Sustainable Energy for New Zealand Dairy Farms by Anaerobic Digestion of Dairy Farm Effluent

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Abstract

This study evaluated the economic feasibility and environmental impact of using a bio-digester to produce methane for energy production from a New Zealand conventional dairy farm.

Parameters effecting the bio-methanation process are examined. Analytical procedures have been carried out to determine favorable conditions for enhanced biogas production. These were: 1) pH, 2) Temperature, 3) Total solids and Total Volatile solids, 4) Gas volume and 5) Gas analysis.

Using locally supplied dairy shed effluent, it was found that 1 L reactors had peak gas production over 15 days, after which pH dropped and gas production dropped. Optimal pH was 7 and maximum gas production was 1.25 L/L reactor.

A three stage digester was set up and run for 62 days with a maximum cumulative gas production of 21.3 L, 11.7 L and 6.6 L in the three reactors. Total volumetric methane production was 0.09 m^3/kgVS/day 0.06 m^3/kgVS/day and 0.07 m^3/kgVS/day respectively from reactors 7, 8 and 9. The reactors produced biogas with an average composition of 74 % methane (CH_4) and 25% carbon-dioxide (CO_2). A typical digester would produce 65-70% CH_4.

1 kg of methane produces 4.66 kWh electricity and 5.72 kWh of heat, a typical farm of 250 cows would produce 548 kWh/day electricity and 665 kWh/day heat from using methane captured in the anaerobic digesters using dairy shed effluent. A typical 250 cow farm consumes 1285 kWh/day total energy 40% is from heat and rest is electricity. So by having installed plug-flow anaerobic digesters it could potentially meet 130% of total energy needs and 113% of total energy needs by using a three stage mesophilic digester.

A life cycle assessment was carried out for a typical New Zealand farm. Methane emissions from enteric fermentation, excreta, manure and farm dairy effluent irrigation and storage ponds contribute to 60% of the total greenhouse gas (GHG) emissions of a farm. Management of dairy shed effluent will only reduce GHG emissions by 1.8%. In addition, spray irrigation will impact on GHG emissions due increased moisture, C and N content, increasing N_2O emissions. Hence from an environmental sustainability

point of view, collecting and digesting diary shed effluent will have little significant impact on overall GHG emissions. Therefore, collecting and digesting dairy effluent is only of value if it results in economic benefits for the farm.

An economic analysis was conducted on installing a digester system. The anaerobic digester systems for 250 cow farm would have a capital cost of $107,745 per year, an operating cost of $134,828 per year, and generate revenue of $132,819 per year, but would not be able to pay back the capital cost. For a 250 cow farm a plug flow digester would have a capital cost of $95,658 per year, operating cost $127,018 per year, generate revenue $194,722 per year, and the resulting payback period is 2 years. A three stage digester for a 250 cow farm would have a capital cost of $259,608 an operating cost of $215,920 per year, generate revenue of $296,389 per year, a payback period of 3 years. But for a large farm size of 600-1000 cows therefore a multi stage digester would be worthwhile. For large dairy farms, CH_4 capture with energy recovery can already be cost effective based on the energy value alone.

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1 Introduction

New Zealand's dairy farms produce an estimated 70 million m^3 of effluent annually (Saggar et al., 2004). Manure is collected mostly from the milking shed and feed pads, as dairy farming in New Zealand is predominantly pasture fed. Estimates of the volume of methane, which could be derived from this resource, range from 37 to 120 L/cow/day. This methane would have a total energy (heat and electricity) value of 62 to 200 kWh/cow/year (based on a 270-day season) (Broughton et al., 2009). It has been estimated that the power requirements of an average New Zealand dairy farm equate to 160kWh/cow/year (Wells, 2001). Using this figure, the power output from an on-farm biogas system could cover from 41 to 133% of a farm's power needs (Broughton et al., 2009).

A typical 350 head dairy farm in New Zealand produces around 17.5 m^3 of effluent daily, based on typical effluent production of 50 L/cow/day (Dexcel, 2006; Vanderholm, 1984). This effluent has the potential to produce over 40 m^3 of methane per day under suitable conditions which would be sustainable energy and power for the dairy farm. Craggs (2006) reported use of methane production from mesophilic digesters in the New Zealand context is thought to only be financially viable for farms that have more than 700 cows. It has been estimated that covering ponds for methane capture is only economically viable for New Zealand dairy farms with herds larger than 1000 cows (Craggs, 2007).

In New Zealand many dairy farms capture and treat the farm dairy effluent (FDE) using a two-pond system, which, consists of a 4-meter deep anaerobic pond followed by a shallower aerobic pond. In the New Zealand agricultural sector, greenhouse gas (GHG) emissions are dominated (72.6%) by enteric fermentation and nitrous oxides from soil (21.5%) (Ministry for the Environment 2015). Methane output from these anaerobic ponds has been estimated at 0.02 m^3/m^3 of pond per day (NZ Ministry of Agriculture and Fisheries, 1994). Assuming a typical depth of 4 m for farm anaerobic ponds, this equates to a methane production rate of 0.08 m^3/m^2/day (Broughton, 2009).

Park and Craggs reported a lower areal methane production of 0.023 m^3/m^2/day from anaerobic ponds on dairy farms (2007). At such low volumetric gas production, it is not economical to cover ponds that typically have an area ranging from 300 m^2 for

small herds to over 1000 m^2 for herds of 500 cows. Typical anaerobic ponds in New Zealand are designed on an organic loading basis (0.020–0.028 kg BOD5/m^3/day), which results in long hydraulic retention times of 50 to 120 days (Dexcel, 2006). Studies indicate that solids are retained up to five years because of the large holding capacity of the effluent ponds but pre-treatment of the FDE to remove solids could decrease the amount of methane that could be potentially captured.

Although the average sized dairy farm may be able to produce sufficient sustainable energy from effluent digestion, the cost of energy capture is not economically viable where the costs of either installing a heated mixed digester or of covering the large surface area of conventionally designed dairy farm anaerobic ponds is challenging. Broughton (2009) reported that developing smaller pond reactors that could efficiently convert the organic matter held in FDE into biogas could be a solution. However by doing so the biomethanation process has to be enhanced because of the reduced hydraulic retention time (HRT). In psychrophilic (ambient temperature) biomethanation the rate limiting step is hydrolysis (Noike et al., 1985), the transfer of organic matter from the solid to the liquid phase. Broughton (2009) has demonstrated that improved hydrolysis and acidogenesis could result in better biomethanation of FDE but removal of solids could impact the total methane production. His study also revealed although there is a trade-off in the total methane production, the reduction in pond size could make the covering of the ponds more economically viable.

1.1 Thesis objectives

The primary aim of this study is to improve the process of biomethanation of farm dairy effluent (FDE) by proposing a continuous stirred up flow three-stage mesophilic bio digester, which would be efficient in capturing more methane but also reduce the HRT. It is assumed that the cost of covering the three stage digesters as opposed to a standard effluent pond may not vary much but the efficiency of the process will be improved, thus making it more cost effective. The rationale behind this is that improved biomethanation occurs in the in the first stage of a three-stage system, where the effluent has higher total solids content and volatile fatty acids which reduce the pH therefore inhibiting the growth of methanogens. The effluent will result in a liquid feed with a high soluble organic content, which can be fed into the second stage methanogenic reactor. The amount of methane, which could be recovered in the second

stage, is assumed to be lower than in the first stage. The effluent from the second stage is fed into the third stage. Assuming that the methane content from the third stage digester is the lowest. The effluent from the third digester is drawn out for irrigation of the dairy farm.

The secondary aim of this research is to develop a structured study of dairy farms and do a life cycle assessment of the dairy farm. The objective is to estimate the cradle to gate eco-profile of a hypothetical commercial process producing and capturing methane from the digesters and analyzing energy use and greenhouse gas emissions. Research focused on whether it is economically and commercially sustainable to be progressing with the current practice of using FDE mainly for irrigation and composting or to capture methane and convert to biogas. Aiming at identifying which portions of the LCA would have contribution to impacts.

In order to achieve the above aim, the objectives of this thesis are:

- To investigate the effects of various factors influencing biomethanation
- To investigate the effects of having a three stage biomethanation process as opposed to the regular practice of a single large bio digester.
- To investigate the total methane content of the gas produced.
- To investigate the total volatile solids in the processed effluent to find impact on the total methane/total VS.
- To use the findings of the above investigations to design a reactor processes that aims to achieve a sustainable self-sufficient dairy farm energy process.
- To develop a detailed cost analysis for the farm scale bio digesters.
- To develop a life cycle inventory and lifecycle impact assessment based on mass balance and economic balance
- To identify significant conclusion and recommendation based on inventory and impact assessments of data.

1.2 Thesis structure

In this thesis, firstly a literature review is carried out in Chapter 2 to analyze the current dairy farming system in New Zealand, understand the treatment systems in place for farm dairy effluent and understand the concept of anaerobic digestion. A methodology is proposed in Chapter 3 for experiments of anaerobic digestion process

and to regulate the parameters effecting the bio-digesters. A detailed life cycle analysis of dairy farm is carried out in Chapter 5 evaluating the resource inputs and environmental emissions so that the most effective options for improvement could be defined. Results and conclusions of the experiments and methodologies carried out were discussed in chapters 4 and 6.

2 Literature Review

This chapter will give an overview of biofuels and biogas. Also included are the literature review of New Zealand dairy farming, different production systems, cow housing systems, farm dairy effluent and its characteristics, areas of effluent capture and FDE treatment both solid and liquid.

2.1 Biofuels

Biofuels are fuels derived from biomass-from plants and other naturally occurring organic materials. Biofuels are renewable forms of energy and in the recent years there is an increased production and usage of sustainable forms of energy around the world. Not only do biofuels enhance energy security but also reduce the greenhouse gas emissions and other pollutants. They are affordable thus promoting economic development and sustainability. Although biofuels proved to be a promising solution for the growing world energy needs certain environmental and social risks need to be considered to make it a potentially significant clean energy resource for the future. Risks posing a challenge for the biofuels include use of sustainable feedstocks which does not involve deforestation and food crop displacement, using biodegradable materials, creating positive greenhouse gas emissions, water use, process efficiencies, limited nature of oil and avoid or control of invasive species (Mousdale et al., 2010, Rutz & Janssen et al., 2007).

Biofuels are classified in three types: biodiesel, bioalcohols and biogas (EIA, 2015).

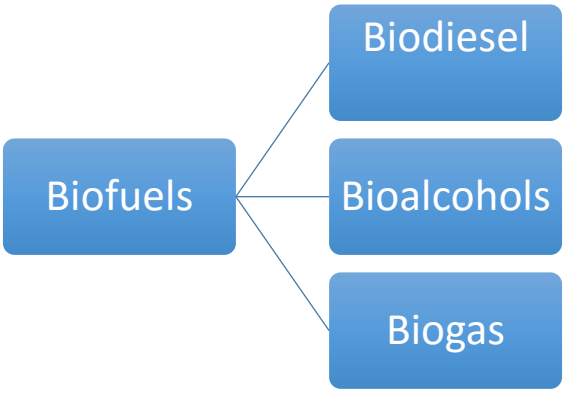

Figure 2-1: Types of biofuel.

Biodiesel is made by trans-esterification of vegetable or soybean oil or other natural oils and fats is an alternative for diesel or as a diesel additive (Howell & Weber, 2015). Bio-alcohols (bioethanol for example) are derived from fermentation of carbohydrates in crops like corn and sugarcane. Bio-alcohols can also be produced from fermentation of cellulosic biomass from non-food sources like grass (Shah & Sen 2011). Biogas is produced by anaerobic breakdown of organic matter or wastes (manure) (Rutz and Seadi 2008).

Platforms for producing biofuels include thermochemical combustion, indirect liquefaction, and direct liquefaction (Verma & Godbout et al., 2012). In indirect liquefaction conversion of the solid or liquid feedstock into liquid fuels from an intermediate mixture of carbon monoxide and hydrogen called syngas occurs.

Syngas is produced by steam reforming of gaseous or volatile feedstocks (methane and other volatile organic compounds VOC's) (Puigjaner et al., 2011). Fisher Tropsch (FT) synthesis, methanol synthesis and methanol to gasoline (MTG) synthesis are the different processes of indirect liquefaction. This process is suitable for any carbonaceous feedstock like mixed biomass streams, municipal solid wastes (MSW), and waste water sludge but challenges include large scale set up to achieve favorable economics, high capital costs, high pressure operation and higher cost of unit processes to clean the syngas (Puigjaner et al., 2011).

Direct liquefaction uses heat and sometimes a catalyst to convert organic solids to liquids and vapors that can be recovered. Pyrolysis and solvent liquefaction are the processes for direct liquefaction. Pyrolysis is the thermal decomposition of organic matter in the absence of oxygen and produces bio-oil as the primary product. Solvent liquefaction is thermal decomposition of the organic matter in a solvent (Verma & Godbout et al., 2012).

Brazil, the United States and the European Union countries are leaders in production, export and use of biofuels, with Brazil exporting 5 billion liters of ethanol fuel in 2008 (Stephan Bringezu et al., 2009)

2.1.1 Why biogas?

With climate change being a global concern and more demanding emissions reduction targets coming, there is increasing interest in using renewable energy sources. New Zealand has the third highest renewable energy supply in the OECD with 38% of the total consumer energy met by renewable energy dominated by geothermal, hydro and biomass (MBIE, 2011). More than 75% of New Zealand's electrical supply is from renewable resources (Greenpeace, 2013). Attention is also focusing on greenhouse gas emissions on-farm, and the capturing of biogas is receiving some interest from farmers and commercial companies.

Capturing the methane and using the resulting energy has several advantages subject to an assessment of the economics to:

- Off-set electricity costs on farm
- Provide an energy source in established farming regions with "old" power infrastructure that can struggle with inefficient network capacity at peak demand
- Provide heat for farm operation
- Even out the power load curve which could help a number of farms with peak demand supply issues
- Reduce odor and greenhouse gas emissions.

Biogas is the fuel produced by anaerobic breakdown of organic matter or waste (manure) (NNFCC, 2016). Biogas is gas produced during the breakdown of biological organic matter into carbon dioxide and methane, which can then be used to provide electricity, heat and transport fuel. It can be produced from effluent from farms, crops, crop wastes, fats and oils and sewage or at landfills. Biogas contains methane (a greenhouse gas), which is the combustible portion of biogas. The most common method of producing biogas is an anaerobic (without air) digestion system. In the case of dairy effluent this would be either a covered effluent pond/tank or by the installation of an enclosed anaerobic digester. Biogas also contains hydrogen sulphide, carbon dioxide and water vapor. The hydrogen sulphide and water vapor need to be removed

for the electrical energy generation process. If the biogas is to be used solely for heating, then the gas can be used much as it is produced except for the excess water vapor, which should be removed.

2.1.2 Sources of feed stock for Biogas production

Biogas can be made from most biomass and waste materials and from the left over organic material from both ethanol and biodiesel production. Potential waste feedstocks include residual sludge from wastewater treatment plants, dairy production, food waste, food processing wastewater, dairy manure, poultry manure, aquaculture wastewater, seafood processing wastewater, yard wastes, and municipal solid wastes (Wilkie et al., 2015). Food processing wastewaters may come from citrus processing, dairy processing, vegetable canning, potato processing, breweries, and sugar production and potential energy crops (sugarcane, sorghum, napier grass, as well as, woody crops (tree crops)).

For this thesis we considered using dairy effluent as feedstock as New Zealand has a predominant dairy industry.

2.2 New Zealand Dairy Farming

2.2.1 North Island and South Island dairy farming

A review between North and South Island dairy farming shows that 75% of dairy herds located in North Island and 62% of dairy cows located in the North Island, with the greatest concentration (30%) situated in the Waikato region. Of the 62% dairy cows in north island 24% cows are from Waikato region. Taranaki, with 15% of dairy herds, is the next largest region on a herd basis.

Although South Island dairy herds account for 25% of the national total, they contain 38% of all cows. Twenty-four per cent of all dairy cows are located in the Waikato region, followed by North Canterbury (13%), Southland (11%) and Taranaki (10%).

