discussion

4.1 Manure characterisation

4.1.1 Chemical composition

The results from the characterisation analyses of fresh, pad and stockpiled manure samples are displayed in Table 12 – Chemical components of the fresh, pen, and stockpile manure from feedlot 1, 2 and 3.

Analysis of the organic matter content in the form of lignin, fat (lipid), volatile fatty acids (VFA), cellulose, hemicellulose, starch and protein are also found in Table 12 – Chemical components of the fresh, pen, and stockpile manure from feedlot 1, 2 and 3. Starch was not analysed for F1 SM, F1 PSM and F2 PSM. Not all sample components resulted in a full mass balance of all organic matter. It was noted that the levels of lignin were particularly high for F3 PSM, F3FM and F3 FSPM. Also, protein levels for these samples were not estimated due to variances in the total Kjeldahl nitrogen (TKN) and NH_4-N values.

Table 12 – Chemical components of the fresh, pen, and stockpile manure from feedlot 1, 2 and 3

	Unit	F1 SM	F1 PSM	F2 PSM	F3 PSM	F3 FM	F3 FSPM
TS	%wb	73.0	52.5	74.2	39.5	20.7	50.6
VS	%TS	42.4	81.4	72.9	77.2	87.9	75.2
Lignin (measured)	%TS	2.4	4.5	5.0	17.8	21.3	16.2
Lipid (measured)	%TS	0.7	1.3	1.4	0.6	2.3	0.5
VFA (measured)	%TS	0.1	1.9	0.5	0.02	0.54	0.05
Cellulose (measured)	%TS	16.0	24.5	27.2	18.4	15	18.2
Hemicellulose (measured)	%TS	7.4	22.8	17.9	17.3	18.7	15.2
Starch	%TS	-	-	-	3.5	3.3	3.7
Protein (est.)	%TS	13.8	13.9	14.3	-	-	-
Measured & est. VS	%TS	42.4	70.9	68.4	77.16	87.5	74.3
Measured & est. VS as a proportion of total VS	%	100%	87%	94%	100%	99.5%	98.8%

Table 16 shows that VS contents of pen surface manure ranged from 72.9 to 81.4 TS while VS for stockpile manure was 42.4 (%TS). This is in keeping with the higher VS contents found in Australian harvested pen manure compared to US feedlots. In contrast to US feedlots, most new Australian feedlots have a pen surface that was well compacted, often gravelled and levelled prior to cattle entry. Pen cleaning usually aims to leave a shallow interface layer of manure so as not to disrupt the compacted pen surface. Hence, in most Australian feedlots, the amount of soil removed during pen cleaning should be minimal.

Figure 21 A, B and C - Components of manure samples A) F1 SM, B) F1 PSM and C) F2 PSM based on dry basis illustrates the ash and organic components (%TS) of pen surface manures from two feedlots (F1 PSM and F2 PSM) and one stockpile manure (F1 SM). The pie charts include the calculated ash content for all 3 manure samples and incorporate a portion of 'unknown' organic matter which is likely to be starch and other sugars as mentioned above.

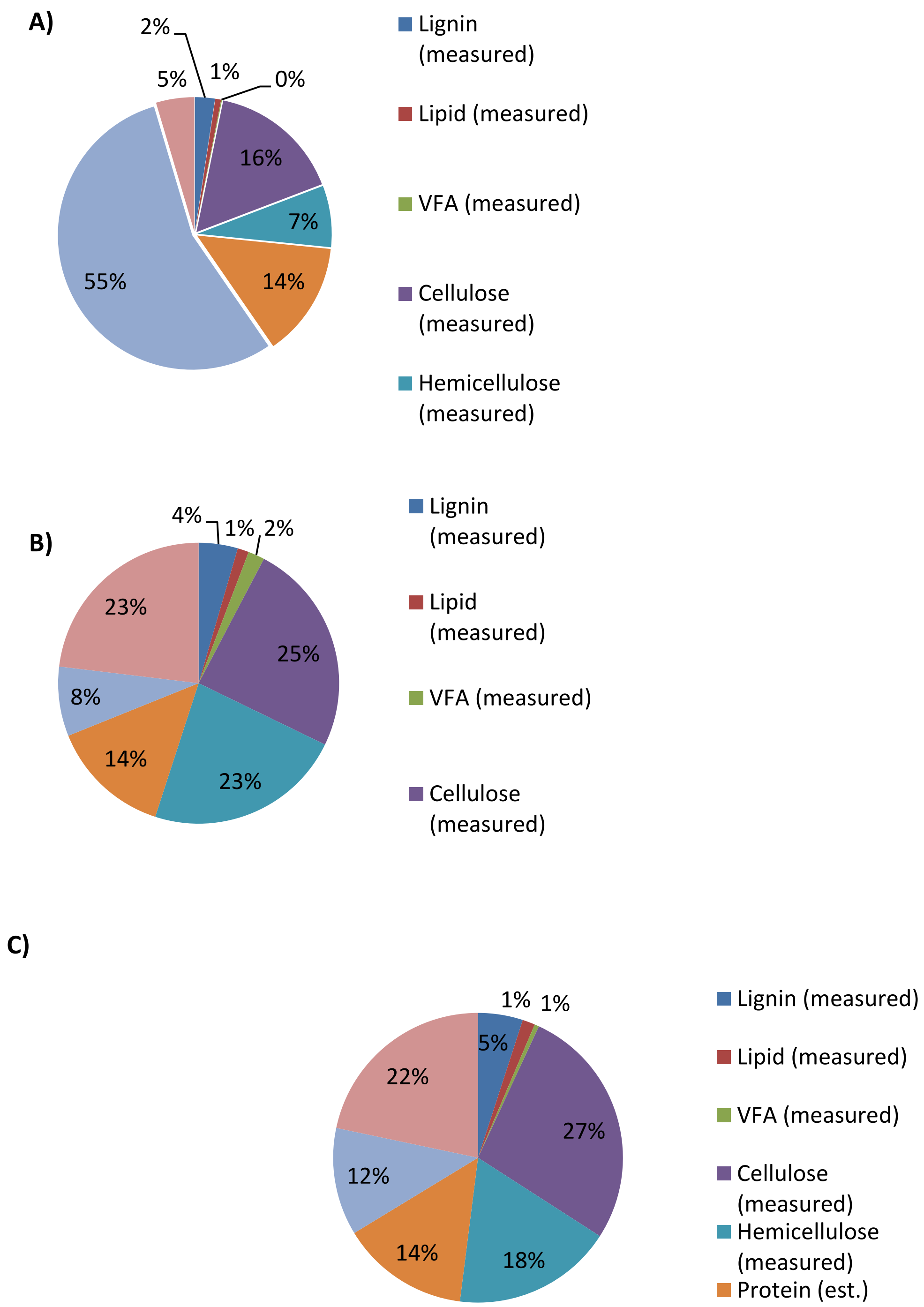


Figure 21 A, B and C - Components of manure samples A) F1 SM, B) F1 PSM and C) F2 PSM based on dry basis

The chemical compositions of the two pen manure samples (F1 PSM and F2 PSM) were very similar. F1 SM (stockpile manure) shows a high proportion of ash content (55%) compared to the pen surface manures, F1 PSM and F2 PSM, which were 8% and 12% respectively. Conversely the amount of organic matter constitutes the larger portion for pen surface manure samples. The biomethane potential results show a similar relationship where the high organic contents of PSM samples produce greater methane potential (See Figure 22).