From Dairy NZ statistics report more than 1.8 million cows are in the South Island with the largest average herd size (791) in North Canterbury. Also from the study it was reported that South Island average herd sizes increasing faster than North Island

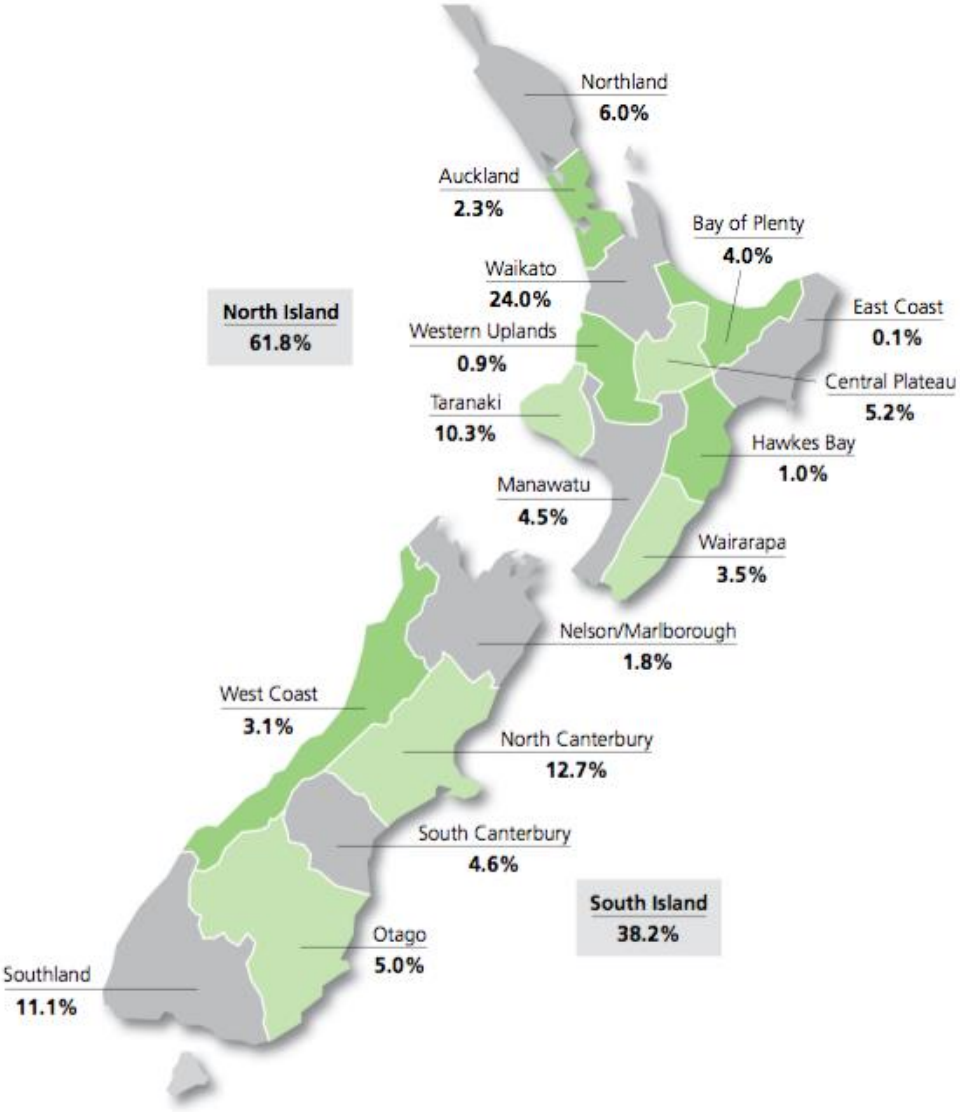

Figure 2-2: Regional distribution of dairy cows 2012-2013 (Dairy statistics, Dairy NZ 2013)

Farms in the South Island are, on average, larger than those in the North Island (in terms of both farm area and cow numbers, see Table 2.1. Sixty-two percent of all cows are in the North Island, with 24% in the Waikato region. The average herd size in both islands continues to increase. Within the South Island, North Canterbury has the largest average herd size (791 cows). In the North Island, Hawkes Bay has the largest average herd size of 673 cows. The smallest average herd sizes are in Auckland, Taranaki, and Northland, averaging 260, 283 and 306 cows respectively. North Canterbury has the highest average cows per hectare (3.49), followed closely by South Canterbury (3.45). The regions with the lowest average cows per hectare are the West Coast (2.16), Northland (2.29) and Auckland (2.30).

Table 2-1: Herd analysis by region 2012/13 (Dairy statistics, Dairy NZ 2013

Farming region	Total herds	Percentage of herds	Total cows	Percentage of cows	Total effective hectares	Percentage of effective hectares	Average herd size	Average effective hectares	Average cows per hectare
Northland	935	7.9	285,956	6.0	124,747	7.4	306	133	2.29
Auckland	431	3.6	111,976	2.3	48,655	2.9	260	113	2.3
Waikato	3,554	29.9	1,148,553	24.0	390,211	23.3	323	110	2.94
Bay of Plenty	598	5	192,877	4.0	68,853	4.1	323	115	2.8
Central Plateau	470	4	247,046	5.2	90,757	5.4	526	193	2.72
Western Uplands	86	0.7	42,106	0.9	16,861	1.0	490	196	2.5
East Coast	9	0.1	4,899	0.1	1,846	0.1	544	205	2.65
Hawkes Bay	71	0.6	47,781	1.0	16,870	1.0	673	238	2.83
Taranaki	1,734	14.6	490,528	10.3	172,571	10.3	283	100	2.84
Manawatu	559	4.7	214,710	4.5	77,654	4.6	384	139	2.76
Wairarapa	465	3.9	168,570	3.5	60,757	3.6	363	131	2.77
North Island	**8,912**	**74.9**	**2,955,002**	**61.8**	**1,069,782**	**63.8**	**332**	**120**	**2.76**
Nelson/Marlborough	237	2	86,203	1.8	30,338	1.8	364	128	2.84
West Coast	371	3.1	147,660	3.1	68,399	4.1	398	184	2.16
North Canterbury	768	6.5	607,811	12.7	174,308	10.4	791	227	3.49
South Canterbury	278	2.3	218,514	4.6	63,360	3.8	786	228	3.45
Otago	396	3.3	236,981	5.0	76,886	4.6	598	194	3.08
Southland	929	7.8	532,079	11.1	194,322	11.6	573	209	2.74
South Island	**2,979**	**25.1**	**1,829,248**	**38.2**	**607,613**	**36.2**	**614**	**204**	**3.01**
New Zealand	**11,891**		**4,784,250**		**1,677,395**		**402**	**141**	**2.85**

Between 1980/81 and 2007/08 total herd numbers declined at an average rate of about 170 herds per season, however, the total number of herds in the 2012/13 season increased by 93 to 11,891 (LIC, 2012/13). Average herd size exceeds 400 cows (LIC, 2012/13). This trend of increased herd numbers and herd sizes is shown in figure below.

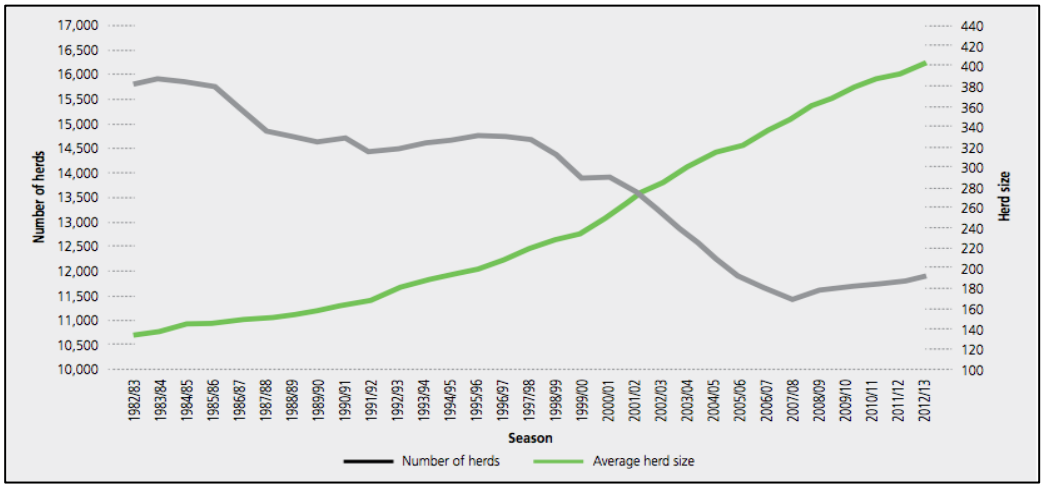

Figure 2-3: Trend in the number of herds and the average herd sizes in the last 30 seasons (LIC, 2012/13).

2.2.2 Production System in New Zealand

In New Zealand dairy farming is pasture. Intensification on pastoral land has continued to increase to the detriment of the soils. Walking cows too far, exposing cows to weather changes or even big feed variations of energy, DM, protein or quality will upset the cow (Pow & Longhurst et al.,2014). Cows using too much energy for either cooling or heating themselves or energy lost in walking or searching for feed, all suppresses milk production.

From Dairy NZ statistics report South Island farms have, on average, higher per herd production than herds in the North Island, with North Canterbury recording the highest average herd production at 309,244 kilograms of milk solids. This reflects a combination of larger herd sizes, a high stocking rate, and high kilograms of milk solids per cow. In the North Island, Hawkes Bay has the highest average herd production of 209,803 kilograms of milk solids, reflecting large herd sizes.

From Dairy NZ report (2012/13), average production per effective hectare and production per cow was higher in the South Island than in the North Island. North Canterbury recorded the highest average milk solids per hectare in the South Island (1,363 kg), while Manawatu had the highest average milk solids production per hectare in the North Island (996 kg). North Canterbury also had the highest average milk solids per cow (391 kg), followed by Southland (384 kg). In the North Island, Manawatu had the highest average milk solids per cow (360 kg), followed by Taranaki (344 kg) and

Wairarapa (338 kg).

Table 2-2: Herd production analysis by region in 2012/13 (Dairy NZ,2013)

Farming region	Total kg milksolids	Percent milk-solids	Average litres per herd	Average kg milkfat per	Average kg protein per herd	Average kg milksolids per	Average kg milkf	Average kg protein per	Average kg milksolids	Average kg milk	Average kg prot	Average kg milksolids
Northland	80,518,080	4.9	1,001,423	49,066	37,050	86,116	368	278	645	160	121	282
Auckland	35,027,882	2.1	950,740	46,189	35,082	81,271	409	311	720	178	135	313
Waikato	378,529,678	22.8	1,219,447	60,786	45,722	106,508	554	416	970	188	141	330
Bay of Plenty	63,247,399	3.8	1,231,464	60,169	45,596	105,765	523	396	919	187	141	328
Central Plateau	79,149,649	4.8	1,943,868	96,269	72,134	168,404	499	374	872	183	137	320
Western Uplands	11,569,193	0.7	1,526,791	76,788	57,738	134,525	392	294	686	157	118	275
East Coast	1,253,113	0.1	1,659,168	78,985	60,249	139,235	385	294	679	145	111	256
Hawkes Bay	14,896,001	0.9	2,454,940	117,853	91,950	209,803	496	387	883	175	137	312
Taranaki	168,611,878	10.2	1,068,051	55,678	41,561	97,239	559	418	977	197	147	344
Manawatu	77,311,849	4.7	1,616,790	77,800	60,504	138,304	560	436	996	203	158	360
Wairarapa	56,932,042	3.4	1,386,543	69,487	52,948	122,434	532	405	937	192	146	338
North Island	967,046,764	58.3	1,240,026	61,835	46,676	108,511	515	389	904	186	141	327
Nelson/Marlborough	29,835,366	1.8	1,401,507	71,860	54,028	125,888	561	422	983	198	149	346
West Coast	48,991,932	3.0	1,432,445	75,897	56,156	132,054	412	305	716	191	141	332
North Canterbury	237,499,124	14.3	3,533,797	172,828	136,416	309,244	761	601	1,363	218	172	391
South Canterbury	83,460,485	5.0	3,436,620	167,765	132,453	300,218	736	581	1,317	213	169	382
Otago	86,639,796	5.2	2,508,960	122,574	96,214	218,787	631	496	1,127	205	161	366
Southland	204,248,847	12.3	2,481,241	123,353	96,505	219,859	590	461	1,051	215	168	384
South Island	690,675,550	41.7	2,628,920	130,142	101,706	231,848	638	499	1,137	212	166	378
New Zealand	1,657,722,313	100.0	1,587,980	78,948	60,462	139,410	560	429	988	196	150	346

The Five Production Systems are a way to group farm production systems by allocation of imported feed. As New Zealand pastoral farming is about profitably balancing feed supply and demand, five production systems have been described by Dairy NZ primarily on the basis of when imported feed is fed to dry or lactating cows during the season and secondly by the amount of imported feed and/or off farm grazing (Dairy NZ, 2012, The 5 Production Systems). The definitions do not include grazing or feed for young stock.

System 1 - All grass self-contained, all stock on the dairy platform

No feed is imported. No supplement fed to the herd except supplement harvested off the effective milking area and dry cows are not grazed off the effective milking area.

System 2 - Feed imported, either supplement or grazing off, fed to dry cows

Approx. 4 - 14% of total feed is imported. Large variation in % as in high rainfall areas and cold climates such as Southland, most of the cows are wintered off.

System 3 - Feed imported to extend lactation (typically autumn feed) and for dry cows

Approx. 10-20% of total feed is imported. Westland - feed to extend lactation may be imported in spring rather than autumn.

System 4 - Feed imported and used at both ends of lactation and for dry cows

Approx. 20 - 30% of total feed is imported onto the farm.

System 5 - Imported feed used all year, throughout lactation and for dry cows

Approx. 25 - 40% (but can be up to 55%) of total feed is imported.

*Note: Farms feeding 1-2kg of meal or grain per cow per day for most of the season will best fit in System 3.

2.2.3 Types of cow housing systems

In NZ cows dairy farming is predominantly pastoral, so the cows are mainly on paddock. Less time is spent on feed pads and stand-off pads. Dairying in New Zealand has a major impact on environment and economy. Environmental effects from dairying in New Zealand are noted to have been detrimental. Key water quality issues for dairy farmers are the significant amount of excess nutrients, nitrogen (N) and phosphorus (P), that leach or runoff into waterways. The MfE (2007) reports that N and P levels continues to rise, with 39% of monitored groundwater sites in New Zealand having nitrate levels above natural background levels. More concerning is that there are areas where nitrate concentrations exceed the drinking water standard of 11.3mg/L (MfE 2007).

In striving for increased profitability, national average stocking rates have increased from 2.10 cows/ha in 1982/83 season to 2.85 cows/ha in 2012/13 season (DairyNZ 2013). This means that over the past 30 years the average carrying capacity has increased from 945 to 1,283 kg LWT (assuming 450 kg cows) (Pow & Longhurst et al.,2014). With the higher stocking density there is increased risk of greater stock/hoof treading pressure causing damage to soil structure, particularly on sensitive soil types or where winter grazing pressures are high (Drewry et al, 2000; Singleton et al, 2000. Drewry et al. (2004) demonstrated a linear decrease in pasture yields of 1-2% for every 1% unit decrease in soil macro porosity values.

Solid effluent deposited on the feed pads and stand-off pads is then collected and

stored. The NZ GHG inventory assumes that in 2009 (MfE 2012) the average NZ dairy cow excreted 900 kg faecal dry matter (FDM) and 116.5 kg TN per year. With a lactation period of 270 days, 8% (Ledgard and Brier 2004) of FDM deposited at the milking shed, the TS and TN figures listed in Table 2-3. Effluent collected in the milking shed is flushed daily and manure is scraped. In the past, in particular the MfE solids figures have been questioned as being too low (Saggar et al. 2004, Pratt et al. 2012, Chung et al. 2013), and have consequently been suspected as one of a number of factors most likely causing NZ dairy manure management methane GHG emissions to be underreported (Craggs et al. 2008, Pratt et al 2012).

Table 2-3: Key industry guideline figures for cow shed effluent for FDE flow, Total Solids (TS), Total Nitrogen (TN) and Total Phosphorus (TP) by various authors (Craggs et al., 2014).

Source		Vanderholm (1984)	DEC (2006)	MfE (2012)	International Burke (2001)^
Average flow	(L/cow/day)	50	50	18-	
Flow range	(L/cow/day)	20 - 90	30 - 100	-	38 - 114
Average solid	(kgTS/cow/day)	0.36	0.55	0.20#	
Solids range	(kgTS/cow/day)	? - 0.55	0.3 – 0.6	-	0.64 – 0.95
Average TN	(gTN/cow/day)	10.4	22.0*	25.5+	
TN range	(gTN/cow/day)	6.8 - 19.0	7.0 – 30.0*	-	28.6 – 42.9*
Average TP	(gTP/cow/day)	1.76	2.5	-	
TP range	(gTP/cow/day)	1.0 – 2.0	0.5 – 4.5	-	4.5 – 6.7

The rapid intensification on dairy farms in New Zealand since 2000, has increasingly focused attention on issues relating to effluent management. Increased cow numbers, greater use of fertilizer N and higher supplementary feed inputs on dairy farms has resulted in marked changes in the volume, content and types of effluent produced (Longhurst et al., 2012). dairy farms have not produced significant quantities of manures and slurries (accumulated animal wastes in a semi-liquid or semi-solid form), however this situation has changed with intensification and recent technology developments in effluent irrigation (DairyNZ, 2011; Houlbrooke et al., 2004; Houlbrooke and Monaghan, 2010; Monaghan et al., 2010), and off-pasture systems

(Longhurst et al., 2006). The two main sources of dairy farm manures and slurries are separated solids from FDE and manure collected from stand-off pads and wintering barns/animal shelters (Longhurst et al., 2012). The increasing uptake of feed and stand-off pads and animal shelters, while acknowledged as having the potential to minimise adverse environmental effects and accumulation of higher solid content effluent has also contributed to the generation of dairy farm sludges and slurries (Longhurst et al., 2006).

2.2.4 Examples of different types of off paddock systems in different countries

Examples of paddock systems are listed below:

Feed pads: A permanent feed pad is a specifically designed area with a hard surface used to feed out supplements. These are normally located next to the farm dairy.

Figure 2-4: Feed pad (Dairy NZ, 2015).

Loose housed barn-soft bedding: A fully covered facility, usually built with plastic or steel roofing. The base is a soft bedding material such as straw, sawdust or woodchips, which will absorb some effluent.

Figure 2-5: Wintering Barn (Dairy NZ, 2015)

Loose housed barn-slatted concrete: A fully covered facility, usually with a plastic film over a frame type roof and a concrete slatted floor covering an effluent holding bunker, large enough to hold the effluent for extended periods.

Figure 2-6: Slatted concrete barn (Dairy NZ, 2015)

Free stall barn: A fully covered facility usually built with steel roofing. Usually have a concrete floor area and a softer surface area that provides individual spaces (free stall) where cows lie down.

Figure 2-7: Free-style Barn (Dairy NZ, 2015)

Stand-off pads: A semi-permanent feed pad is a specially built area where cows can be taken off paddock for periods of time.

Figure 2-8: Stand-off Pads (Dairy NZ, 2015)

Cow housing systems using woodchip bedding and slatted concrete flooring are identified as compliant farm system infrastructure investments (Dairy NZ, 2015). Both housing systems incorporate duration controlled grazing, supplementary feeding systems and nutrient management ability. These systems have been shown to reduce nitrogen leaching by ~50% on dairy farms. This is achieved by limiting the grazing window in which cow urine is able to be deposited on pasture, instead directing this to the controlled collection and storage area within housing system. Collecting and controlling this effluent represents a greater environmental control for the farm system and the nutrient value of this effluent can be applied to land evenly, avoiding high concentration patches as well as targeting the nutrient toward areas of lower fertility on the farm.

Through minimizing pugging damage (winter) and overgrazing (summer) cow housing systems preserve both the quality and quantity of pasture grown. Removing cows from pasture at key times is shown to increase annual dry matter production by 0.5-2.0 tons per hectare annually. Within these systems, financial benefit is derived from the value of additional pasture grown and reduced under sowing cost of 90% (Dairy NZ, 2015).

Farm dairy effluent (FDE) is the collective term for dairy cow urine, faeces, and wash-down water. It varies in volume and composition and is a reflection of many factors, including the number of cows milked, feed type, shed practices, wash-down methods, weather, and the time of year. Typical farm dairy effluent (FDE) composition is 10 % excreta, 4 % teat washings, 86 % wash water + foreign material, 0.04-4.96 % solid content (avg 0.9 %) (Gibson, 1995; Longhurst et al.,2000).

During the milking process it is estimated that around 10 % - 20% of a cow's daily urine and faeces is excreted in the dairy shed or yard (Vanderholm, 1984). The FDE may also include material collected from laneways, feed pads, wintering pads, silage stacks, and stock underpasses. Generally, the FDE captured from these sources is retained in a temporary containment facility and irrigated to pasture. However, there are times when soil conditions are not suitable for FDE irrigation and its deferred storage is required. Farm dairy effluent ponds range in size, shape, construction materials, and capacity (Dairy NZ, 2013). Earthen embankment ponds are formed from compacted earth material with a compacted clay liner (CCL) or geomembranes (also knows as synthetic liners), while concrete ponds may be formed from a series of concrete cast in-situ precast panels or sprayed (Shotcrete) concrete (Dairy NZ, 2013).

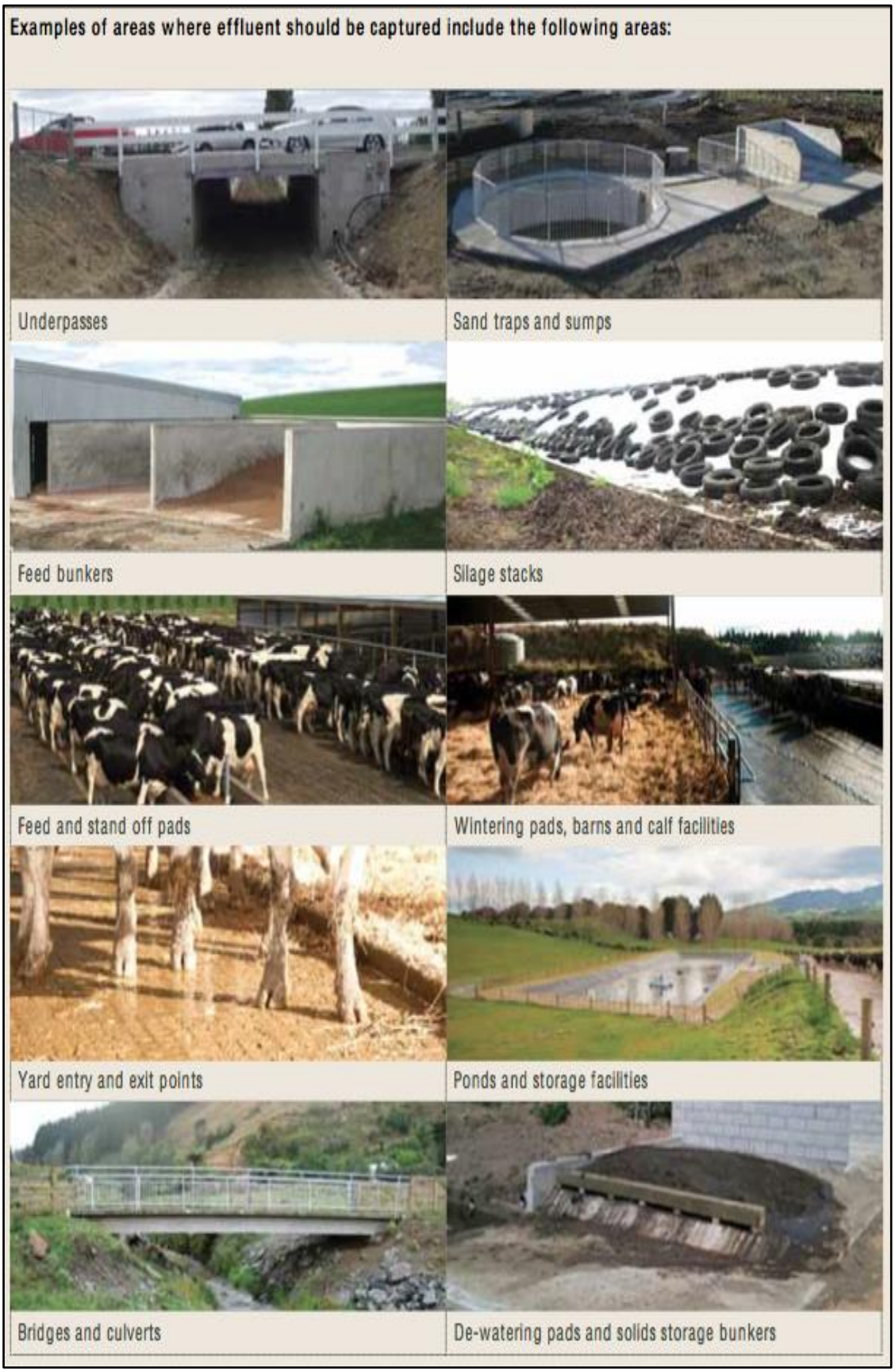

Figure 2-9: Areas for capturing FDE, (Farmers guide to managing FDE,,Dairy NZ, 2013)

2.2.5 Types of ponds for effluent capture

Effluent capture pond systems were introduced to New Zealand dairy farmers in the 1970's and for many years this was the most commonly used system for farm dairy effluent treatment (Dairy NZ, 2015). Ponds utilize biological processes to convert the organic content of the effluent to more stable and less offensive forms. The first pond, commonly known as the anaerobic pond, carries out a process without oxygen and can effectively treat the initial high strength effluent while allowing solid material to settle out as sludge (NIWA, 2012)

The second pond, commonly known as the aerobic pond, requires dissolved oxygen to further break down effluent flowing into it from the anaerobic pond before discharging it to a waterway (Dairy Insight & Environment Waikato et al. 2007; IPENZ,2013). This practice was efficient at removing biological oxygen demand (BOD), but high concentrations of nutrients were still present after treatment (Longhurst et al. 2000). The discharge of FDE therefore led to eutrophication of water bodies and loss of fertiliser nutrient resources (Houlbrooke et al. 2004).

Advanced pond systems comprise up to three different types of ponds, designed to optimise natural wastewater treatment processes, and spray irrigation of untreated effluent (Craggs et al., 2004). Different types of effluent pond systems used include single pond, two pond, multi-stage.

Single-pond systems provide for moderate settling of the solids (forming a sludge unless stirred) prior to the fluid component being discharged and pumped to a land application area. In many cases the single pond is used for bulk deferred storage with no requirement for settling; it may have a stirrer installed to mobilize the sludge for irrigation to land

A two-pond system involving a typically anaerobic primary pond used for settling solids, before flowing into a secondary pond which can be aerated to further treat the effluent before it is discharged, or being further clarified (through solids settling or removal).

Multi-stage ponds that are similar to wastewater treatment facilities with various settling, clarification, aeration, and disinfection processes occurring prior to the effluent being discharged (typically) to a waterway or land (Craggs et al., 2010).

Untreated effluent may also be collected in one to two-day capacity sumps, which is then discharged via a high-rate travelling irrigator to pasture. These are not considered suitable in some regions to manage effluent and maintain compliance throughout the year (Houlbrooke et al., 2008).

Current good-management practice is for the construction of deferred irrigation storage ponds, so when the soil moisture conditions are low the effluent can be discharged to land (Dairy Insight & Environment Canterbury et al. 2007; Dairy Insight & Environment Waikato et al. 2007; IPENZ 2013).

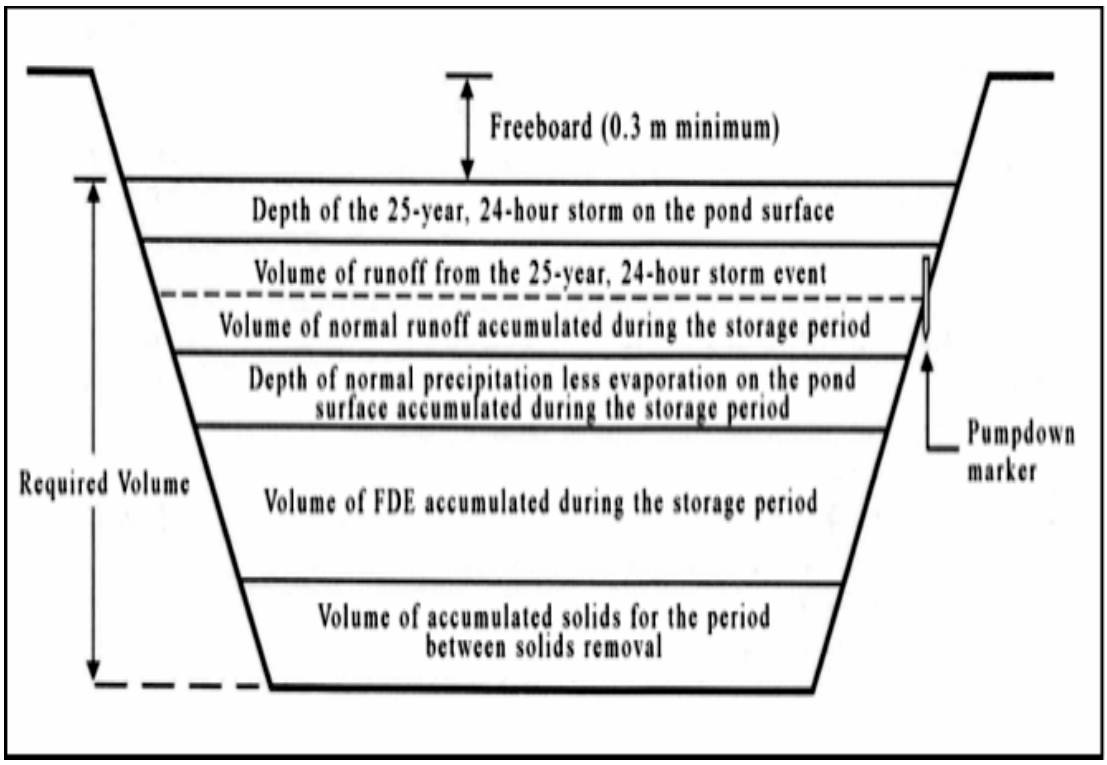

Figure 2-10: Example of Liquid FDE storage pond with a watershed, (Dairy NZ, 2013)

2.2.6 Dairy shed effluent characteristics

The percentage of manure deposited by a dairy cow in the dairy shed has been estimated at 10%-20% of its daily manure output (Vanderholm, 1984). The volume of urine and excreta that each cow produces per day is estimated at 54 L. The amount of material that is available for digestion and biogas production is dependent on the

amount of time that a cow spends on hardstand areas from which manure can be collected. On farms without feed-pads or stand-off areas this is typically estimated at 2 hours per day (Dexcel, 2006).

Broughton et al., 2009 reported that the amount of manure collected can be estimated as ts/tw x Vm where

ts = time on hardstand

tw = waking hours (typically 16)

Vm = the volume of manure produced every day (typically 54 L)

The estimates of average volumes of effluent per cow per day from wash down dairy sheds vary from 45 L to 80 L per day (Hickey et al., 1989). A large portion of this figure is made up of wash down water. The volume of wash down water is highly variable and dependent on the wash down method; scrape, hose down, flood wash or a combination of the three. A figure for wash down water of 50 L/cow/day (Vanderholm, 1984) is most commonly cited for design purposes. Effluent volumes per cow for larger herds can vary significantly; a herd of 500 cows can have a wash water volume between 30 and 120 L/cow/day.

The average composition of farm dairy effluent (FDE) comprises 10% excreta, 4% teat washings, and 86% wash-water plus other foreign material (Gibson, 1995). Solids content of the effluent can range from .04 to 4.96% with the average content being 0.9% (Longhurst et al., 2000). The higher solids figure may relate to farms with low water usage or feed pad effluent, which is typically higher in solids due to less frequent wash down procedures.

Various mean nitrogen levels in FDE have been reported ranging from 181 mg/l to over 500 mg/L (Longhurst et al., 2000). Nitrogen levels are seasonal and tend to peak in the spring when start of lactation and increased pasture growth coincide. Reported levels of nitrogen have been rising in recent years. This may be due to the increased use of nitrogen fertilizers.

Organic nitrogen is the main N source (80-95%), followed by ammonium (typically 17%) and small amounts of nitrate (<1%) (Longhurst et al., 2000). FDE tends to have high levels of phosphorus (21-82 mg/l) and potassium (164-705 mg/l).

Cow manure has relatively high COD/BOD ratio ranging from about 4:1 to 12:1(Broughton 2009). It also has a lower fraction of biodegradable volatile solids (VS) compared to other farm manures. This is due to the efficiency of the cow's rumen digestion system and its high fiber diet. It has been estimated that only between 23 to 43 % of VS in cow manure is readily digestible compared to 63% in pig and poultry manure (Wilkie et al., 2004).

Methane productivity is usually expressed on a per kg volatile solids (VS) added basis, but sometimes it is based on VS removed or destroyed, total solids (TS), influent mass, influent volume, chemical oxygen demand (COD), biological oxygen demand (BOD) or animal unit (Broughton 2009). The theoretical methane yield (Bu) is a calculation based on conversion of lipids, proteins, carbohydrates, volatile fatty acids (VFAs) and lignin to methane using Bushwell's formula (Moller et al., 2004). The ultimate methane yield (B_o) is the methane productivity in terms of VS added (L CH_4 /kg VS added) as residence time approaches infinity. This is typically determined using a specific methane potential test where a substance is digested for up to 90 days under ideal conditions of temperature, inoculum, nutrients and dilution. The specific methane yield is the volume of methane produced per influent VS for experimental set ups, trials and other reactors. The specific methane yield is typically a measure of a reactor's performance whereas the ultimate methane yield is an attempt at characterization of a starting material. Table 2-4 below shows B_o values for cow manure and other farm wastes by various researchers. Values for pig manure are also shown for comparison purposes. The range presented, from 125 up to 284 L CH_4/kg VS added, is relatively consistent considering the variability that can exist in cow manure due to types of feed, climate, breed and location. (Broughton 2009)

Table 2-3: Literature values for ultimate methane yield of dairy, pig and poultry manures (Broughton 2009).

Study	Dairy Manure LCH_4/kg VS added	Pig manure LCH_4/kg VS added
(Moller et al., 2004)	148±41	356
(Angelidaki & Ellegaard, 2003)	200	300
(Vedrenne et al., 2008) (Amon et al., 2007)	243±41 125-166	297±40
(Bryant et al., 1976) reported in (Safley & Westerman ,1922a)	170	
(Morris, 1976) reported in (Safley & Westerman ,1922a)	240	

2.2.7 Pre-treatment of Farm Dairy Effluent

2.2.7.1 FDE Solids management

Removing solids reduces the volume needed for storage in the ponds and makes the effluent more manageable (Broughton, 2009). Removing 52 % of volatile solids from slurry resulted in 30 % reduction in biogas (Pain et al., 1984). Hills and Kayhanian found that a 30-minute settling period retained 54 % of methane potential in the settled sludge (Wilkie et al., 2004) FDE systems incorporate a stone trap prior to flow to a large transfer sump (or tank) of 20–140 m^3 in size. On days where irrigation is allowed, "raw" FDE is pumped directly to irrigation without separation. During days where irrigation is not permitted, effluent can either be passed through a solids separation process (or not) or stored until irrigation is again permitted. The FDE is then either pumped directly from the pond to irrigate the pasture or returned to the sump for irrigation from there.

FDE solids management has mainly gravity separation (no-mechanical) and mechanical separation practices in New Zealand.

Mechanical separators are typically designed to remove solids down to less than one millimeter (Dairy NZ, 2013; Ford and Fleming et al., 2002). The resulting liquid contains only fine suspended organic material and silts/clays, plus all the dissolved

nutrient value (these are mainly Nitrogen (N) and Potassium (K). Phosphorus (P) tends to be in the solid fraction but may also form soluble salts and fine particulates in the effluent). Mechanical separators are normally either slope screen, rotary screen or screw presses (Dairy NZ, 2013; Ford and Fleming et al., 2002).

Screw press separators force the effluent under pressure through one or more layers of fine mesh screens to separate the solids and liquids. Screw press separators are normally built on raised platforms over concrete pads so that solids (15-25% TS) can pile up below for easy removal (Broughton 2009).

Figure 2-11. Screw press separator (Dairy NZ, 2012).