4.1.2 Physical characteristics

Table 17 below provides data on turbidity; bulk density and settling velocities for the 5 manure samples (see section 6.1.2 for sample details).

Table 17- Physical characteristics: turbidity, bulk density and settling velocities for 5 manure samples

Manure Sample	Bulk Density (Kg/m^3)	Time	Turbidity (at 5% TS)	Settling velocity (at 5% TS) Fraction settled (%)	m/s
F4 FM	1160	10 s	187	82.5	0.003
		5 min	115	0.87	1.0×10^{-4}
		36 hr	48.46	0.74	2.3×10^{-7}
F4 PSM	1040	10 s	2248	69.8	0.003
		5 min	1905	10.8	1.0×10^{-4}
		36 hr	246	4.6	2.3×10^{-7}
F4 SM	1600	10 s	988	85.2	0.003
		5 min	719	3.2	1.1×10^{-4}
		36 hr	131	2.1	2.4×10^{-7}
F5 PSM	1170	10 s	392	93.0	0.003
		5 min	242	1.6	1.0×10^{-4}
		36 hr	56	0.75	2.3×10^{-7}
F5 SM	1720	10 s	2906	91.1	0.003
		5 min	2668	2.1	1.1×10^{-4}
		36 hr	679.6	3.4	2.4×10^{-7}

Analysis on the settling rates of feedlot manure found that a large percentage of solids (69.8 to 93.0%) could be removed quickly with a settling velocity of >0.003m/s based on the methods used in the study. This is in contrast to Lott et al. (1994) who found that 35 to 75% of solids could be removed quickly with a settling velocity of >0.003m/s, assuming a depth of 1.8m this is a removal time of 10 minutes.

4.2 Methane yields (BMP)

Figure 22 below, details the methane production (in L methane produced per kg VS added) obtained from each manure sample at the end of anaerobic digestion.

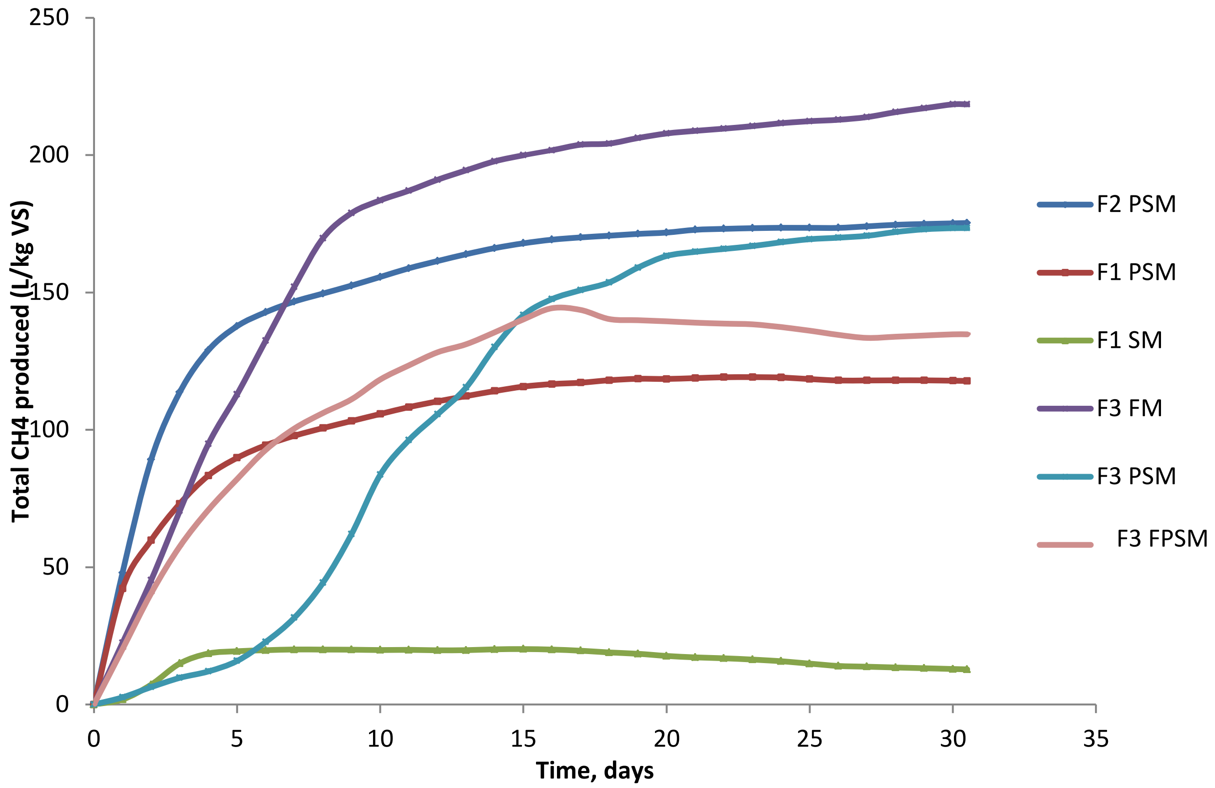


Figure 22 - Methane yields from three manure types originating from three feedlots

Table 13 below, displays the biomethane potential (B_o) of all manure types for the three feedlots after 32 days of incubation.

Table 13 - Biomethane potential (BMP) of fresh (FM), pen surface (PSM), freshly scraped pen manure (FSPM), and stockpile (SM) manure from feedlot 1, 2 and 3 after 32 days incubation

	Unit	F1 SM	F1 PSM	F2 PSM	F3 PSM	F3 FM	F3 FSPM
Total CH_4 produced	(L/kg VS)	13	118	175	173	218	135
VS	%TS	42.4	81.4	72.9	77.2	87.9	75.2

Total methane produced for fresh, pen surface and freshly scraped pen surface manure ranges from 118 to 218 L/kg VS, while stockpile manure produces relatively low levels of methane (13 L/kg VS). Gopalan (2013) measured BMP values of 200 L/kg VS stockpile manure (See Table 8 above) which is much higher than the 13 L/kg VS found in the current study. Given the high ash content measured in stockpile manure (55%) (Figure 23 A) it is assumed that a BMP value of 13 L/kg VS for stockpile manure would be a more realistic value and the use of stockpile manure as a feedstock for biogas production would not be economically feasible. In addition, the range of BMP values for pad manure (118-175 L/kg VS) and fresh manure (218 L/kg VS) are comparatively lower; Gopalan (2013) measured BMP values as high as 350 and 280 L/kg VS for fresh and pad manure respectively.

Table 14 below, presents BMP values for pen surface manure from 3 different feedlots. Whilst it is difficult to compare the BMP values of pen surface manure given the limited information available it is noted that pad manure harvested within 6 weeks produces has a higher BMP value (173 L/ kgVS) compared to pad manure left for over 6 months (118 L/ kgVS).