Belt presses (pressure separators) – these are continuously fed dewatering systems that use chemical conditioning, gravity drainage and mechanically applied pressure to dewater the manure. These belt-pressed solids come out at between 30-50% TS. Table 2 below shows the percentage solids capture that can be expected from various technologies. (Broughton 2009)

Mechanical separation of FDE requires a smaller physical area for installation and produces better filtration of the liquid effluent resulting in drier solids to store and spread (Dairy NZ, 2013; Ford and Fleming et al., 2002). But, mechanical separators require ongoing mechanical maintenance and removal of stone and grit prior to separation. Also the capital cost and energy cost are higher and the risk of breakdown is more (Ford and Fleming et al., 2002).

Non mechanical separation methods include weeping walls, settling ponds, slope screens and rotating drum systems (Dairy NZ, 2013).

Weeping-wall sludge stores are normally built above ground on a concrete or packed earthen base where effluent enters in one end of the store and flows out through 50 mm slots between wooden or concrete paneling at the opposite end, while the solids are retained in the sludge store (Broughton, 2009). The excess liquid that drains through the slots is discharged to a pond or applied to land. The weeping-wall store is suitable for wastes containing a lot of fiber such as wastes from feed pads. The walls can be between 1 and 2 meters high. If they are mechanically cleaned once a year, approximately 40 m^3 storage is required per 100 cows per year (Scandrett, 2005).

Figure 2-12. Weeping wall separation (Dairy NZ, 2012).

Non mechanical separation of FDE has low risk of breakdown, low energy input and low ongoing labor input. But, it is specific design to each farm needs and requires large physical area for installation. Also the solids product have higher moisture content and can become anaerobic causing odor (Dairy NZ, 2013). To clear the bunkers professional help is required.

Table 2-4: Percent capture of total solids for separator technologies (Southern-California-Edison, 2005)

Solid / Liquid Separator Technology	**Total Solids Capture Efficiency**
Static Inclined Screen	10-20%
Inclined Screen with Drag Chain	10-30%
Vibratory Screen	15-30%
Rotating Screen (Drum)	20-40%
Centrifuge	20-45%
Screw Press	30-50%
Settling Basin	40-65%
Weeping Wall	50-85%
Scrape and Dry	50-90%

2.2.8 Treatment of FDE

Typical treatment options for dairy farms in New Zealand are direct application to land from a holding tank, application to land from a holding pond, treatment in a two stage pond system followed by discharge to water or land, solids separation before irrigation of liquid effluent, and anaerobic digestion (NZ Ministry of Agriculture and Forestry, 2005 . The ultimate fate of effluent (liquids and solids) after treatment tends to be as irrigation to land or incorporation into soil (Broughton, 2009). In New Zealand regional councils require farms to discharge effluent on land. With the introduction of the Resource Management Act (1991), discharge of effluents to surface waters is now a controlled or a discretionary activity that requires resource consent (Selvarajah, 1999; Wang et al., 2004).

Over the duration of last ten years New Zealand farming has drifted to using storage and deferred irrigation as opposed to treatment and discharge using a two-stage pond system (Haulbrooke, 2008). It is still common practice for FDE to be treated using a two-stage pond system. Many regional councils in New Zealand require that farmers

have ponds with storage capacity ranging from 4 to 13 weeks depending on soil conditions, rainfall and irrigation methods (Dairy NZ 2012).

To achieve effective biogas production or treatment a pond must have a certain hydraulic residence time; this is relative to the filled volume of the pond. However, effective storage capacity is dependent on available empty space; a full pond has no effective storage capacity (Broughton, 2009).

Different treatment options available for farms in New Zealand are waste stabilization ponds and lagoons, digesters and leach-beds. These practices have been described as below.

2.2.8.1 Waste stabilization ponds and lagoons

In New Zealand, the practice of covering dairy ponds and lagoons for methane recovery has been limited. Many dairy farms in New Zealand have used two-stage waste stabilization ponds to treat wastewater prior to discharge or application to land. This system typically has an anaerobic pond (4-5 meters deep) followed by a shallower facultative pond (1-1.5m deep) (Craggs et al., 2004). The anaerobic ponds are usually sized for hydraulic retention times (HRT) of 85-120 days. Methane output from these anaerobic ponds has been estimated at 0.02 m^3/m^3 of pond per day (NZ Ministry of Agriculture and Fisheries, 1994).

Safely and Westerman (1992b) reported satisfactory digester performance for both winter and summer conditions in a low temperature (10.6 -15^0C) covered lagoon fed with screened FDE with a mean methane yield of 0.322 m^3 CH_4/kg VSadded . This compared favorably with other reported values of 0.20 m^3 CH_4/kg VSadded (Hills & Kayhanian, 1985) for the liquid fraction of separated FDE (35°C, 10-day HRT). Safely and Westerman attributed the improved performance to the longer HRT used (67 days). (Broughton, 2009)

Anaerobic pond is an adaptation of a fermentation pit (Oswald et al., 1994) and is a deep pit that has influent fed in from the bottom. Most solids form a sludge blanket as they settle and the fresh influent passes through the sludge blanket. The anaerobic pond operates as a simplified up flow anaerobic sludge blanket reactor (UASB). Gas produced is higher on methane content and CO_2 and N_2 are removed by passing

through water column. Ponds usually have a solid retention time (SRT) of nearly 20 years and hydraulic residence time (HRT) is only 1-3 days.

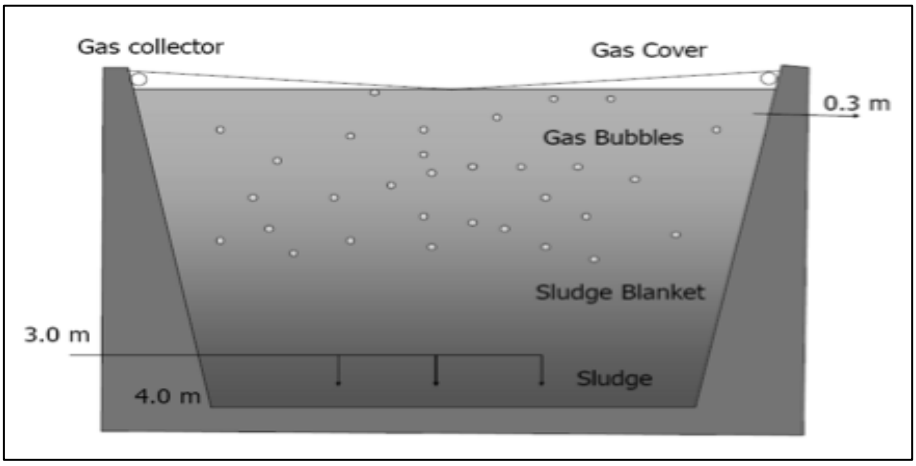

Figure 2-5: Fermentation pit (Craggs, 2006).

2.2.8.2 Digesters

The continuously stirred tank reactor (CSTR) also known as the complete-mix suspended growth reactor can run in batch mode or continuous mode and is suitable for manure that is 3 to 10 % solids such as dairy manure collected by a flush system (Broughton et al., 2009). Most sewage treatment plants and many industrial treatment plants use a completely mixed reactor to convert waste to gas (Dairy Waste Handbook, 2000). Completely mixed thermophilic digesters are used in the European Economic Community (EEC) to treat animal manure (Ahring, Ibrahim et al. 2001). In 2010, 162 anaerobic digesters generated 453 million kWh of energy in the United States in agricultural operations, enough to power 25,000 average-sized homes. In Europe, anaerobic digesters are used to convert agricultural, industrial, and municipal wastes into biogases that can be upgraded to 97 percent pure methane as a natural gas substitute or to generate electricity. Germany leads the European nations with 6,800 large-scale anaerobic digesters, followed by Austria with 551. Recently, completely mixed thermophilic digesters were proposed in Oregon to treat dairy manure (Tillamook 1999). The advantage of the completely mixed thermophilic reactor is the rapid conversion of solids to gas and biomass (Ratkowsky, Olley et al. 1981) and that the rate of conversion is three times greater with thermophilic reactors as the HRT can be lower and the gas production greater.

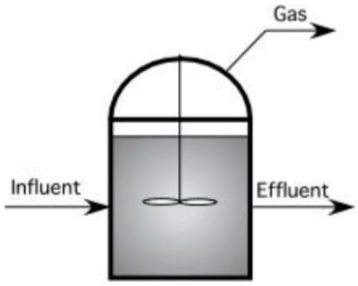

Figure 2-14: Completely stirred tank reactor (CSTR), (Dairy Waste Handbook, 2000).

UASBs (up flow anaerobic sludge blanket reactors) have been used by a number of researchers (Castrillon et al., 2002; Chen & Shyu, 1996; Luostarinen & Rintala, 2005) for the treatment of FDE but in nearly all of these instances the emphasis has been on COD reduction rather than biogas production. UASBs are particularly efficient at converting soluble waste streams, such as those containing sugars, to methane. Typically, they are run at short retention times (< 3 days), which make them unsuitable for substrates that require significant hydrolysis such as FDE.

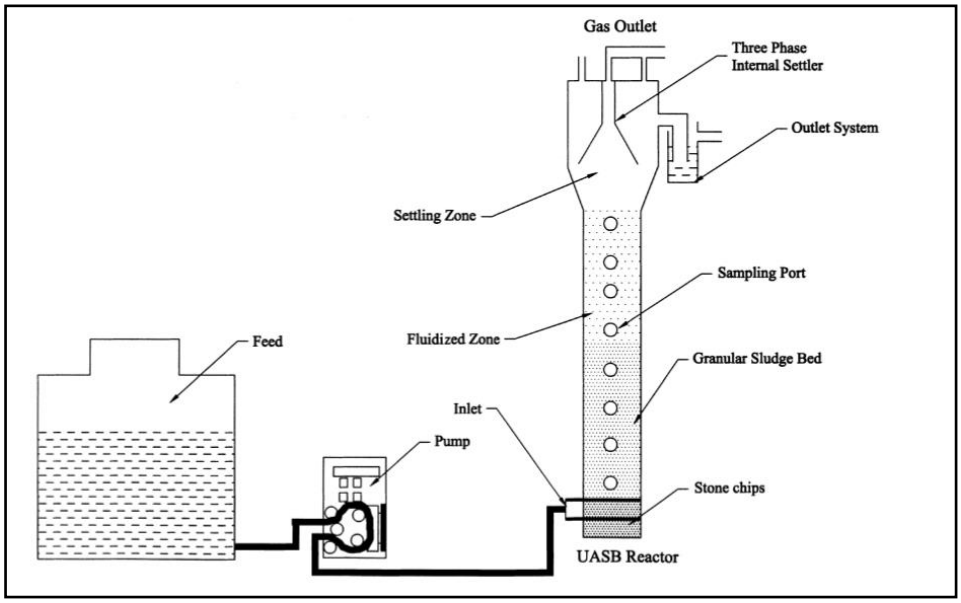

Figure 2-15: Generic UASB reactor arrangement (Rajeshwari, Balakrishnan et al. 2000).

The plug flow anaerobic digester is the simplest form of anaerobic digestion (Jewell, Kabrick et al. 1981). Consequently, it is the least expensive (Jewell, Dell-Orto et al. 1981). The anaerobic plug-flow digester is suited to wastes with a high solids content (TS 11-13%). It is a long trough with roughly 1:5 width to length ratio that is covered by a flexible cover to trap biogas (Lusk, 1998). Waste moves along the trench in plug-flow fashion pushed along by the daily addition of a fresh application of manure and a

slight gradient in the trench. These digesters are typically run at mesophilic temperatures and are designed for 20-30 day HRTs. They are not suitable for farms running flush systems as they require a high solids content for stable operation. Plug flow reactors are common in European countries.

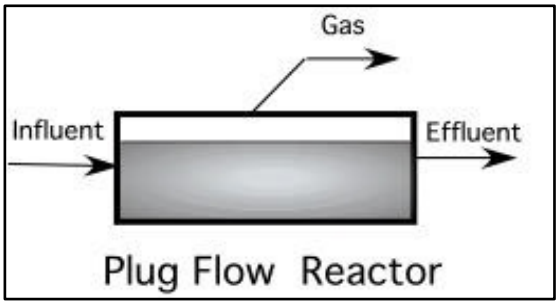

Figure 2-16: Schematic of plug flow reactor (Dairy Waste Handbook, 2000).

The anaerobic filter or attached growth anaerobic reactor or biofilm reactor is a reactor which enables the retention of biomass through addition of growth media to a reactor tank. The growth media is colonized by active biomass and retained in the reactor while the treated liquid phase is allowed out. Early filters in the 1960's employed stones as media. These however had low void volumes and were prone to blockages due to solids and biomass. Other media used have included plastic rings, slag, woodchips, ceramics and various sheeting materials. Hernandez and Rodriguez (1992) treated screened and settled cattle waste in a down-flow anaerobic filter filled with ceramic Raschig rings at retention times from 0.5 to 4 days. The methane productivity was exceptionally high at 0.7-2.8 L CH_4/L reactor/day.

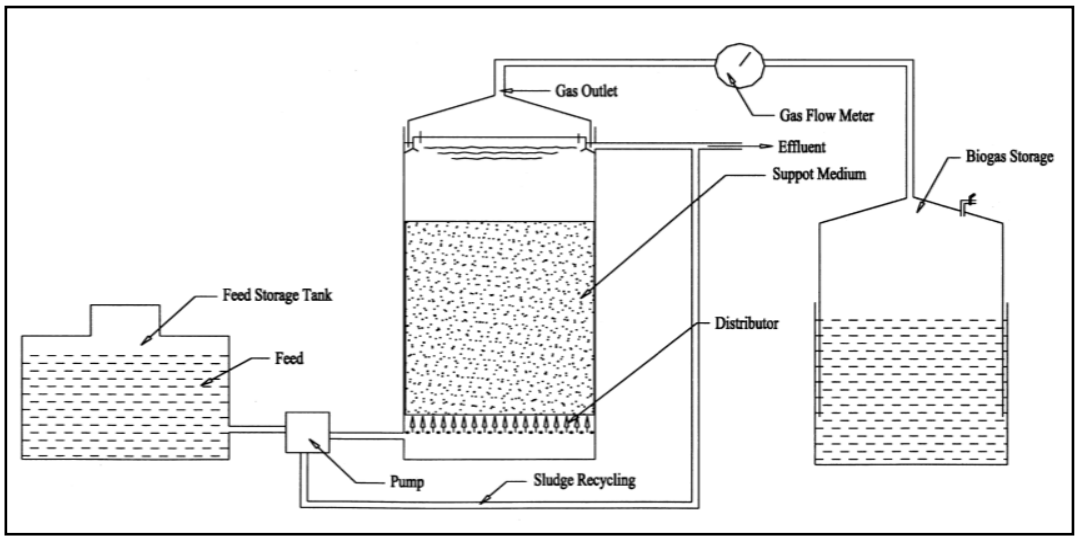

Figure 2-17: Fluidised Bed Reactor (Rajeshwari, Balakrishnan et al. 2000).

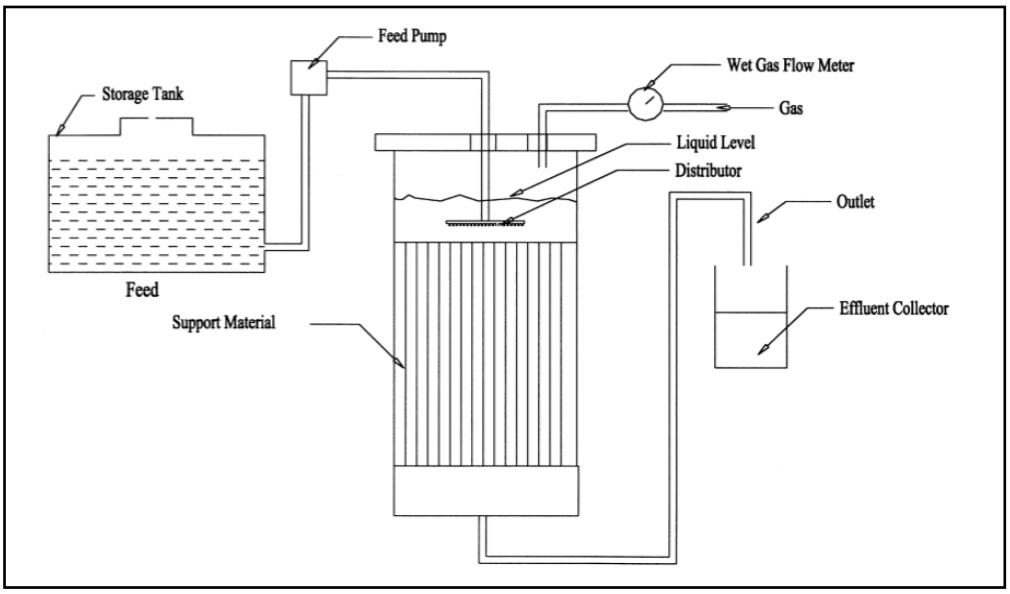

Figure 2-18: Fixed film reactor (Rajeshwari, Balakrishnan et al. 2000).

Table 2-6 below presents a summary of the process attributes such as solids concentration, presence of foreign material, odor control, nutrient concentration of the different anaerobic processes that can be used to convert all or a fraction of dairy manure to gas.

Table 2-6: Summary of process attributes for different types of anaerobic reactors (Dairy Waste Handbook, 2000).

Attribute	Complete Mix mesophilic	Complete mix thermophilic	Contact mesophilic	Plug flow mesophilic	Lagoon	Fixed film
Not limited by solid concentration	*	*	*			
Not limited by foreign material	*	*	*			
Digest entire dairy waste	*	*	*			
Sand and floating solids processing	*	*	*			
Odor control	*		*			
Concentrate nutrients in solids			*			*
Treat additional substrate	*	*	*			
Stability			*	*	*	*
Simplicity				*	*	
Flexibility			*			
Net energy production		*	*			*

2.2.9 Leach beds

Leach beds are reactors that retain solids while allowing liquid to drain out. Liquid is often applied to the top of leach beds in order to flow through the amassed solids and remove the products of hydrolysis. Leach beds can be run as one stage processes, where leachate is recycled through the solids and methanogenesis is allowed to develop in the leach bed, or as a two-stage process where the leachate is fed into a high rate methane reactor such as a UASB. This technology has been trialed for enhancing hydrolysis and acidogenesis of the solid fraction of municipal waste (Chugh et al., 1999; Ghanem et al., 2001; Jiang et al., 2005; Wang & Banks, 2000), grass residues (Lehtomaki et al., 2007; Yu et al., 2002) and a mixture of cotton gin waste and dairy manure (Funk et al., 2005). Lehtomaki et al found that recycling of digestate through a UASB in a two stage process significantly increased methane potential extraction (66%), compared to recycling of the digestate in a one stage process, which extracted

only 20 % of the methane potential of the starting material (2007). Lehtomaki et al (2007) attributed this to the removal of soluble products by the UASB, whereas the one-stage process suffered from product inhibition. At the time of the experimental stage of this study, no leach bed trials had been reported using only FDE. Since then Myint and Nirmalakhandan (2009) have reported successful hydrolysis and VFA production using a leach bed packed with pistachios-half-shell as porosity enhancers. Myint and Nirmalakhandan (2009) reported that the increased porosity of the leach bed was intended to improve contact between liquids and solids in the reactor and enable more efficient removal of products in the leachate. They reported a 132 % increase VFA yield compared to a control reactor that had no pistachio porosity enhancers (Broughton, 2009).

2.2.10 Bio digester systems for dairy effluent in New Zealand

Anaerobic digestion relies on naturally occurring microorganisms to break down biodegradable material. The process starts with the bacterial hydrolysis of the input materials to simple sugars which are then converted to carbon dioxide, hydrogen, ammonia and organic acids by acidogenic bacteria. Acetogenic bacteria convert the organic acids into acetic acid and finally methanogens convert these products into biogas. Digestate is the by-product of anaerobic digestion and can be used as a fertilizer and/or soil conditioner (Dairy NZ, 2015).

There are two main bio digester systems used in New Zealand running as a full energy capture systems. These are the covered effluent storage pond/tank and the purpose built anaerobic bio digester.

Covered anaerobic pond systems: Effluent from the yards and feed pads would first enter this energy capturing/solids separation pond and will then drain to the main storage pond. The main storage pond is covered. The cover is usually a synthetic geomembrane material which is flexible, UV resistant and cost effective. Weight pipes are used for rainwater guidance and an electric rainwater draw-off pump removes built up rainwater. A ring pipeline is used for efficient biogas draw-off. Once captured, the biogas is converted to electricity using combined heat and power (CHP) units or it can be used as a boiler fuel to heat hot water for use in the farm dairy (Dairy NZ, 2015).

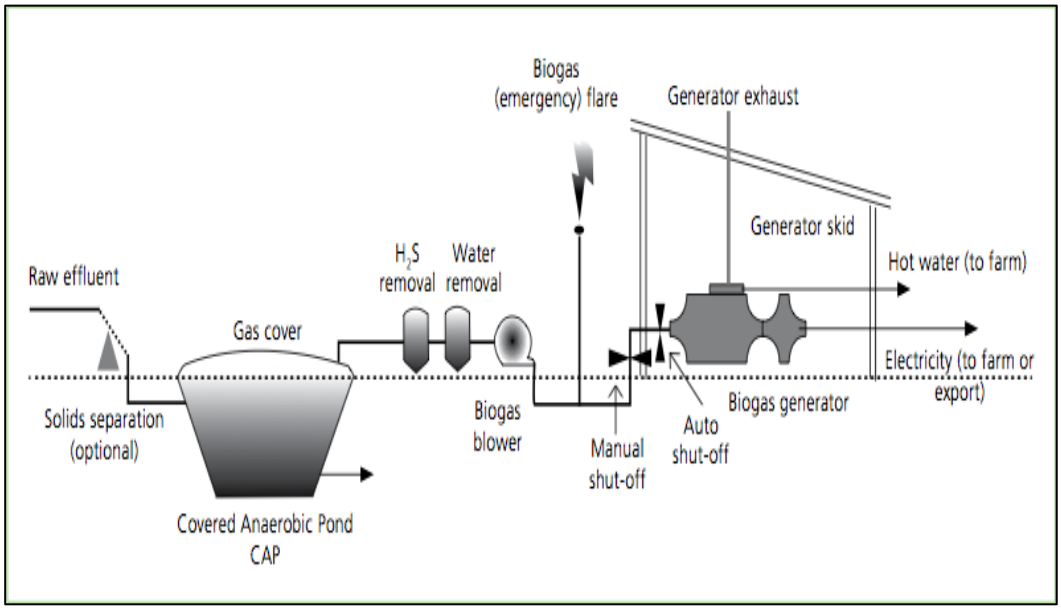

Figure 2-19: Covered anaerobic pond system (Dairy NZ, 2015)

Anaerobic digesters: Anaerobic digesters can be designed and engineered to operate using a number of different process configurations: Batch or continuous, temperature mesophilic (30-38°C) or thermophilic (49-57°C), solids content (high or low), complexity (single stage or multi stage) (Dairy NZ, 2015).

2.2.11 System performance

Table 2-7 below shows the biogas production rates per reactor volume per day of a selection of reactor types fed with dairy farm effluent. Heated lagoons (Pain et al., 1984) and anaerobic filters generally always outperform low temperature reactors and lagoons. The highest gas production is that achieved by an anaerobic filter filled with ceramic rings (Hernandez & Rodriguez, 1992). This reactor was able to achieve biogas production of 4.7 m^3/m^3 per day with HRTs of less than one day. It is not clear if this reactor was heated or not. They achieved methane conversion rates of 0.17 m^3 CH_4/kg VS added (Broughton et al., 2009).

Table 2-7: Literature values for volumetric gas production rates of various psychrophilic reactor configurations fed with dairy effluent (Broughton et al., 2009).

Researcher	System	Feed	Temperature (oC)	HRT (days)	Organic loading (kg VS/m3/day)	CH4 production (m3/kgVSadded/day)	CH4 production (m3/m3 reactor/day)
Safely and Westerman (1992b)	Lagoon	Screened	10.6 -15	67	0.12	0.39	0.109
Hernandez & Rodriguez(1992)	Anaerobic Filter	Screened and settled	Not reported	0.5	16.3	0.17	2.8
(Vartak et al., 1997)	Anaerobic filter (polyester matting)	Unscreened	10	33	0.12	0.08	0.013
(Lo & Liao, 1986)	CSTR	Screened	22	10	2.94	0.06	0.18
(Lo & Liao, 1986)	Fixed film reactor	Screened	12	1	28.7	0.01	0.3
(MAF, 1994)	Typical dairy farm anaerobic pond	Unscreened	Ambient	50-120			0.02

2.3 Biochemistry and Microbiology of Anaerobic digestion

2.3.1 Overview

The biochemical conversion of a complex substrate involves the interactions of many different consortia of microorganisms (Broughton, 2009). Currently anaerobic digestion process has become an intensive field of research, since the organic matter in the food waste is suited for anaerobic microbial growth (Zhang and Jahng, 2012). During anaerobic digestion process organic waste is biologically degraded and converted into clean gas (Apples et al, 2011).

Tables showing the different species of microorganisms can be found in Appendix 1. The conversion of organic material into methane gas (biomethanation) can be broken down into four major stages; hydrolysis, acidogenesis, acetogenesis and methanogenesis. These stages along with substrates and products are shown schematically in Figure. However according to (Molino et al, 2013), anaerobic process is divided into three steps: hydrolysis, acidogenesis and methanogenesis but both the approaches work on the same principle. Anaerobic digestion is historically used by humans for waste management and waste water treatment (Palmisano et al, 1996).Anaerobic digestion is the biological process by which the biodegradation and stabilization of complex organic matter in the absence of oxygen with a consortium of

microbes leading to the formation of energy rich biogas .It is used to replace fossil fuel (Yang et al, 2004). The residues of anaerobic digestion process is nutrient rich, used as soil amendment (Lisboa and Lansing, 2013). Anaerobic digestion is carried out at different temperature conditions called as mesophilic, thermophilic and psyrcophilic .Many factors affect the anaerobic digestion (Muzaffar Ahmad Mir, Athar Hussain, Chanchal Verma, 2016). Acetogens and mathanogens produce methane gas through hydrolysis, acidogenesis, acetogenesis and methanogenesis (Park et al, 2005; Charles et al, 2009).

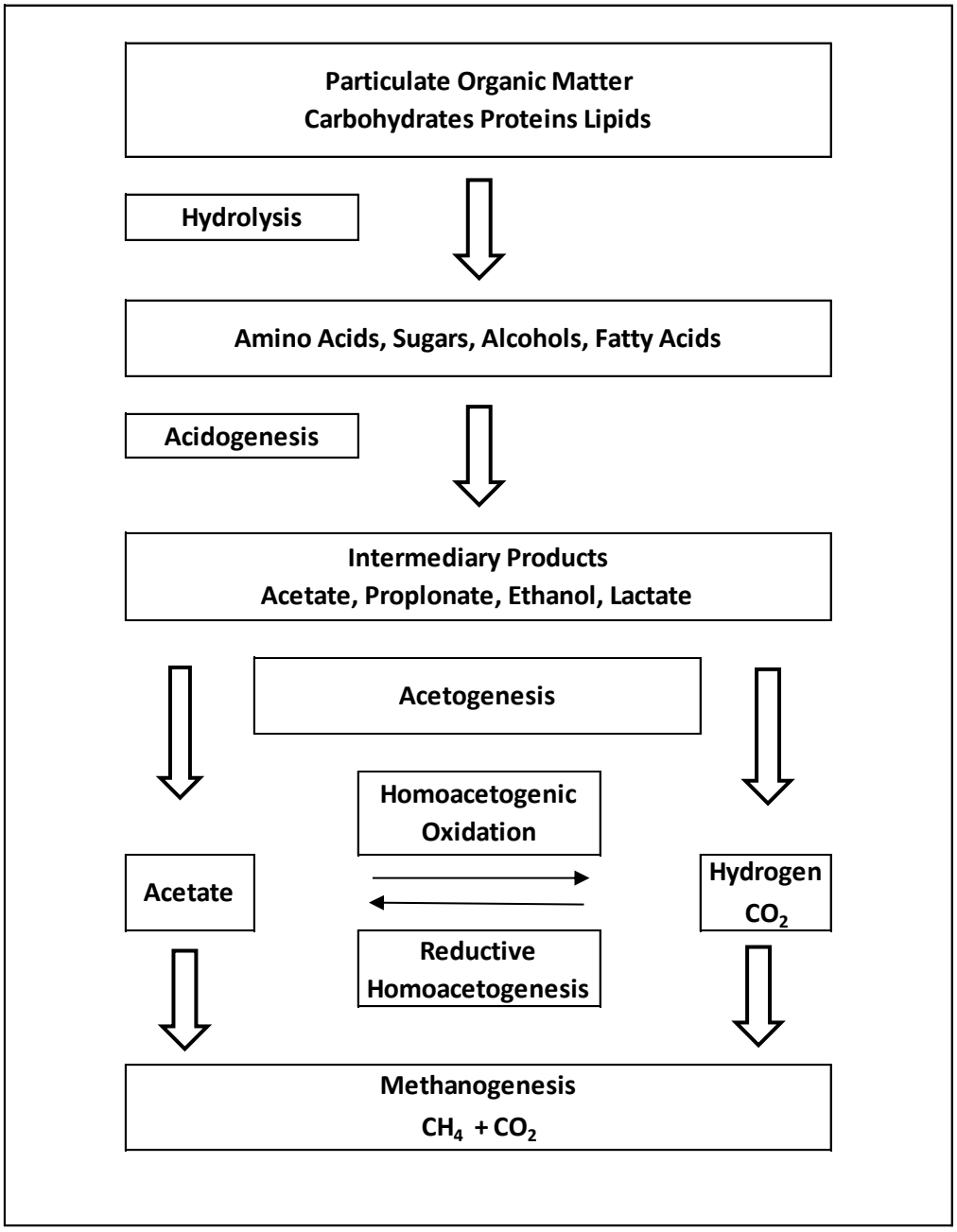

Figure 2-20: Process of biomethanation (Demirel & Schere,2008)

2.3.2 Hydrolysis

Hydrolysis is the first step of anaerobic digestion and it is more accurately called depolymerisation as hydrolysis is just one process of breakdown of macromolecules (Chynoweth & Pullammanappallil, 1996)

The breakdown of complex organic molecules like proteins, polysaccharides and fat are converted into simpler ones like peptides, saccharides and fatty acids by exoenzymes like cellulose, protease and lipase produced by hydrolytic and fermentative bacteria (Noike,et al,1985). The complete modeling of hydrolysis is coupled to a number of factors; substrate concentration, product concentration, biomass concentration, surface kinetics, temperature and toxicity (Vavilin et al., 2008)

End products are soluble sugars, amino acids, and glycerol and long chain carboxylic acids (Ralph and Dong, 2010; Ostrem and Themelus, 2004). Overall reactions (1) are represented by following equations:

$C_6H_{10}O_4 \rightarrow C_6H_{12}O_6+H_2O$ (1)

Hydrolysis is relatively slow process and generally limits overall reaction. For complex substrates with a high solids content, hydrolysis is usually the slowest step and hence the rate-limiting step in the overall anaerobic digestion process (Noike et al., 1985). Overall, the products of the hydrolysis process that can ultimately be converted to methane are carboxylic volatile acids, keto acids, hydroxy acids, ketones, alcohols, simple sugars, amino acids, H_2 and CO_2 (Kashyap et al., 2003). The major classes of anaerobic bacteria that degrade the cellulose include bacterioides-succinogenes, clostridium lochhadii, clostridium celobioporus, ruminococcus flavefaciens, ruminococcus albus, butyrivibrio fibrosolvens, clostridium, thermoculum, clostridium stercorarium and micromonospora bispora (Noike,et al,1985). Hydrolysis can be seen as taking placing through two separate methods. Bacteria can release enzymes into the bulk liquid where they are adsorbed onto a particle or react with a soluble substrate (Vavilin et al., 2008). Alternatively (or concurrently) organisms can attach to a particle, produce enzymes in its vicinity and take up the soluble products released by the enzymatic reaction (Vavilin et al., 2008).

2.3.3 Acidogenesis

In acidogenesis, the product of hydrolysis peptides, saccharides and fatty acids are converted into simpler molecules having low molecular weight like organic acids alcohols, carbon dioxide, hydrogen and ammonium (Muzaffar Ahmad Mir, Athar Hussain, Chanchal Verma, 2016). The existence of oxygen and nitrates are considered toxic and inhibits the anaerobic process. So presence of oxygen removing bacteria is vital to remove the oxygen and facilitate anaerobic conditions. During acidifation process pH reduces to 4 (Dhamodharan and Ajay, 2014). Byproducts like ammonia and hydrogen sulphide is also produced. In the case of cattle manure the acidogenic biomass grow on the soluble products of hydrolysis consisting of a readily degradable component, hemicellulose; and a slowly degradable component, cellulose (Myint et al., 2007). Acidification is strongly affected by temperature according with the Arrhenius law, however thermophilic temperatures which result in cell death and higher energy costs may result in sub-optimal temperatures being preferable (Guerrero et al., 1999).

The overall reaction is represented by following equations (2) and (3) (Mata-Alvarez, 2002):

$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$ (2)

$C_6H_{12}O_6 \rightarrow 2CH_3CHOHCOOH$ (3)

The acid phase bacteria belonging to facultative anaerobes use oxygen accidentally introduced into the process, creating a favorable conditions for the development of obligatory anaerobes of the following genera: Pseudomonas, Bacillus, clostridium, Micrococcus, or Flavobacterium (Shah,et,al., 2014).

2.3.4 Acetogenesis

In acetogenesis, the product of acidogenesis is converted into acetic acid, hydrogen and carbon dioxide by acetate bacteria. Before methanogenesis acetic acid is formed. Acetogenesis is produced by acetate from hydrogen and carbon dioxide. The H_2 utilising bacteria in turn rely on the acetogens for their hydrogen source (Ahring, 2003).

Overall reactions (4), (5) and (6) (Ostrem and Themelus, 2004; Rallph and Dong, 2010) are shown as:

$CH_3CH_2COOH+2H_2O \rightarrow CH_3COOH+CO_2+3H_2$ (4)

$CH_3CH_2CH_2COOH+2H \rightarrow 2CH_3COOH+2H_2$ (5)

$CH_3CH_2OH \rightarrow CH_3COOH+2H_2$ (6)

The first three steps are together known as acid fermentation. In this process no organic matter is removed from liquid phase but converted to as substrate for further process of methanogenesis (Dhamodharan and Ajay, 2014). In this process, the acetate bacteria convert the acid phase products into acetates and hydrogen which may be used by methanogenic bacteria.

2.3.5 Methanogenisis

In this final step of anaerobic digestion the products of the acetogenesis are converted in to methane gas by two groups of microbes known as acetoclastic and hydrogen utilizing methanogens. The acetoclastic methanogens convert acetate into carbon dioxide and methane. Hydrogen utilizing methanogens reduce hydrogen and carbon dioxide into methane (Muzaffar Ahmad Mir, Athar Hussain, Chanchal Verma, 2016) . The former process is dominant produce about 70% of methane in anaerobic digestion because hydrogen is limited in anaerobic process (Chu et al, 2008).