Table 14 - Comparison of feedlot pen surface manure - BMP and age of pen surface manure

	F1	F2	F3
Steam flacking	Yes	No	Yes
Manure collection date	Jan 31st 2014	Feb 5th 2014	Jun 18th 2014
Age of pen surface manure (weeks elapsed since last pen cleaning)	25	n.r. [a]	6 [b]
Rainfall events	Unknown	Unknown	6mm 2 days prior
BMP results (L/kg VS)	118	175	173

[a] not reported by feedlot manager; [b] estimated by feedlot manager

Figure 23 below provides data from one feedlot for 3 manure types. The methane yields for fresh and pen surface manure were 218 L/kg VS, and 173 L/kg VS, respectively. This represents a 20% decrease in BMP between fresh manure and pen surface manure harvested at 6 weeks. Freshly scraped manure resulted in slightly lower BMP (135 L/kg VS) compared to pen surface manure.

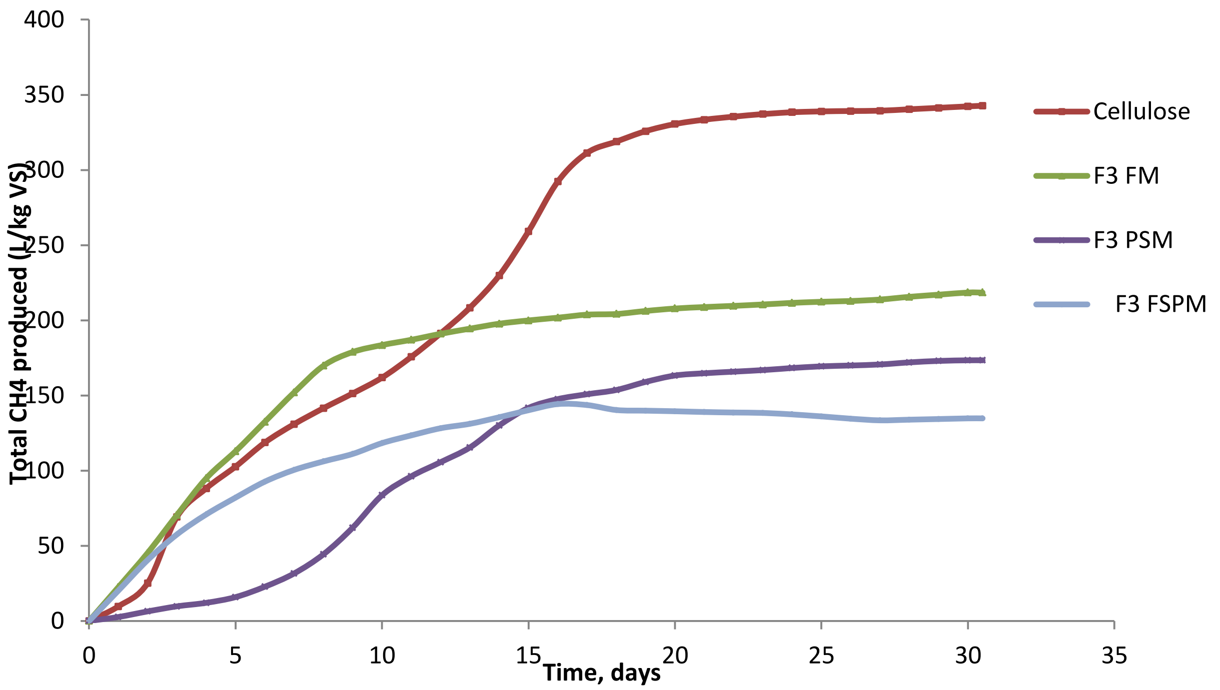


Figure 23 - Methane yields from three manure types (fresh, pen surface and freshly scraped pen) types originating from one feedlot

4.3 Preliminary pre-treatment trials

Table 15 details the TS and VS contents of the various manure samples collected before treatment.

Table 15 - Chemical components of the fresh, pen and stockpile manure from feedlot 1, 2 and 3

	Unit	F1 SM	F1 PSM	F2 PSM	F3 FM	F3 PSM	F3 FSPM
TS	%wb	73.0	52.5	74.2	20.7	87.5	47.8
VS	%TS	42.4	81.4	72.9	87.9	75.1	68.6

4.3.1 Effect of stirring on particle sizes

Pre-treatment was only performed on manure from Feedlot 3 in the preliminary trial. Due to the rainfall event (6 mm) two days before manure sampling, pen surface and freshly scraped pen manure samples had higher moisture content than pen manure samples from Feedlot 1 and 2. The stirring reduced manure particle sizes from 50-100 mm to less than 30 mm (See Photograph 50).However, this was found to be limited and large clogs (15-30 mm) could still be found at the bottom of the mixing bin.

Photograph 50 – Particle sizes of freshly scraped pen manure from feedlot 3 before (bottom) and after (top) the pre-treatment

4.3.2 Effect of pretreatment on TS and VS contents

In Trial 1, both pen surface and freshly scraped pen manure mixes had a higher TS content in the bottom layer than the mid layers, reflecting that complete mixing was not achieved inside the vessel. The differences became more obvious as the TS content increased (See Figure 24). The measured TS content of the freshly scraped pen manure mixture reflected the predicted TS for the three trials. Figure 28 also details the initial results from the FSPM mixing trial. The results show a minor increase in TS content as the theoretical TS increase rose, but the measured values were far below the expected values, demonstrating that the standard mixing procedure was inadequate to breakup and suspend PSM.