The overall reaction (7), (8) and (9) ((Kossmann et al, 2007) of methane production is described by following chemical reactions:

$CH_3COOH \rightarrow CH_4+CO_2$ (7)

$2CH_3CH_2OH \rightarrow CH_4+ 2\ CH_3COOH$ (8)

$4H_2+CO_2 \rightarrow CH_4+2H_2O$ (9)

During CH_4 formation process, the co-enzyme M and F420 play important role. They convert CO and formate into CH_4. Further co-enzyme M also helps in acetate and carbonyl transformation during the metabolic process of methane formation (Appels, 2011). Conversions of complex organic

compounds to CH_4 and CO_2 are possible owing to the cooperation of four different groups of microorganisms and are presented in Table 2-1.

Temperature is very important for methanogenic bacteria, due to a limited temperature resistance of their enzymatic structures. Methanogenic bacteria usually develop in inert conditions, with environmental pH from 6.8 to 7.2.

Anaerobic digestion involves several processes that only occur in the absence of oxygen (Craggs et al., 2006). These processes convert biodegradable organic waste to volatile fatty acids (VFA) and alcohols and then to methane and carbon dioxide (Pavlostanthis & Giraldo- Gomez, 1991). The rate of anaerobic digestion is influenced by a number of factors including: waste characteristics, organic loading rate, hydraulic retention time, temperature, pH, mixing, and presence of inhibitory substances (Craggs et al., 2006). Table 2-9 summarizes optimal conditions for different anaerobic digestion conditions.

Table 2-8: Optimal conditions for psychrophilic, mesophilic and thermophilic anaerobic digestion.

Digester Type	Psychrophilic	Mesophilic	Thermophilic	Reference
Optimal Temperature and Range (^oC)	22 (7 - 25)	35 (25-42)	60 (49-72)	1,2,6,7
Organic Loading Rate (kg VS m^{-3} d^{-1})	>0.1	2.5-3.5	< 17.7	7
Hydraulic Retention Time (d)	>50	20-40	5-20	1,2
Biogas Production (m^3 d-1)	Increases with temperature			1,3,4
Biogas Production (% of VS)	25	35-45	45-55	7
Ultimate Biogas Production	Same but slower	Same	Same but faster	5,7
Gas Composition (% CH_4)	55-70%			7

1.Wellinger et al. (1985), 2. Safely and Lusk (1992), 3. Lusk (1998), 4. Safley and Westerman (1988), 5. Safley and Westerman (1990), 6. Zeeman et al. (1998), 7.Wellinger (1999)

2.4 Parameters Affecting Biomethanation

Factors influencing biomethanation are identified as temperature, pH, residence time, mixing, C/N ratio and nutrients, moisture content and inhibitory factors. These are listed in and discussed in detail below.

2.4.1 Temperature

Operating temperature is very essential for survival, optimum thriving of the microbial consortia and performance of anaerobic digestion (Muzaffar Ahmad Mir, Athar Hussain, Chanchal Verma, 2016). The metabolic and growth rates of chemical and biochemical reactions tend to increase with temperature, until the temperature tolerance of the microorganism is met. At extreme temperatures denaturation of the cell occurs and the cell life is decreased. Microorganisms exhibit optimal growth and metabolic rates within a well-defined range of temperatures, which is specific to each species (Broughton, 2009). Psychrophilic organisms thrive in temperatures below 25^0C, mesophilic between 25 and 40^0C and thermophilic higher than 45^0C. Anaerobic digestion can occur under the two temperature ranges defined as mesophilic (25-40℃) and thermophilic (50-65℃) (Muzaffar Ahmad Mir, Athar Hussain, Chanchal Verma, 2016) .Thermophilic conditions allows higher loading, yield, substrate digestion, methane production and pathogen destruction but gas producing bacteria die due to toxin and small environmental changes (Arsova et al, 2010). Anaerobic digestion process is temperature sensitive. Higher temperature affects the activity of hydrogenotropic methanogens, causes higher production of hydrogen and spore forming bacteria (Speece, et al, 1996). Mesophilic microbes are more tolerate to environmental changes, which suggests mesophilic digesters have easier operating conditions and maintenance which allows lower investment capital cost. Disadvantages are retention time is high and lower biogas production (Van and Lettinga, 1994).

Methanogenic bacteria in the digesters are more sensitive to temperature variations (Marchaim, 1992). This is due to the faster growth rate of the other groups, such as the

acidogens, which can achieve growth even at low temperatures (Marchaim, 1992). It has been reported that long term adaptation of active psychrophilic microbial communities is required for the efficient digestion of cattle manure at low temperatures (Yadvika et al., 2004).

Degradation of organic matter and biogas production occur at faster rates at thermophilic temperatures (Ogawa et al n 1998, Kim et al. 2002) resulting in a shorter retention time (5 to 20 days) compared to mesophilic digesters (20 to 40 days). Therefore, thermophilic digesters designed to treat the same waste stream can have up to double the volume and volumetric loading rate of mesophilic digesters, (kg VSS / d) while maintaining similar overall gas production. Volatile suspended solid (VSS) decomposition at mesophilic temperatures is typically 40% while higher (up to 55) % VSS degradation has been observed at thermophilic temperatures (Wellinger.1999) due to enhanced hydrolysis of recalcitrant organic waste material (Sung & Santha, 2004).

2.4.2 pH

pH value is very important factor as methanogenic bacteria are sensitive to acidic environment by which growth and gas production is inhibited (Muzaffar Ahmad Mir, Athar Hussain, Chanchal Verma, 2016). The pH value varies along the different stages of anaerobic digestion (Zhang et al, 2011). The pH variation is caused by volatile fatty acids bicarbonates; alkalinity and CO_2. Chemicals like NaOH and $NaHCO_3$ are used to maintain the pH Value (Goel et al, 2003). Methanogens could die if the pH drops below 5 during acetogenesis causing acid accumulation and digester failure. Constant pH is vital for starting the digestion, maintain by buffer like calcium carbonate or lime (Ray et al, 2013). The methane producing bacteria require neutral to slightly alkaline environment (pH 6.8-8.5). This is not necessarily the optimum pH for all the microorganisms involved in biomethanation but it suits the widest range (Tchobanoglous et al., 2003). The hydrolysis of readily degradable substrates in landfills was found to be inhibited at pH below 5.6 and the optimum for hydrolysis of polysaccharides is 6.5-7.0 (Vavilin et al., 2008). Fermentation of simple sugars can occur between pH 4.5 and 7.9 with an optimum range between 5.7 and 6.0 (Demirel & Yenign, 2002). Stable acidification of unscreened cattle manure has been reported at pH 6.0 (Demirer & Chen, 2005), while Myint and Nirmalakhandan reported a stable pH of 5.0 for a leachbed reactor containing cattle manure (2009). The optimum pH for

the breakdown of VFAs and methanogenesis is 6.5-7.5 (Hobson & Wheatly, 1993). Burke suggests an optimum pH range between 6.8 and 8.5 (Burke, 2001).

The hydrolysis and acetogenesis occurs at pH between 5.5 and 6.5 respectively (Xiaojiao et al, 2012).The pH value for anaerobic digestion waste was discussed by various researchers but optimal range was found around 7.0(Sosnowski et al, 2002).

2.4.3 Residence time

Residence time is the time during which feedstock remain in the reactor. It is the measurement of chemical oxygen demand and biological oxygen demand of interfluent and the effluent material. Muzaffar Ahmad Mir, Athar Hussain, Chanchal Verma, 2016 reported that there is optimal retention time for complete biological conversion, 12-24 days for thermophilic and 15-30 day's mesophilic digester. Retention time depends upon the type of substrate, environmental conditions and intends use of digested material (Ostrem and Themelus, 2004). Parameters like organic loading rate, hydraulic retention time and temperature must be monitored to reduce instability of digester (Mechichi and Savadi, 2005).

As with all biological treatments, the solids retention time (SRT) must not be less than the growth rate of the slowest growing bacteria in a reactor. The growth rate will vary depending on the pH, temperature and available nutrients. The minimum retention time will also vary depending on the nature of the waste (Broughton, 2009). Methanogenesis of a highly soluble waste will generally be limited by the growth rate of acetate degrading methanogens. In this case a maximum specific growth rate (max) of 0.4 day-1 suggests a minimum SRT of 2.5 days (Mawson, 1986). In a study of the digestion of cattle manure slurry Linke calculated that the critical SRTs for wash-out of methanogenic bacteria at 24^0C and 35^0C were 7.75 d and 2.76 d respectively (Linke, 1997). Acidogens have much higher growth rates than methanogens, which in turn results in much shorter retention times needed to prevent washout. For simple sugars, a minimum retention time of 2.5 to 3.5 hours is sufficient to prevent washout of acidogenic bacteria (Demirel & Yenign, 2002). The minimum retention time for effective acidogenesis of swine manure has been reported as 0.4 days (Hwang et al., 2001) while stable operation of an acidogenic reactor fed with unscreened dairy manure has been reported with an HRT and SRT of 2 days (Demirer & Chen, 2005).

For mixed solid waste, a max of 2.0 day-1 (minimum SRT of 0.5 days) has been reported (Chynoweth & Pullammanappallil, 1996).

2.4.4 Mixing

Mixing is an important operating factor for achieving digestion of organic matter (Tchobanoglous et al, 1991). It is vital for achieving uniformity among the substrate concentration, temperature and environmental conditions to reduce the chance of scum formation and solid deposition (Agunwamba et al, 2007). Mixing is usually done by mechanical stirrers or gas recirculation. However excessive mixing can disrupt microbes, so slow mixing is preferred (Khalid et al, 2011). Ong showed that the rate of biomethanation in a continuously stirred digester was inferior to that of a non-stirred one (Ong et al., 2002). Stroot et al (2001) also showed that high solids reactors which were minimally mixed performed better. In terms of acidogenesis a study using primary sludge found a 70% increase in VFA production in an unmixed reactor compared with VFA production in a mixed reactor (Banister & Pretorius, 1998). In contrast to this, others have found that mixing improves methane production from cattle slurries (Kalia & Singh, 2001; Sakar et al., 2009) and that this effect is more pronounced when scale up occurs (Vesvikar & Al-Dahhan, 2006)

2.4.5 C/N ratio and nutrients

The ratio of C and N play the crucial role in anaerobic digestion where carbon acts as energy source and nitrogen serves to enhance microbial growth. These two nutrients often act as limiting factor (Richard, 1998). Optimum ratio is between 20-30 (Vandevivere et al, 2000). Higher C/N ratio could result in increased consumption of nitrogen causing lower gas production while lower C/N ratio would cause accumulation of ammonia. pH greater than 8.5 is toxic to methanogenesis. Optimum C/N ratio can be achieved by mixing substrate of low and high C/N ratio (Khalid et al, 2000). Muzaffar Ahmad Mir, Athar Hussain, Chanchal Verma, 2016 reported that conversion of carbon to nitrogen in digestion process is 30-35 times faster, so ratio of C/N should be 30:1 in raw substrate. Nitrogen is considered as limiting factor and nitrogen sources like urea, bio-solids and manure could be used as supplements' (Richard, 1998). C/N ratio between 20-30 provide sufficient nitrogen for anaerobic

process(Weiland et al,2006). Carbon to phosphorus ratios suggestions range from 75:1 to 113:1 (Speece, 1987).

2.4.6 Moisture content

High moisture contents usually facilitate the anaerobic digestion; however, it is difficult to maintain the same availability of water throughout the digestion cycle (Hernandez et al., 2008). Moisture content has profound effect on anaerobic digestion. An anaerobic process was carried out at different moisture levels i.e., 70% and 80%. It was found that bioreactor operated at 70% moisture content produce more methane than the bioreactor operated at 80% moisture content. However the ratio of BOD and COD were remained same. (Hernandez et al, 2008).

2.4.7 Inhibitory factors

Inhibition of the anaerobic processes has often been reported resulting from high concentrations of VFAs, H_2, NH_3 and extremes in pH (Hobson & Wheatly, 1993). Partial pressure of CO_2 can affect conversion of propionate and acetate, with conversion to methane being inhibited at high concentrations. The optimum CO_2 concentration is reported as 20%. The concentration of methane has not been found to affect methanogenesis (Hobson & Wheatly, 1993).

Broughton 2009, reported that ammonia could be inhibitory at concentration higher than 3000 mg/l but at higher pH (>7) ammonia can be inhibitory at above 1500 mg/l, as free ammonia is more inhibitory at than the ammonium ion (NH_4+). These two forms are in equilibrium and ammonia dominates at higher pH (Hobson & Wheatly 1993).

VFA with concentrations over 1,000 mg/l have been reported as having an adverse effect on methanogens (Hobson & Wheatly, 1993). High levels of VFA have been shown to inhibit hydrolysis (Vavilin et al., 2008), though there is some debate as to whether this is in fact due to the lowering of pH that VFAs cause or the actual inhibitory action of the VFAs (Pin- Jing et al., 2006). Veeken et al (2000) concluded that no inhibition by VFA or by non-ionized VFA can be measured at pH values between 5 and 7, and that acidic pH was the inhibitory factor. They proposed a linear function of pH inhibition in the interval between 5.0 and 7.0

In studies by Yu and Fang (2001), zinc and copper were found to inhibit acidogenesis at concentrations over 10 mg/L and 5 mg/L respectively. Copper was found to be 1.4-4.3 times more toxic than zinc with regard to production of fatty acids and hydrogen as well as degradation of carbohydrate and protein (Yu & Fang, 2001).

Advanced anaerobic digestion includes thermophilic digestion, staged thermophilic batch reactors, staged mesophilic batch reactors, acid/gas phase digestion and temperature phased digestion which can be seen in Figure 2-20 (Metcalf & Eddy et al., 2014). Advanced anaerobic digestion processes increase the volatile solid reduction and the reaction rate producing more gas in less time which can reduce the volume requirements of the reactor. This could mean capital savings. But the disadvantages include higher energy requirements for operation and process may not be as stable as using a single stage reactor.

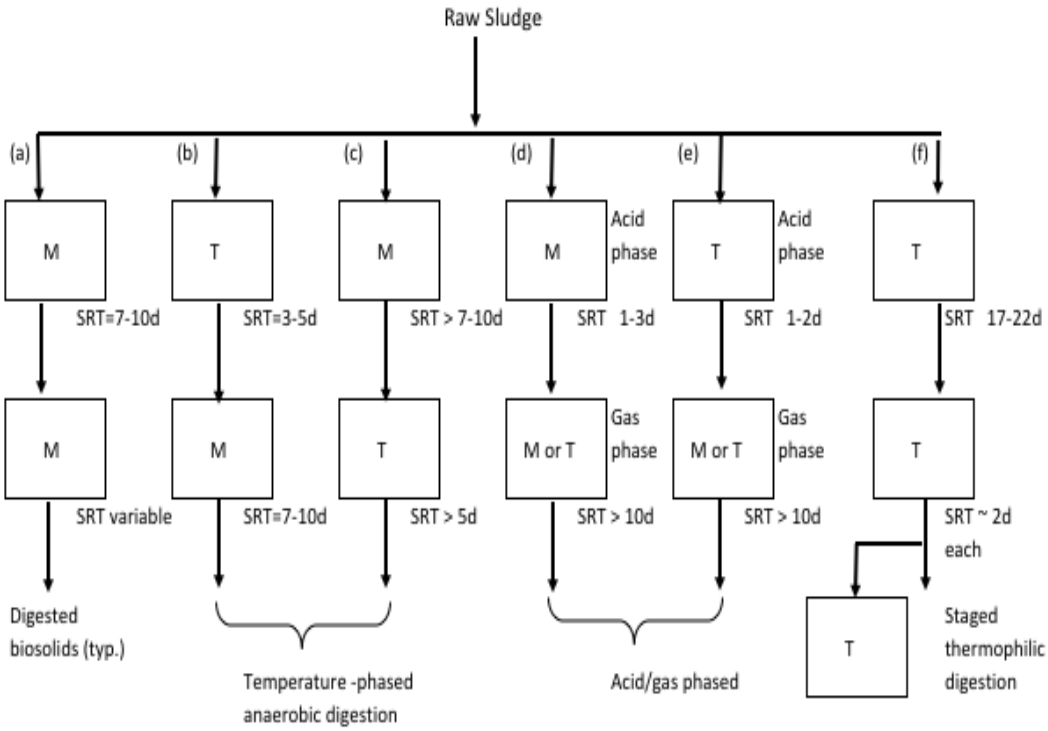

Figure 2-21: Options for staged anaerobic digestion (a) staged mesophilic digestion, (b) temperature phased thermophilic- mesophilic digestion, (c) temperature phased mesophilic-thermophilic digestion, (d) acid/gas phased digestion with mesophilic acid-phase, (e) acid/gas phased digestion with thermophilic acid phase, and (f) staged thermophilic digestion. (Adapted from Schafer and Farrellm, 2000 and Moen, 2000)

Although research has been done in the past for anaerobic digestion in reactors coupled in series not much information is available on operation of the two-stage heated and

mixed high rate digesters (Metcalf & Eddy et al., 2014). Researchers Torpey and Garber found from their study that using two series tanks as compared to single stage high rate process had few benefits in volatile solids reduction and gas production (Torpey and Melbinger et al., 1967). Schafer and Farrell (2000) reported that two-stage mesophilic digestion may produce more stable, less odorous bio-solids that are easier to dewater (Schafer and Farrell et al., 2000).

The various parameters affecting the biomethanation process of anaerobic digester for production of biogas from dairy effluent and existing literature have been reviewed and a conventional three stage batch digester has been proposed for the purpose of research where optimal conditions can be maintained to achieve cost effective energy capture. The rationale for developing a multi stage anaerobic digestion process comes from the advanced anaerobic digestion technologies employed for waste water treatment plants.