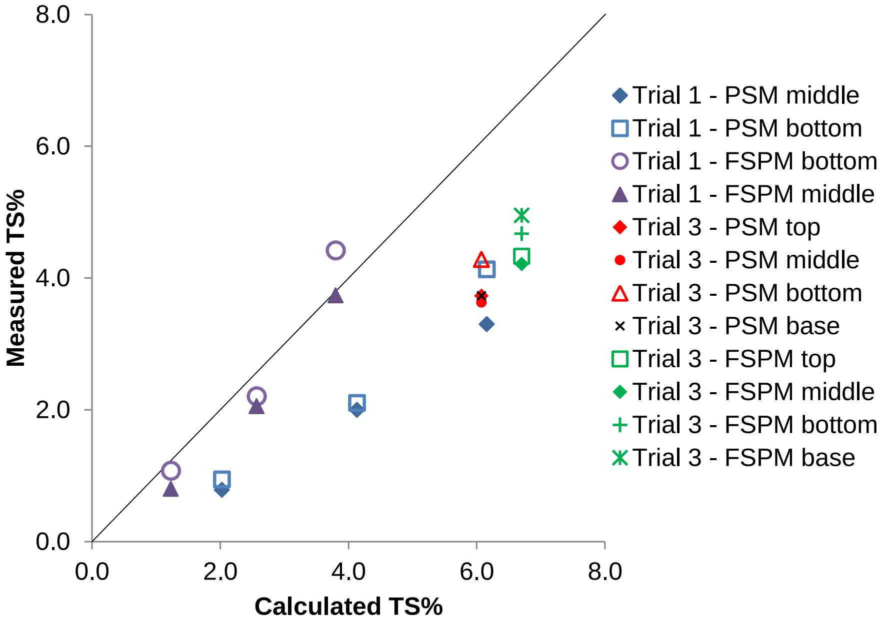


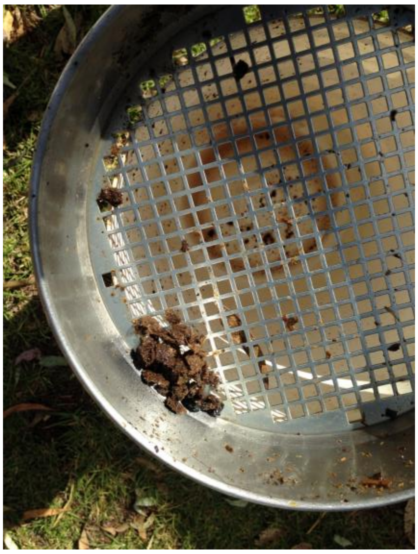
Figure 24 - Calculated and tested TS% (wb) of freshly scraped pen manure (FSPM) and pen surface manure (PSM) from feedlot 3 through top, middle, bottom and base layers of the pre-treatment system

The trial results of the FSPM mixing accurately reflected the calculated TS loads which were put into the bin. This is attributed to both the lower TS loading (1 - 4%), which is within the mixing capability of the stirrer and the higher moisture content. As the substrate was softer and wetter, the manure was able to be incorporated into the mixed water column a lot quicker. Further testing will need to be completed at increased TS% between the 4-8% range.

4.3.3 Effect of secondary pre-treatment on particle size

The secondary treatment option was tested on each of the substrates at one calculated TS%. The PSM was trialled at 6.1% and the FSPM was trialled again at 6.7%. A major change in the solid state and consequently the mixing of the manure was achieved with the revised technique.

The most important effect of the manure rolling was to break up the hard outer crust which forms around the surface of the manure substrate. Testing found this was most relevant to the crustier pen surface manure. By breaking through this outer layer, the water jet was able to cut through the manure clods and the manure was pushed to through the 10mm holes much quicker than when the jet was applied to raw manure. The reduced thickness from the rolling allowed a uniform approach to the manure spraying which reduced the time required to disperse the particles. The oscillating circular jet was the most effective; a broader 'single line' spray did not have the same cutting power. At the end of the washing period only gravel and tough clods greater than 10mm remained (See Photograph 51). The wet manure that passed through the sieve resembled slurry with the consistency of fresh cattle manure (See Photograph 52).



Photograph 51 – Gravel and tough manure clods after cleaning

Photograph 52 – Wetter manure slurry after pressurized washing

As the revised approach to the methodology between trial 2 and 3 varied slightly the results of trial 3 were reported. The laboratory TS results from Trial 2 were similar with Trial 3 except that top layer was not sampled during trial 2.

The laboratory TS results from Trial 3 are illustrated in Figure 28. The results indicate differences in TS content between the various sample layers. With the decreasing particle size, the recovery rate of input TS to recorded TS was up to 70%. Similarly to Trial 1, it is believed that the mixer may be forcing solids into the corner of the bin, which did not allow sampling.

4.4 Proposed physical design parameters of a feedlot biogas plant

The literature review provided examples of successful manure-based biogas plants operating in both Australia and the USA, mainly for dairy and pig operations. Key components of the technology already exist and are proven technologies. However, only a few biogas plants based on feedlot manure exist across the world. Hence, it is necessary to identify the key features and constraints of a feedlot system that require adaption in the design of a biogas facility. This is outlined in following sections.

4.4.1 Manure harvesting

To maximise methane yield and minimise in-digester sludge accumulation, fresh manure should be skimmed frequently from the pen surface without contamination by soil and gravel. Photograph 53 documents that, with a good pen surface and utilisation of box scrapers, it is possible to only remove fresh manure from the pen surface, leaving the compacted manure interface layer intact. Photograph 54 documents manure being mounded within pens. This manure would then loaded into body trucks and taken to the biogas unit (See Photograph 55).

4.4.2 Manure screening

Freshly-scraped pen manure should be used as soon as possible to minimise methane potential loss. However, some provisions for short-term storage adjacent to the biogas facility should be made. Regardless of the quality of pen manure harvesting, the manure should be screened. Existing technology includes vibrating screens (some with multiple screen options – See Photograph 56) or rotating trommels (See Photograph 57). The final screen size should be 10 mm (See Photograph 58) to ensure that large contaminants are removed and the manure clods are broken down into small particles which will readily dissolve in the mixing tank. A percentage of the harvested manure will be rejected. This percentage will depend on the moisture content and age of the manure and the degree of contamination with rocks and gravel. The reject material would be taken to the existing manure stockpile area.

The use of wet manure is not desirable as methane potential has probably already been lost and screening of wet manure is difficult. One option for screening wet manure is to use a trommel that includes sprays to wash the manure through the 10 mm screen. This technology is already used for washing vegetables such as carrots (See Photograph 59). A large trommel, such as that documented in Photograph 60, could be adapted to include internal sprays and a washed manure collection tray underneath. Alternatively, wet manure could be washed using a vibrating screen such as used in the mining industry. In both cases, wash-water would be supplied, initially from the feedlot holding pond until the mixing tank has reached operating capacity after which water would be recycled from the mixing tank over the screen until the digester influent has reached the design solids content. The feedlot holding pond would then only be required to “top up” the mixing tank on an as required basis.

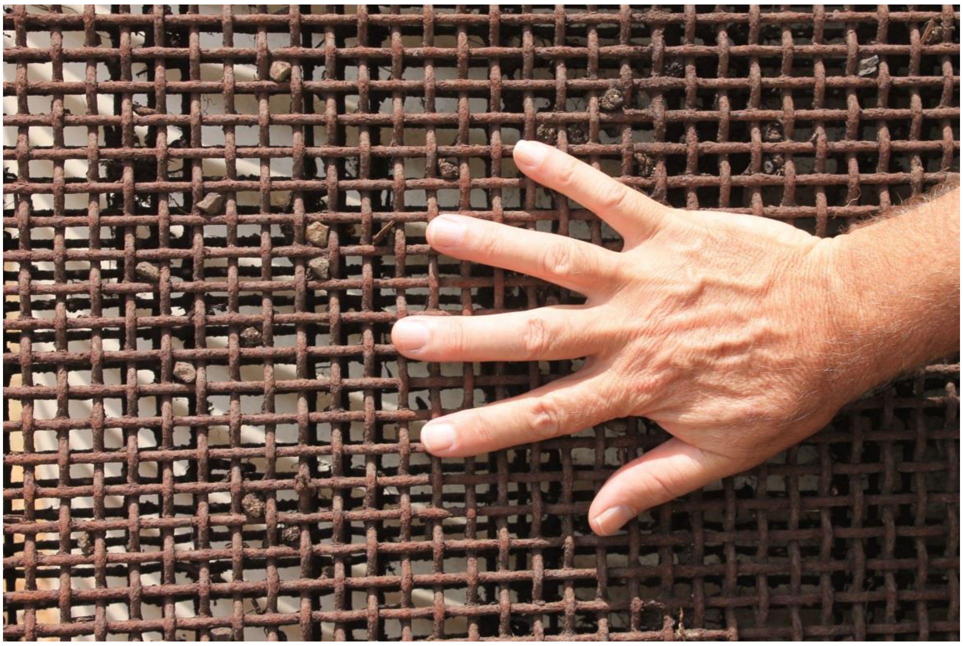
Photograph 53 – Pen cleaning of surface material only