The literature review has revealed a number of parameters identified like the temperature, pH, mixing; dilution, total solids, total volatile solids, solid retention time (SRT), hydraulic retention time (HRT) and various forms of chemical and physical treatments and reactions effect the biomethanation and the amount of gas which can be generated (Burke et al., 2001).

In this study, it was decided to focus the investigation on those parameters which would allow using the already existing technologies on farm but also focusing on enhancing the process of biomethanation by regulating the parameters of temperature, pH, total solids. Also further research is focused on making the biodigester as a three stage coupled mesophilic stirred biomethanation process. Also the focus of this study is to propose a sustainable bio digestion system with a minimum energy input. Broughton (2009) from his study reported that the current average sized dairy farm is now of a sufficient size to be energy self-sufficient but not yet of sufficient size to make the capture of this energy economically viable with the main challenges being large installation costs for the heated mixed digester or of covering the large surface area of conventionally designed dairy farm anaerobic ponds. He proposed a solution could be to develop smaller pond reactors that are more efficiently able to convert the organic matter held in farm dairy effluent into biogas. The use of smaller sized ponds results in a reduced hydraulic retention time (HRT). If the HRT is to be reduced, the biomethanation process must be sped up. This requires the optimization of the rate-

limiting step. In psychrophilic (ambient temperature) biomethanation the rate limiting step is hydrolysis (Noike et al., 1985), the transfer of organic matter from the solid to the liquid phase.

However, there has been little application of this technology, hence this study has undertaken to investigate the life cycle of dairy farm effluent and investigate whether it is more cost beneficial to continue with the current practice of treatment of the FDE and use it for irrigation or to make the capture of energy more economically viable.

2.5 Case review

2.5.1 India's biogas program

India has vast resource of livestock and poultry, which plays a vital role in improving the socio-economic conditions of the rural masses. India ranks first in respect of cattle and buffalo population in the world. India has 57% of the world's buffalo population. India's milk output during the year 2013-2014 was estimated to be 146.3 million tons (NDDB, 2015). This has not only placed the industry first in the world, but also represents sustained growth in the availability of milk and milk products for the burgeoning population of the country. Dairying has become an important secondary source of income for millions of rural families and has assumed the most important role in providing employment and income. The average milk procurement during April-October 2003 was 15595 ton /day. During 2003-04 (April-October), an average of about 14.9 million liters' milk per day (Annual report, NRCE India, 2004). Table 2-5 summarizes comparison between dairy farms in India and New Zealand.

Table 2-9: Scaling a dairy farms: New Zealand vs. India, Literature review

Dairy Farm features	**NZ**	India
Average size	141 hectares – 402 cows, 2.85 cows/hectare	1.5 adult cows/buffaloes per farm
Total herds	11891	75,000,000
Total cows	4,783,250	113,000,000
Total farming hectares	1,677,395	
Annual production of milk	20.7 million tons (2014)	146.3 million tons (2014-15)
Dairy production system	Intermediate output/intermediate input	Low output/low input system
Feed	Mainly grazing, 5 production systems, seasonal production peaking in November (180% of annual avg)	Straw, crop residues, green fodder, supplemented by low cost compound feed.
Exports	95 % of annual milk exported	0.27 % exported, 100 % self-sufficient with zero imports
Manpower	Owner operated, owner/share milker or contract milker Share milker – wage based or 50 % ownership Average 4.5 fulltime equivalent	Owner operated, employees 1-4 avg employees

India has developed the first digestion plant in 1859. With the livestock population of 529.7 million (National Dairy Development Board (NDDB), 2016) and the yearly dung production exceeding 1500 million tons (The Importance of Cattle in Biogas Production, 2012) biogas could be a great source to bring better social and economic parity to rural India while providing a sustainable and sound energy system.

India was one of the pioneering countries, using biogas as far back as the 1920's and Indian Agricultural Research Institute was the first such institution to start the research on biogas (Ottinger, 2013). With the oil crisis in the 1970's, the government was forced to look for the alternatives to fossil fuels, and thus commissioned 50,000 biogas plants of which 70 percent were built and subsidies were introduced by the government for biogas installation. The impetus to implement household biogas plants to a broader

economic base began in India only in 1981 with the government of India implementing the National Project on Biogas Development (NPBD) (Gustavsson et al., 2000).

2.5.2 Government Policies

The National Biogas and Manure Management Programme (NBMMP) was an initiative to provide gaseous fuel and enriched organic fertilizer as a by-product, besides as a type of waste disposal system at the domestic level (MNRE, 2012). Funded by the government, this project provides financial assistance for installation of biogas plant, training technical support and publicity (NBMMP, 2012). Components of the program include (NBMMP, 2012) installing of biogas plants with designated local departments and agencies for implementing the program and providing training and technical support for running the biogas plants. Also various financial incentives are provided including subsidies to farmers for installation of biogas plants, maintenance, operational costs, service charges to state departments/agencies and support training and publicity (Ottinger, 2013).

Central government subsidy of Rs 4000-8000 per plant and Rs 14,700 for plants in North Eastern States are provided installation of an average 2 m^3 biogas plant costing Rs 17000 (Ottinger, 2013). Biogas Development Training Centers are providing technical and training support for the revival of non-functional plants and receive 50% subsidy from government for repair of no-functioning plants (MNRE, 2012). The per kW central government financial assistance of Rs 40000 (3-20 kW), Rs 35000 (>20 to 100 kW) and Rs 30000 (>100 to 250 kW) is available for the installation of biogas-based power generation units. (MNRE et al., 2012, Ottinger, 2013)

3 Methodology Bio-digestion Experiment

3.1 Terminology for the anaerobic digestion

In this thesis a number of terms are used to describe the various portions of farm dairy effluent (FDE)

Manure refers to a mixture a faeces and urine as excreted from the cow. This was collected by scraping off the surface of the milking shed within an hour of having been dropped by the cows.

Total solids (TS) is a measure of the suspended and dissolved solids

Total suspended solids (TSS) are solids that can be retained on a filter and are capable of settling out at the bottom when rested for a period of time due to gravity

Total dissolved solids (TDS) refer to any minerals, salts, metals and some small amounts of organic matter that are dissolved in the effluent

Total volatile solids (TVS) refers to a measure of the weight of solids that are combustible "volatilized" at temperature of 600^0C. TVS is reported as a percent of total weight of the manure sample. Methane production is based on the volatile solids portion of the manure.

Hydraulic retention time (HRT) is the time liquid portion of the manure is in the digester and solids residence time (SRT) is the time solids are retained in the reactor.

3.2 Overview

The primary aim of this study is to improve the process of biomethanation of farm dairy effluent (FDE) by proposing a continuous stirred up flow three-stage mesophilic biodigester, which would be efficient in capturing more methane but also reduce the HRT. This was chosen on an assumption that efficiency of the process of biomethanation can be improved and so make it more economically viable. In order to quantify the process it is necessary to first define the starting material, or substrate, effluent characteristics, physical and chemical properties and the four stages of anaerobic digestion. As discussed in the literature review above the amount of methane

that could be captured is defined by the efficiency of each process of the digestion. Assumption has been made that the rationale behind this is that improved biomethanation occurs in the in the first stage of a three-stage system, where the effluent has higher total solids content and volatile fatty acids which reduce the pH therefore inhibiting the growth of methanogens. The effluent will result in a liquid feed with a high soluble organic content, which can be fed into the second stage methanogenic reactor. The amount of methane, which could be recovered in the second stage, is assumed to be lower than in the first stage. Again the effluent from the third stage is fed in to the third stage. Assuming that the methane content from the third stage digester is the lowest. The effluent from the third digester is drawn out for irrigation of the dairy farm. In order to have a continuous process in the biodigesters fresh effluent is fed into the first digester to regulate the pH (when less than 6). Also total solids are measured in the treated effluent from the biodigester to measure total volatile solids consumed to produce the volumetric gas.

The secondary purpose of this research is to develop a structured study of dairy farms and do a life cycle assessment of the dairy farm and the objective is to estimate the cradle to gate eco-profile of a hypothetical commercial process producing and capturing methane from the digesters and analyzing energy use and greenhouse gas emissions. Research focused on using empirical and analytical data acquired from literature and practical data acquired from farm visits to derive capital cost analysis and also mass economic balance of methane in regards to dairy farm.

3.3 Experimental procedures

Effluent for all the experiments is mainly collected from the effluent pond Rockhill farms limited, Huntly. In experiment C effluent used in reactors 5 and 6 are from different farms to draw a comparison. Effluent used in reactor 5 is collected from the gravity separator and is fresh from the milking shed with the wash down water from Greenhill Road Farm, Hamilton and effluent for reactor 6 is from Rockhill farms limited, Huntly.

3.3.1 Characterization

Characterization analysis was carried out to determine the characteristics of the FDE. This included analysis of the effluent and to determine the organic content of the FDE to understand the potential for methane production. When raw manure is mixed with wash-down water from a milking shed it forms a slurry. This slurry typically comprises 10% excreta, 4% teat washings, and 86% wash-water plus other foreign material (Gibson 1995). For the experiments in this study, slurry was prepared by weighting 1L part of fresh dairy effluent with 5% total wet solids. The effluent for all experiments is acquired fresh from effluent pond, weeping wall or leach pads. Effluent is analyzed for solids content (TS, VS).

3.3.2 Bench-scale methanogenic reactors

3.3.2.1 Experiment with 1L methanogenic reactors

Three sets of two 1L methanogenic reactors (E1, E2, E3) with 5 % total wet solids are set up. pH is measured as neutral and temperature is ideally mesophilic ranging in between 35-44^{0}C. Each of the digester has a magnetic stirrer. The influent is warmed to reach the temperature. The digester is set in a temperature-controlled heated water bath on a heater equipped with stirrer. The digester is held vertical with all ports of influent, effluent and gas outlets vacuum sealed to the contact surface. The digester along with the heated water bath is set up on a heater and magnetic stirrer. Flexible tubing to both the influent and effluent tubes are connected and tubing is done to gas port. The gas line is connected to the water column to collect the gas and the volume of gas is recorded. Also the gas is analyzed by using a gas chromograph.

The purpose of the bench scale trials was to determine volumetric methane yield (LCH_4/Lreactor/day), methane yield relative to volume of influent (LCH_4/Linfluent) and specific methane yield (LCH_4/gVSadded).

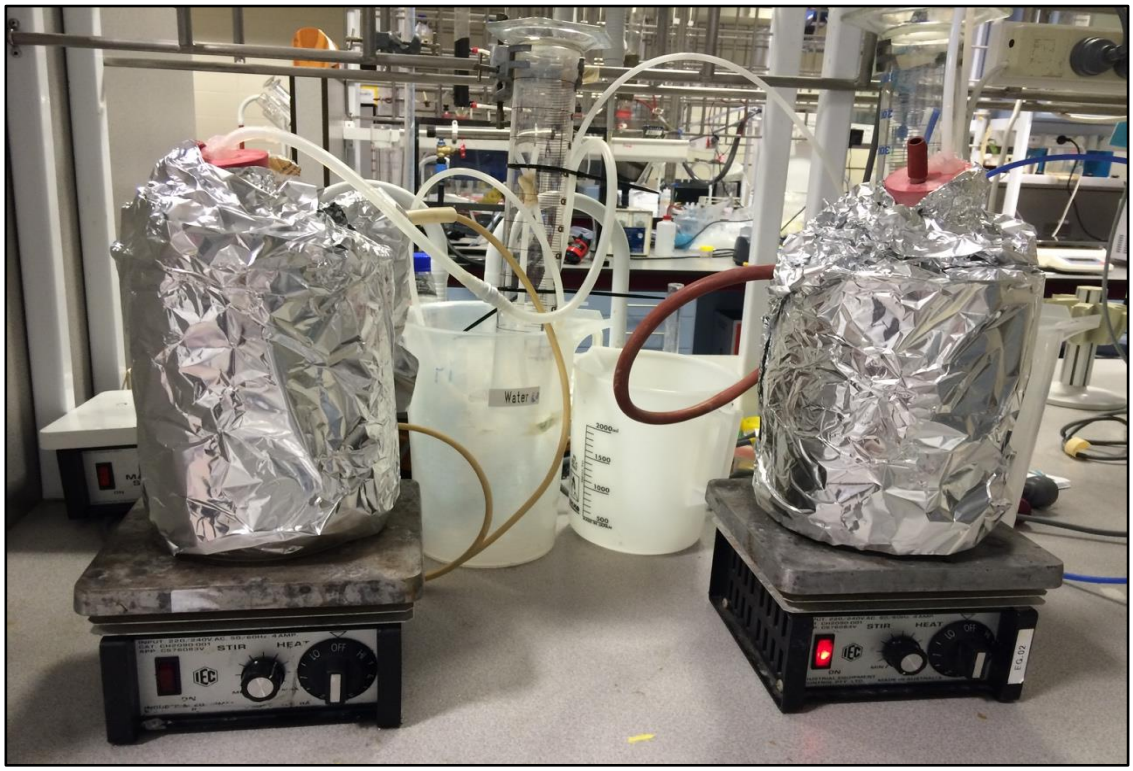

Figure 3-1: Bench scale 1L methonogenic reactor set up.

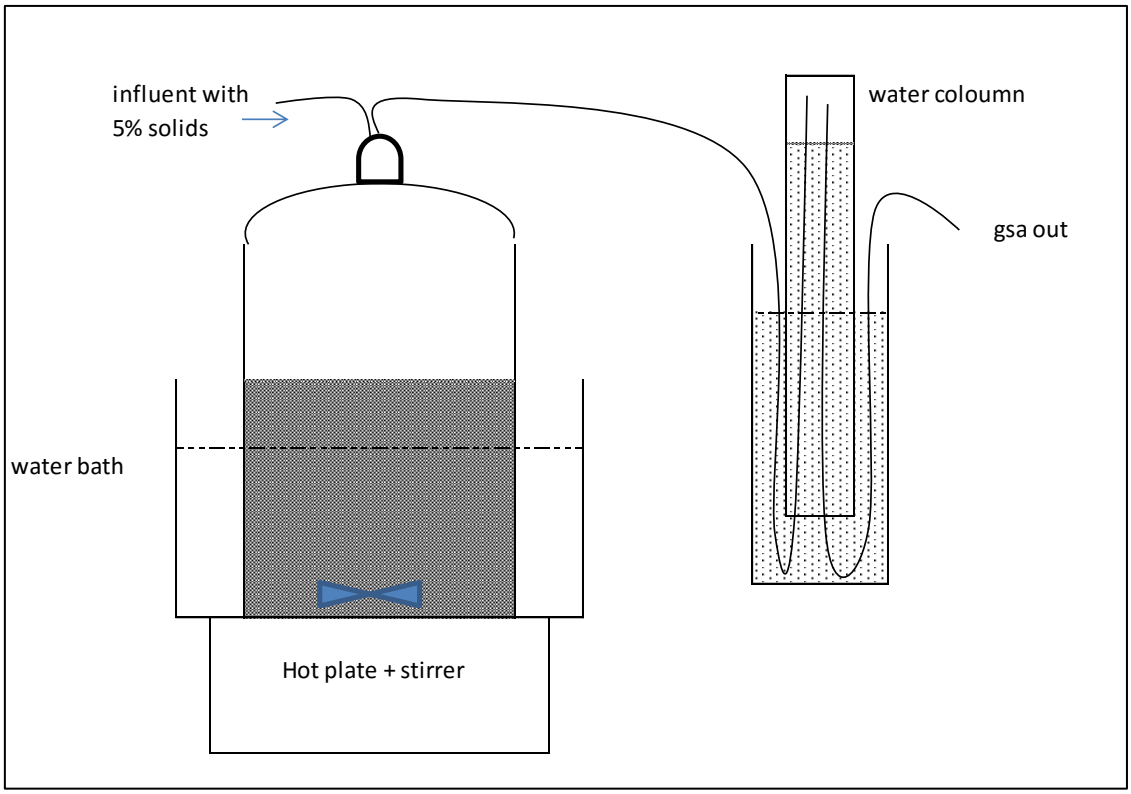

Figure 3-2: Schematic representation of the 1L benchscale reactor

3.3.3 Experiment with three-stage coupled mesophilic anaerobic digesters

A bench-scale model of continuous stirred three-stage mesophilic anaerobic biodigester coupled in series is set up. Three 5 L jar are secured as the biodigesters. Each of the biodigesters are secured airtight. The first digester is placed at an elevated height compared to the other two digesters and second digester is placed higher than the third as shown in the figure. All the ports of influent, effluent and gas outlet are secured airtight and sealed with silicone to the contact surface where needed. Each of the individual digester is connected to a water column to collect the gas. The digesters are provided with two outlets for the influent, of which, one is used draw the effluent for measuring pH and temperature and the other outlet is coupled in series with next digester as a medium for the digester influent. The third biodigester has one outlet to draw the treated effluent and for analysis and further use (at farm for irrigation. Temperature between the digesters is set different for experimental trails.

Condition 1 (digester 7): The digester temperature is regulated in between 40-45^{0}C and the pH is maintained neutral. The magnetic stirrer is kept at medium slow speed.

Condition 2 (digester 8): The digester temperature is kept slightly lower than the first digester and the effluent from digester 7 is influent for digester 8 (digesters coupled in series). Temperature is maintained about 37-41^{0}C. pH is kept neutral. Magnetic stirrer is kept at slightly slower speed than digester 7.

Condition 3 (digester 9): The digester temperature is lowest among all three digesters and is maintained in the range about 32-37^{0}C. pH is kept neutral. Magnetic stirrer is kept at the slowest speed compared to the other digesters.