Photograph 54 – Manure handling within pens

Photograph 55 – Manure removal from pens

Photograph 56 – Three-way vibrating screen

Photograph 57 – Rotating Trommel



Photograph 58 – 10mm screen size

Photograph 59 – Carrot washer

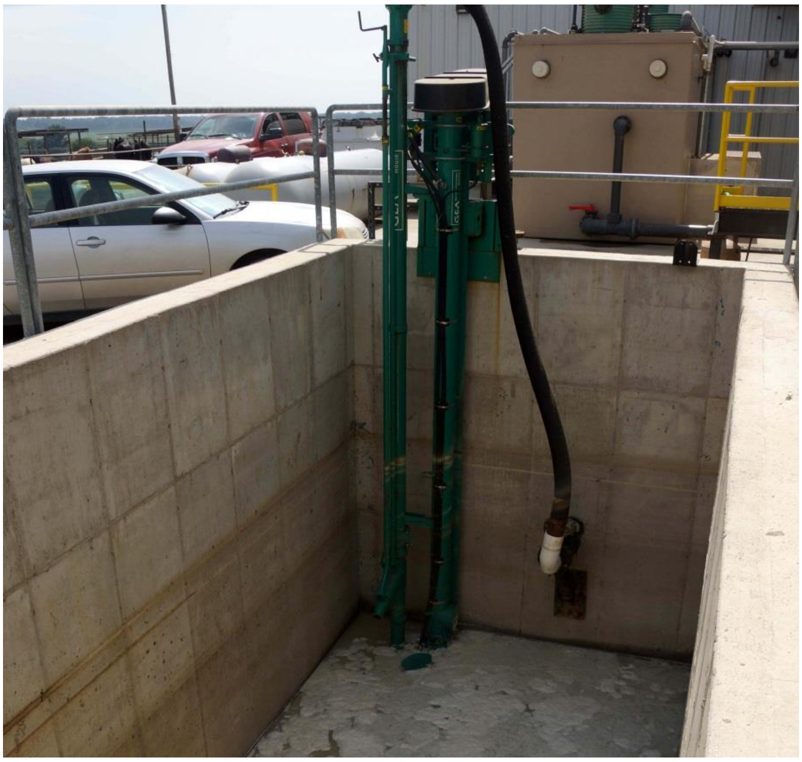
Photograph 60 – Wet vibrating screen

4.4.3 Mixing tank

The influent to the digester should have a solids content of 4-6% total solids with the organic matter broken down into small particles, fully saturated and dissolved. The output from the screening system should be prepared in a pre-mixing tank rather than directly inserted into the digester. This project could find no evidence that higher VS contents could be found at different depths within a mixing tank. Hence, the whole tank should be actively mixed so that no residue is left when the influent is pumped to the digester. Float switches can automate the pumps and mixers (See Photograph 61). The devices that keep the influent fully mixed can be either water jets or propellers (See Photograph 62).

Effluent with high solids content needs to be conveyed with specially designed pumps. The best option is positive displacement pumps (See Photograph 63). If further break-down of the solids is required after the mixing tank, in-line macerators can be used (See Photograph 64).

Photograph 61 – Mixing tank with delivery of manure by conveyor



Photograph 62 - Jet and propeller mixers in mixing tank

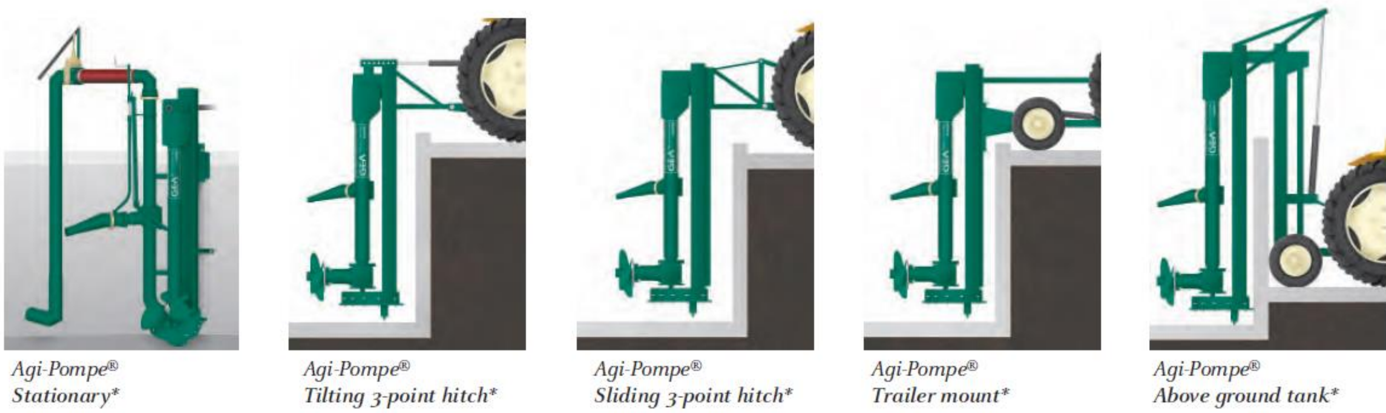


Figure 25 - Five versions of in-tank mixers by GEA

Photograph 63 – Positive displacement slurry pumps

Photograph 64 - In-line macerator

4.4.4 Digester

It is proposed that covered anaerobic ponds (CAPs) should be used rather than large in-tank anaerobic digesters. CAPs have a lower capital cost. The larger foot print is not an issue for feedlots. CAPs are a proven technology in Australia and can be designed with a long hydraulic retention time (HRT) which caters for less-exact influent management. The technology employed to capture the biogas generated by CAPs is relatively simple. An impermeable cover extends across the surface of the pond with its edges buried in the embankment to prevent gas loss and, more importantly, air entry.

CAPs are designed in much the same manner as uncovered anaerobic ponds. Current recommendations for designing a CAP are to construct a steep-sided, deep pond (e.g. 6 m) with a length to width ratio of 3:1. These ponds are designed with a hydraulic residence time of 40-50 days. Photograph 65 documents an example of a CAP at a piggery. Pond covers are constructed from 1.0-1.5 mm high quality geo-membrane cover such as low-density polyethylene (LDPE) or polypropylene (PP). High-density polyethylene (HDPE) - is also used. However, it is generally more difficult to install and there are problems associated with heat expansion.

Photograph 65 – Covered anaerobic pond (CAP)

4.4.5 Biogas handling and use

The handling and use of biogas produced from CAPs is an existing and proven technology. This will not be discussed further in this report.

4.4.6 Digester sludge removal

Sludge removal from CAPs presents specific difficulties as the cover cannot be removed during the operational phase. There are essentially three methods of sludge removal from CAPs. They are:

1. In-situ desludging. In this approach, the solids settle to the base of the CAP and are removed by pumping via a pre-installed pipeline.
2. Suspension removal. In this approach, the solids are not allowed to settle. They are kept in suspension using agitators inside the CAP. The solids are removed as part of the effluent flow out of the CAP.
3. Life-time accumulation. In this approach, solids are allowed to settle but are not removed until the operational life of the pond cover is reached and the cover is removed. In this approach, a large sludge-accumulation volume is needed to be designed as part of the internal volume of the CAP. Suspension removal requires the installation of agitators under the pond cover. This adds cost and, experience from the USA suggests that the agitators can be affected by contaminants in the feedlot manure. Life-time accumulation is not recommended as experience from the USA suggests that sludge accumulation rates can be high and thus the life-time might be quite short. For feedlot manure, regular in-situ desludging is the best option.

In-situ desludging

Continuous or semi-continuous sludge draw-off is desirable for CAPs (Watson 1999). This is done by laying a network of pipes at the base of the pond and sucking the sludge out through inlets on the pipes (See Figure 26 – Watson, 1999). Photograph 66 & 67 document the installation of sludge removal pipes in a high-rate treatment pond (Goulburn Valley Water). Photograph 68 documents the ends of sludge removal pipelines extending beyond the pond covers.

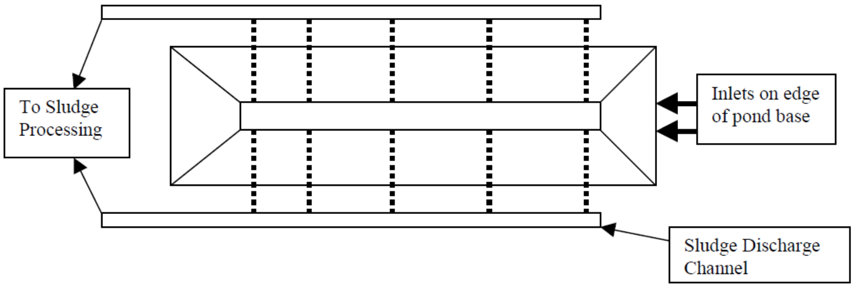


Figure 26 - Desirable layout of anaerobic pond to facilitate desludging (Watson 1999)

Usually, conventional positive-displacement (See Photograph 63) or vacuum pumps are used to remove sludge. Air-lift pump systems have been suggested for sludge draw-off due to their minimal blockages, ability to pump high solids concentrations and to mix sludge (Watson 1999). Compressed air is injected through the air supply line to the lower part of the sludge draw-off pipe, and as the air bubbles upwards through the pipe, the liquid can be taken together with the air flow (Figure 27 - Airlift pump (Watson 1999)). However, limitations of using air-lift pump include that the specific gravity of sludge needs to be close to 1.0 and the flow rate can be limited. More importantly, for desludging covered ponds, strategically located mechanical mixers need to be used to prevent the introduction of oxygen under the gas collection cover and the generation of a potentially explosive atmosphere (Watson 1999).

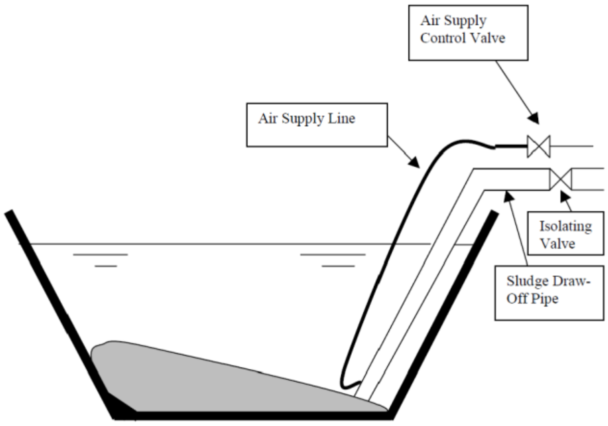


Figure 27 - Airlift pump (Watson 1999)

The main problem with submerged pipes is that they are only effective for removing the sludge near the inlet holes. After a period of time, a sludge void may develop near the inlet holes and the sludge removal will become much less effective. Mechanical scrapers may be used to push the sludge closer to the pipes but this is not likely to be cost-effective or practical for feedlot applications. A few features of pond layout have been suggested to facilitate the in-situ desludging (Watson 1999). These include:

- using deep ponds to increase sludge flow to draw-off pipeline
- using long narrow ponds to permit draw-off from side of pond
- providing two inlets to the pond, discharging towards the sides of the pond to preferentially deposit heavy sludge components closer to draw-off point
- providing sludge discharge channels alongside the pond to receive removed sludge and discharge to the sludge processing area.

The report by Butler and Johns (2012) on the design and operation of a CAP treating red meat processing waste water illustrates a general issue with sludge removal from a covered pond. If sludge removal is frequent, the sludge is likely to be relatively low TS and be fluid so that it can easily be pumped. However, the sludge would not be completely digested thus losing methane generation potential. It is strongly recommended that frequent sludge removal occurs to avoid consolidation of sludge under the cover and loss of active volume rather than being concerned about incomplete methane production.

Photograph 66 – Installation of sludge removal pipe system

Photograph 67 – Installation of sludge removal pipe system

Photograph 68 – Sludge extraction pipelines (deflated pond cover)

4.4.7 Sludge and effluent dewatering

The effluent leaving the CAP, although digested, still contains some solids. This effluent, as well as the removed sludge, needs to be dewatered. The dewatered solids contain the original nutrients (N, P and K) in the pen manure and are thus a valuable resource which should be used. Feedlots are already accustomed to using dried organic materials as organic fertilisers. There are many methods available for removing solids from effluent streams. In the feedlot biogas plants visited in the USA, complex, high-cost and technically sophisticated options had been chosen. This included belt presses with polymer additives, various rotating screens, sand filters and other machinery.

In Australia, feedlots are accustomed to a much simpler method of solids removal from effluent. These are sediment basins that remove solids from feedlot runoff. Similar techniques (i.e. settling basins) can be used to dewater digester effluent and sludge. A large foot print is required but this should not be an issue at a feedlot. The settling basins would be installed so that they drained into the existing feedlot holding pond. The dried sludge would be removed and handled as per existing manure handling methods. Due to the constant inflow of effluent, a system of multiple settling basins – some in use and some drying – would be required. This is a low-cost, low-technology option.

There are two options for settling basins. One is short-term drying bays. The other is a Sedimentation and Evaporative Pond System (SEPS), which is used in some Australian piggeries.

4.5 Economic assessment of a feedlot biogas system

4.5.1 Proposed biogas system design and indicative cost

Current feedlot manure management in solid form offers little opportunity for current digester designs. Aside from slatted floor feedlots in the United States, there are few successful examples of biogas developments using feedlot pen manure from traditional open air earthen feedlots.

The following flow chart provides some key elements of a biogas system potentially suitable for handling feedlot manure for use as a single substrate for biogas production. Central to this system is the use of a CAL which has been identified as a suitable technology for feedlots. For most large feedlots, the greatest energy usage is gas to fire the boiler for the steam flaker. This is the basis of the simple economic assessment outlined below.

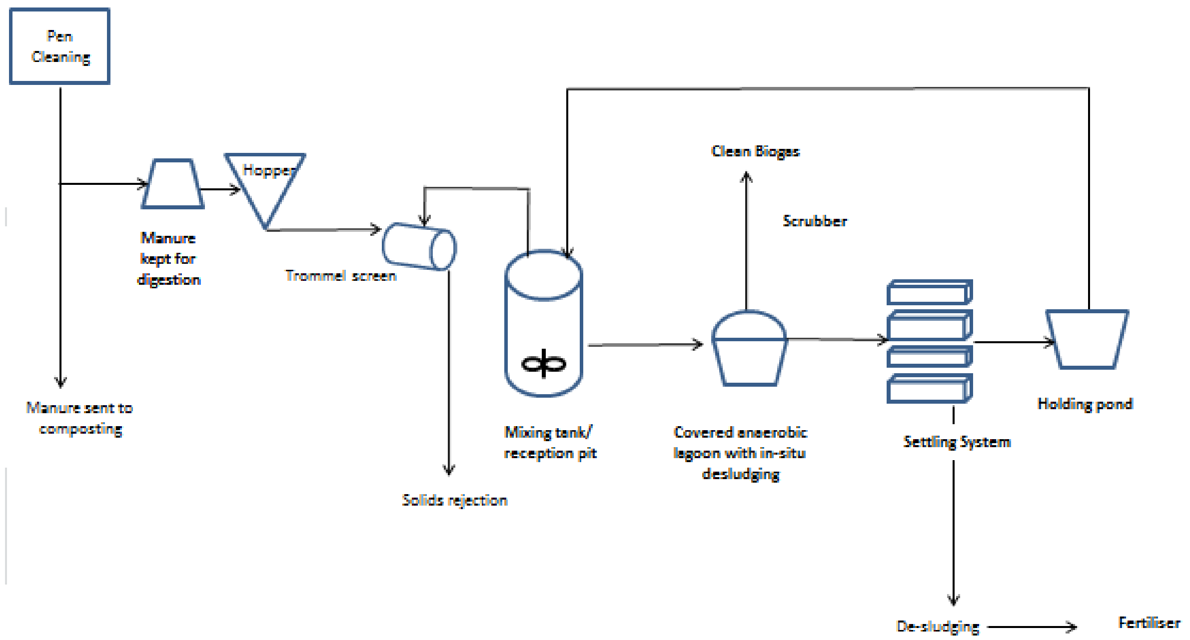


Figure 28 – Flow chart incorporating key elements of a proposed biogas system suitable for feedlots

A simple techno-economic feasibility for a 10,000 SCU using pen surface manure that is less than 60 days old (BMP 170 L CH_4/ kg VS at a VS of 76%) shows that the methane required for steam flaking is similar to the amount of methane produced from a 42 ML covered anaerobic lagoon.

The following assumptions have been made:

- Grain consumption of 23,500 tonnes/year
- Requires thermal energy of 285 MJ/T grain for steam flaker which is equivalent to about 6,700,00 0 MJ/yr
- The equivalent methane requirements for feedlot grain processing is 195,000 m^3 CH_4/yr
- Maximum methane production from covered anaerobic lagoon is 230,000 m^3 CH_4/yr

A 42ML sized covered anaerobic lagoon has been estimated as a suitable maximum size to treat the amount of waste produced by a 10,000 SCU feedlot. It is important to note that this represents a maximum size to factor in sludge accumulation which can reduce the working volume of lagoons. Smaller sized lagoons (10ML to 20ML) can also be suitable if more elaborate in-situ desludging mechanisms are incorporated into the design.

Broad cost examples of covered anaerobic lagoons are provided in a report commissioned by AMPC and MLA (Laginestra, 2012). The report uses costs which are based on varying sized abattoirs. In addition, sizing of lagoons, gas production and costs of covered anaerobic lagoon itself has been adopted from general industry experience and unit rate values. Based on this report the indicative cost for a 42ML lagoon is approximately $3,200, 000. This price includes generic costs of:

- Anaerobic lagoon excavation, cut and fill
- Lagoon liner
- Covered anaerobic lagoon cover

- Biogas flare
- Scrubber
- Ancillaries, pipework and installation
- Contingencies, design, engineering (35%)

This estimate is the cost of the covered anaerobic lagoon and assumes all machinery required for the operation of the system will require purchasing. In reality, a feedlot may have some of the required equipment including the stockpile area, rotary screen, equipment shed, etc.

Additionally, while much of the machinery cost is fixed, the option to drive down the construction cost of the system is available if participating feedlots introduce various measures including, but not limited to:

- Use of materials to meet the minimum safety requirements for biogas use as per the Code of Practice for on-farm biogas production and use (Piggeries) (APL 2015) (e.g. use of buried polyethylene or PVC, rather than stainless steel for biogas transfer lines); and
- Self-management of the construction process.

4.5.2 Fertilizer sales

The likely impact on fertilizer sales is reported in Table 16.This table compares the income of manure sold as fertilizer with the anticipated income from selling the dried anaerobic digestate (dried sludge) and excess manure. The process of anaerobic digestion has a negligible impact on the total availability of Nitrogen, Phosphorous and Potassium available as these key elements are not affected by organic matter breakdown. The digestate material has a number of key attributes which will invariably increase the quality of fertilizer and increase the purchase price. These attribute include: the fertilizer is odourless; stable (no leaching); contains high level of organic matter; increased percentage of N, P and K/kg of fertilizer; and an increased bulk density. This means that less volume of fertilizer must be transported and less fertilizer needs to be applied to the land to achieve the same NPK application rates. Table 15 illustrates that a sale price of approximately $36/tonne of dried digestate will provide the same annual income as selling all manure as fertilizer. Realistically, a conservative price for the dried digestate is $60/t (same price as composting), which will result in a revenue increase of $33,000/year.

Table 16 – Comparative income of manure and digestate as fertilizers

Scenario	Fertilizer Products	Sale Price ($/t)	Tonnage (t/yr)	Revenue ($/yr)
Existing	Raw manure	$ 8	8 995	$ 71 959
	Total		**8 995**	**71 959**
Break Even Digestate Price	Digestate	$ 36	1 388	$ 50 394
	Raw Manure	$ 8	2 696	$ 21 565
	Total		**4 083**	**$ 71 959**
Conservative Digestate Price	Digestate	$ 60	1 388	$ 83 268
	Raw Manure	$ 8	2 696	$ 21 565
	Total		**4 083**	**$ 104 834**
Maximum Digestate Price	Digestate	$ 200	1 388	$ 277 562
	Raw Manure	$ 8	2 696	$ 21 565
	Total		**4 083**	**$ 299 127**

4.5.3 Emissions Reduction Fund (ERF)

Currently there is no methodology addressing the disposal of, and emissions related to feedlot manure. To achieve benefit from the ERF would need to reduce GHG emissions below the existing baseline. The existing baseline would involve harvesting and stockpiling manure until it could be used for land application. In this baseline scenario, the emissions produced would be restricted to the low penitential GHG CO_2. In the proposed biogas system, the burning of CH_4 to reduce CH_4 impacts is not considered a reduction in GHG, as the emissions were purposefully generated *above* the baseline by altering the manure treatment method. Additionally, the key issue with an anaerobic digester is emission leakage. Emission leakage from anaerobic digesters results in the emission of CH_4, a far more potent GHG with a CO_2-equivalence of 25 (i.e 1 CH_4 molecule has the same impact as 25 CO_2 molecules). Hence, if emissions leakage occurred, the likelihood exists that the system would result in emissions exceeding the current baseline.

5. Conclusions and recommendations

The purpose of the project was to provide a techno-economic assessment of using feedlot manure as a substrate for biogas production. In order to do this the project undertook:

- a comprehensive literature review on the application of existing anaerobic digestion technologies and current Australian feedlot manure handling practices,
- measurement of biomethane potential (BMP) of feedlot manure to gain a better understanding of the true biomethane potential of this feedstock, and
- a techno-economic feasibility of a proposed 10,000 SCU manure-biogas development.

The literature highlights that the economic value of feedlot manure for anaerobic digestion is largely determined by the composition (quality) of the manure. Pen cleaning timing, frequency and method affects the quality of the manure removed. This wide range of VS content in material harvested from feedlot pens demonstrates the influence of pen design and management on the quality of manure removed from the pens. Data from these feedlots suggest that the material harvested contains material other than manure. This additional material (e.g. rocks and/or soil) influences the results by increasing quantity of material harvested and lowering the organic content. This is consistent with US feedlots where “feedlot soil” is harvested.

This data in the literature highlights the need to be fully aware of the circumstances behind pen manure samples. The BMP laboratory experiments in this study clearly reflect this. For example, a direct comparison can be made between 3 manure types from a single feedlot. The methane yields for fresh manure and pen surface manure harvested at 6 weeks resulted in 20% reduction in BMP value. Freshly scraped manure resulted in a reduction of 38% of fresh manure BMP. This study also revealed for the first time that stockpile manure has relatively low BMP value, rendering this substrate inappropriate for use as a feedstock for biogas production. However, a full understanding of the BMP value of stockpile manure should be undertaken by analysing multiple samples at different feedlots.

The differences in ultimate methane yields has been highlighted in the literature and can be due to various factors including incubation temperature, source and amount of inocula added, timing and mixing of sample, amount of dilution of the sample and incubation time. The use of specialist anaerobic digestion testing in this study provided real-time performance data at a high level of accuracy and precision and used appropriate methodology to reduce variability.

Ensuring the capture of manure before significant degradation occurs and the minimisation of contamination during pen cleaning is the most effective but may not be the most viable approach given the necessity of dramatic change in feedlot manure management and increased pen maintenance costs.

Pen cleaning without the removal of the interface layer will reduce the amount of soil and other non-degradable materials in the harvested manure. More frequent pen cleaning may be an option. Some form of "selective" cleaning where only fresh faeces is removed would significantly improve the methane potential of the removed material but this would require a pen cleaning technology that does not currently exist.

Based on the experimental work undertaken in this project and information gained on study tours, the following recommendations should be considered:

1. Feedlot manure readily degrades on the pen surface and the methane potential of the manure decreases significantly. Hence, manure must be harvested frequently and loaded into the digester quickly.
2. Feedlot manure is often contaminated with soil, gravel and other physical contaminants. However, good pen design and careful cleaning can minimise that contamination, albeit at an increased cost.
3. Irrespective of the quality and frequency of pen cleaning, some soil, gravel and hair contamination will occur. The biogas digester must be designed to cater for frequent removal of large quantities of settled sludge (soil, gravel, hair, silica from feed).
4. Due to the degradation and loss of methane potential that has occurred during stockpiling and composting, this degraded manure cannot be economically used for biogas production. However, the manure stockpile areas are suitable for handling dewatered sludge.
5. For most large feedlots, the greatest energy usage is gas to fire the boiler for the steam flaker. Hence, biogas can be used directly as a gas rather than used for electricity generation. This reduces the cost and complexity of handling the biogas.
6. Feedlots already use large machinery for manure and feed management (front-end loaders, box scrapers, body trucks, vibrating or rotating screens). The biogas system should be designed to use existing equipment.
7. Currently, the nutrients in manure are a saleable resource at feedlots. The biogas system should ensure that key nutrients (N, P and K) can still be used as organic fertiliser.
8. As feedlots are always located on large areas of land with good separation from neighbours, land area constraints do not apply. A small foot print for the facility is unnecessary.
9. All feedlots have a holding pond which captures contaminated runoff from the pen area. This can provide a water source for the biogas plant that already contains some organic matter.
10. As energy and cattle costs can vary considerably, the capital cost of the facility must be kept as low as possible. Low-tech solutions should be considered before complex, high-technology solutions.
11. Lot feeders are experts in feeding cattle, not operating an industrial facility. The design of the biogas system should not require precision control.

Using these design considerations, a feedlot biogas system can be proposed. Due to these constraints, the type of Australian feedlot most suited to a viable biogas system would:

1. Be located in a low-rainfall and/or summer-dominant rainfall zone to maximise the availability of dry manure.
2. Have well-design and constructed smooth pen surfaces with little gravel.
3. Have a capacity of 10,000 head or more and be run at high occupancy.
4. Have a steam flaker and boiler system to use the biogas.

A simple techno-economic feasibility for a 10,000 SCU using pen surface manure that is less than 60 days old (BMP 170 L CH_4/ kg VS at a VS of 76%) shows that the methane required for steam flaking is similar to the amount of methane produced from a 42 ML covered anaerobic lagoon.

This study has been successful in identifying the appropriate design criteria in terms of cost and the parameters of feedlot manure that lead to highest biomethane potential. However, there are few successful examples of biogas developments using feedlot pen manure. Further research is required to demonstrate the feasibility of low cost pilot scale biogas technology (such as covered anaerobic lagoons) in Australia.

Key recommendations which will assist in increasing the economic feasibility of biogas centre on fundamental changes in holistic feedlot manure management practices and the adoption of alternative biogas design concepts. To enable this paradigm shift a facilitated workshop involving key stakeholders is an important next step which will assist in identifying:

- Innovative and low cost biogas technology solutions which may be suitable for feedlots using manure as a single substrate.
- Feedlot management options and manure harvest management techniques and the modification of existing machinery to improve the quality of the feedstock.
- An investigation into the use of alternative waste streams in addition to feedlot manure (ie co-digestion) and the subsequent exploration into supply chain logistics and management (eg trucks travelling to abattoirs and returning with suitable waste to feed into the digester to increase biogas yields).
- Interested feedlot operators capable of scaling up fit-for-purpose trials based on bench trials.

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