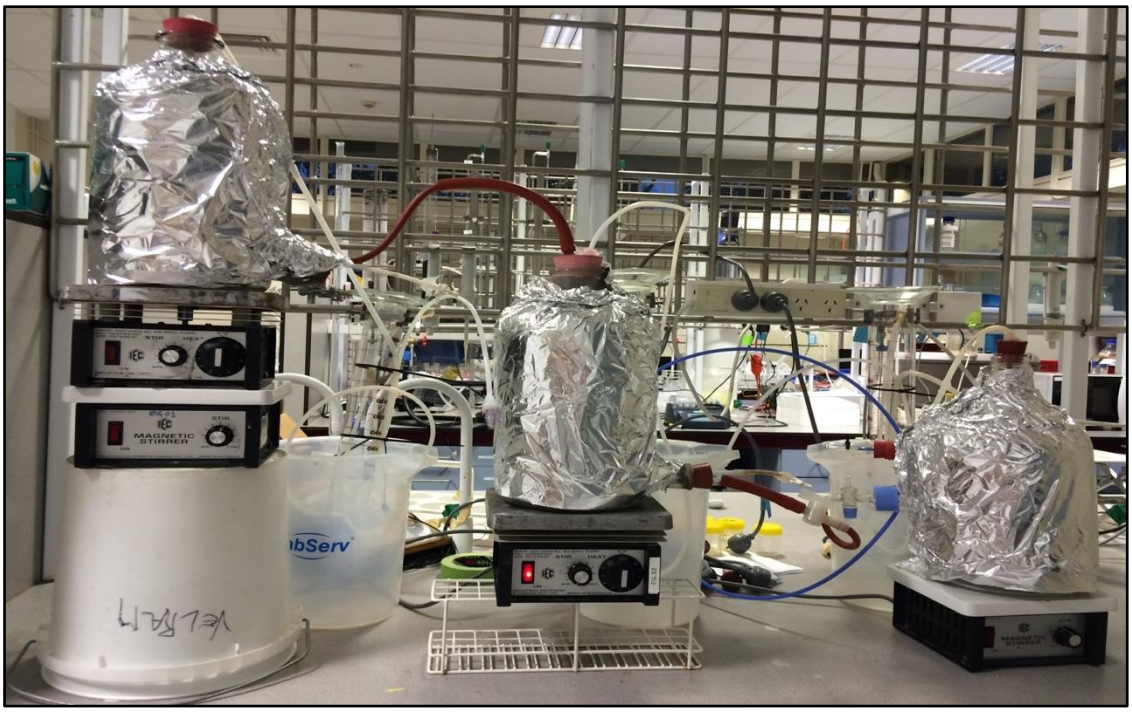

Figure 3-3: Bench scale coupled methanogenic three-stage bio-digester

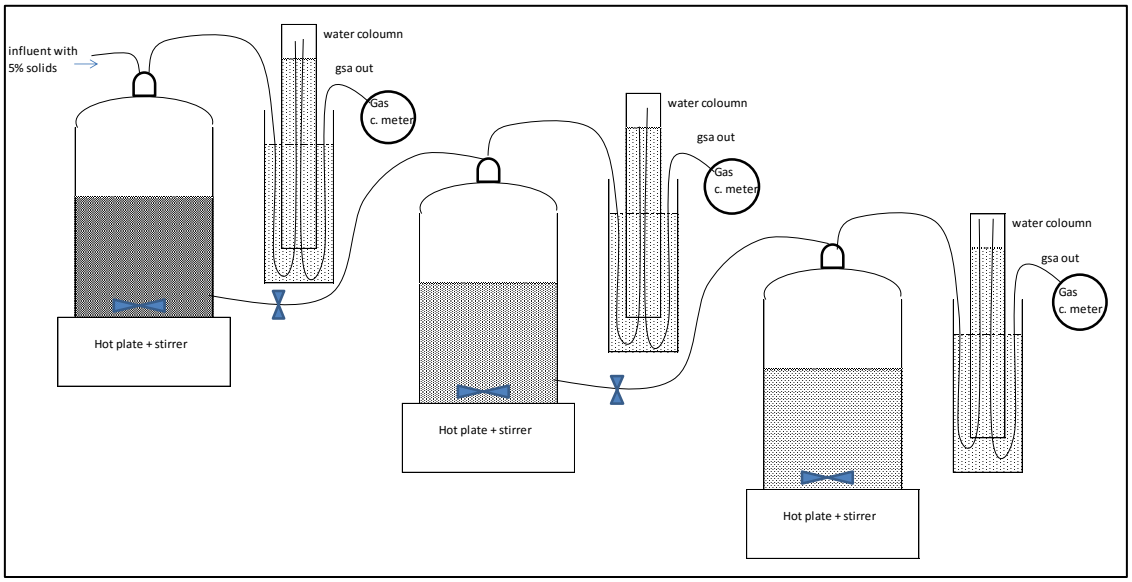

Figure 3-4: Schematic representation of continuous coupled three-stage bench-scale methanogenic reactor

Table 3-1 below summarizes all the operating parameters for the the experiments and the operating conditions for different reactors.

Table 3-1: Operating parameters of bench scale methanogenic reactors

Parameters	Experiment 1						Experiment 2		
	Experiment A		Experiment B		Experiment C		Experiment D		
	Reactor1	Reactor2	Reactorr3	Reactor4	Reactor5	Reactor6	Reactor7	Reactor8	Reactor9
Available Volume (L)	2	2	2	2	2	2	5	5	5
Feed (L)	1	1	1	1	1	1	3	3	3
Temperature (^{0}C)	37-44	37-44	37-44	37-44	37-44	37-44	40-45	37-41	32-37
pH	6.5-7.5	6.5-7.5	6.5-7.5	6.5-7.5	6.5-7.5	6.5-7.5	6.5-7.5	6.5-7.5	6.5-7.5
Total solids (g)	23.2	23.2	23.2	23.2	23.2	23.2	69.6	69.6	69.6

Table 3-2: Summary of experiments and their objectives

Chronological order	Experiment	Objective
1	Characterization	To determine the organic content of the FDE in order to better understand the potential for methane production.
2	Experiment A (Reactors 1 and 2) Experiment B (Reactors 3 and 4) Experiment C (Reactors 5 and 6)	To maintain constant temperature for the water bath and the biodigester and to maintain a neutral pH for the entire length of the experiment. To analyze and compare the gas collected from the water column and determine the volume of methane per kg volatile solids (l CH_4/kg VS added) Effect of different effluents from different farms is investigated in experiment C
3	Experiment D (Reactors 7, 8 and 9)	To maintain neutral pH and constant temperature for the biodigester under specified condition individual to each reactor to ensure better methanation process To analyze the gas collected from the water column and determine the volume of methane per kg volatile solids (l CH_4/kg VS added) To analyze the total volatile solids reduction in the treated FDE from the reactor 9.

3.4 Analytical procedures

3.4.1 Total Solids (TS) and Volatile Solids (VS)

TS and VS were determined following the method set out in sections 2540 B and 2540 E of Standard Methods (APHA, 1998). All TS and VS analysis was carried out in duplicate. TS and TVS are important because organic matter reduction represents the theoretical mass that is converted to biogas. TVS are determined by placing an oven-dry sample in a crucible in the muffle furnace set to 550°C plus or minus 50°C for 10 hrs. The mass of the crucible and the mass of the dried material plus the crucible is measured before placing in the furnace. After 10 hours, furnace is turned off and samples are allowed to cool slowly in the furnace. Total mass of the ash and the crucible after cooling is measured to find TVS.

3.4.2 pH measurement

The pH of samples was measured using an Orion model 230A pH meter. The pH meter was calibrated prior to use using pH 4 and pH 7 color key buffer solutions (BDH Laboratory Supplies)

3.4.3 Temperature

Temperature of effluent in all the biodigester reactors is measured. The effluent is drawn from the 1 litre digesters from the specific port and temperature of effluent and water bath is measured. Temperature for the three stage continuous batch reactors is measured by drawing a sample from the reactors directly. Temperatures for all the bench scale experiments are monitored every day and maintained according to the required set temperature to research.

3.4.4 Gas volume

Gas volume is calibrated by measuring the gas based on the liquid displacement method. Gas produced by anaerobic digestion is accumulated in the headspace and water in the water column is displaced to accommodate the gas. Amount of gas volume collected in the headspace of water column is recorded daily and is tabulated in an excel sheet and used for gas analysis. After reading the gas volume all the gas is drawn

out using 20ml syringes to clear the headspace. This same process is repeated and continuous recording is done every day of the experiment.

3.4.5 Gas Composition

Head space gas samples from reactors 7, 8 and 9 were analyzed using a PerkinElmer™ GC (PerkinElmer Instruments LLC, Shelton, CT, USA) with a thermal conductivity detector (TCD) and a column sequence of HaySep Q (80/100), molecular sieve 13× (pore size 13 A $^{\circ}$ with sodium as the primary cation), and HaySep D (100/120) columns. The molecular sieve separated hydrogen, oxygen, nitrogen, methane, and carbon monoxide. Because carbon dioxide is irreversibly adsorbed by the zeolite, the GC–TCD program was set to reverse gas before carbon dioxide had passed through the HaySep Q columns. The following program was used: oven temperature 50°C, detector temperature 250° C, injection temperature 120 $^{\circ}$ C, carrier gas argon (90 psi), flow rate 20 mL Min^{-1}, a program time of 10 minutes with reversed flow at 2.65 minutes. Gas flow was reversed using pneumatic switches operated with dry air at 65 psi (Li, X., Swan, J. E., Nair, G. R. and Langdon, A. G. et al., 2015). The GC system was calibrated with a standard gas mixture (Matheson Tri-Gas; Grace Davison Discovery Science), the composition and resulting peak areas and residence times are presented in Table 3-3. Head space gas samples from the bioreactors were injected at room temperature to the columns via a 1-mL sample loop operated pneumatically by a dry air supply (Li, X., Swan, J. E., Nair, G. R. and Langdon, A. G. et al., 2015).

Gas composition was determined by identifying the component based on retention time, and calculating % volume of that component by multiplying the peak area of the component in the gas sample by the % volume of the component in the standard divided by the peak area of the component in the standard.

Table 3-3: Calibration of composition and resulting peak area of standard gas sample from gas chromograph

Peak	Time(min)	Area (µV/s)	Height (µV)	Area (%)
1 (He)	2.377	1546580.72	116.843.9	51.00
2 (H_2)	2.547	749643.97	217088.49	24.72
3	2.770	148131.17	18080.51	4.88
4(CH_4)	3.830	243564.56	38111.59	8.03
5 (O_2)	5.198	109758.66	18813.47	3.62
5 (N_2)	5.629	79867.55	11466.69	2.63
6 (CO_2)	7.196	83860.78	6158.20	2.77
7 (CO)	8.443	71168.23	5461.27	2.35

3.4.6 Data Analysis

Data analysis included process monitoring in regard to detailing the frequency of measurements and preferable ranges of parameters such as characterization of the process, inhibitors of the process and various parameters affecting the process. Detailed data analysis is done for parameters characterizing the process which included quantity and quality of the effluent, temperature, pH, total solids and biogas volume and composition. These parameters are monitored to state the overall process stability. Data in regards to gas volume and gas composition is monitored and recorded daily to determine changes which could correlate to be any imbalance in the process.

Data was analyzed using the tools available in Microsoft Excel. Analyzed data is compared to data calculated on basis of data from theory.

4 Results and discussion for bio-digestion experiment

In this chapter the results from the bio-digestion trials of dairy shed effluent are presented and discussed. Bio-digestion bench scale experiments were conducted as bench scale experiments firstly to examine the reproducibility of the results within the operating parameters and to facilitate three 3-L mesophilic reactors for biogas production. Experiments A, B and C are all 1-L bench scale bio-reactors to compare operating parameters such as pH, temperature and biogas volume production with one another and to determine the results between different digesters.

Characterization of the dairy shed effluent collected from the effluent pond was carried out to determine the total solids and total volatile solids. This was done to get an idea of solids content in 1 liter of effluent and for comparison with digested effluent after the digestion trials. The total solids (TS) was 23.19 g/l and total volatile solids (TVS) was 17.62 g/l which accounts for 76 % of the TS.

Total volatile solids were also measured in the processed effluent and after the anaerobic digestion. TVS in reactor 7 was 16%. In reactor 8 TVS was 48.5% and in reactor 9 TVS was about 62.1%. The total volumetric methane production from the three stage bench scale coupled methanogenic reactors was 0.09 m^3/kgVS/day, 0.06 m^3/kgVS/day and 0.07 m^3/kgVS/day respectively from reactors 7, 8 and 9. Table 4-1 shows the total solids content and volatile solids before and after the bio-digestion process from the present study. Methane yield in this study is similar to literature values obtained for an anaerobic filter system with a yield 0.08 m^3/kgVS/day (Vartak et al., 1997), CSTR system yield of 0.06 m^3/kgVS/day (Lo & Liao, 1996) and a typical anaerobic dairy farm system 0.13 m^3/kgVS/day (MAF, 1994). Methane yield for the three stage bench-scale methanogenic reactors is 0.034 m^3CH_4/m^3 reactor/day which is higher in comparison with the literature review data for a typical dairy farm anaerobic pond 0.02 m^3CH_4/m^3 reactor/day (MAF, 1994).

Reactor pH, temperature, gas production and gas composition are presented and discussed in the sections below.

Table 4-1: Total solids (TS) and Total volatile solids (TVS) before and after the bio-digestion process in the three stage mesophilic reactor

Experiment ID	CH_4 output (mL)	Volatile Solids (%)			VS Influent (g)/3L	VS Effluent (g)/3L	Amount VS Removed (g)/3L
		Influent	Effluent	Change of Total Solids			
Reactor 7	3718	76.0	16.0	78.9	52.9	11.16	41.72
Reactor 8	1706	76.0	48.5	36.2	52.9	33.74	19.14
Reactor 9	864	76.0	62.1	18.3	52.9	43.18	9.69

4.1 pH

The Figure 4-1 below shows the change in pH for each reactor over the course of each experiment. All the reactors showed a slight drop in pH from 6.8 and 6.2. In experiment A, reactor 1 shows the pH drop to be between 6.8-6.2 in days 8-11 and between 6.8-6.2 in days 11-21 in reactor 2. This pH drop in reactor 1 suggests more acidification as a result of more readily digestible organic matter. The pH drop can also be correlated to the total solids contents. Although reactors 1 and 2 have the same weight of total solids (5% total wet solids) reactor 2 has more grass clipping content.

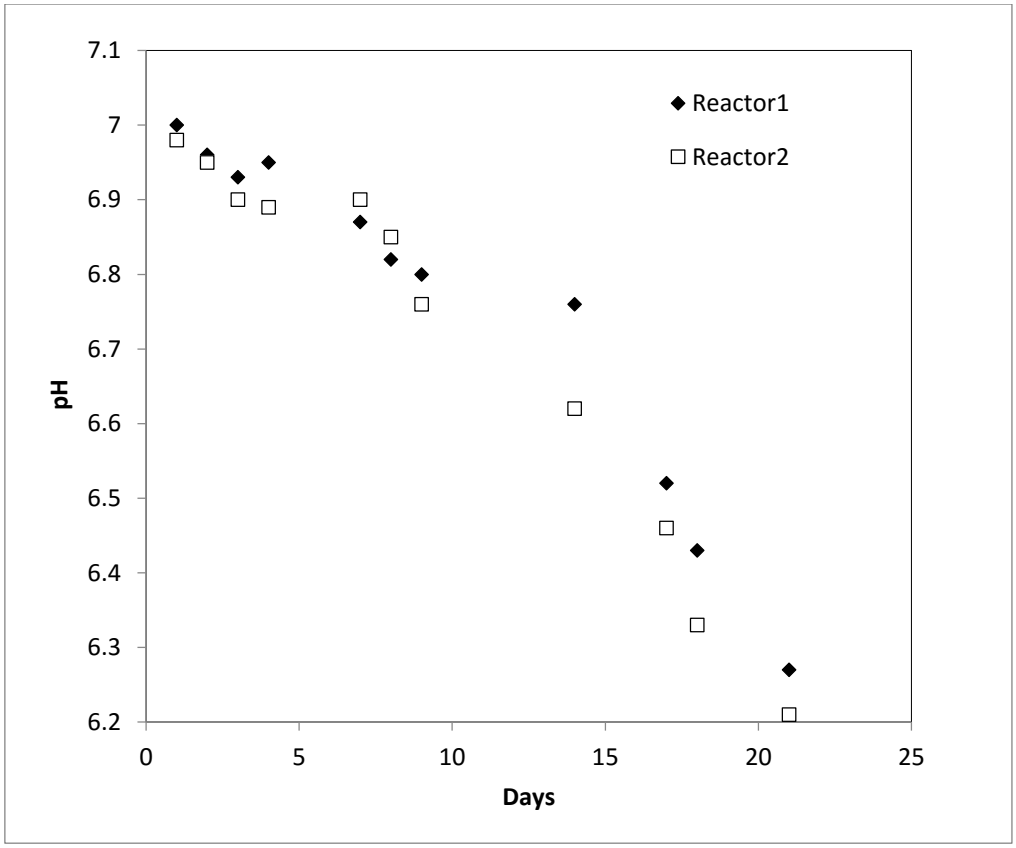

Figure 4-1: Experiment A : pH variation of Reactor 1 and Reactor 2.

The same pH drop seen for reactor 1 and 2 was also observed in reactors 3 and 4 (Figure 4-2). Gas volume yield in the reactors is also similar to reactor 1 and 2 without much fluctuation (Figure 4-8).

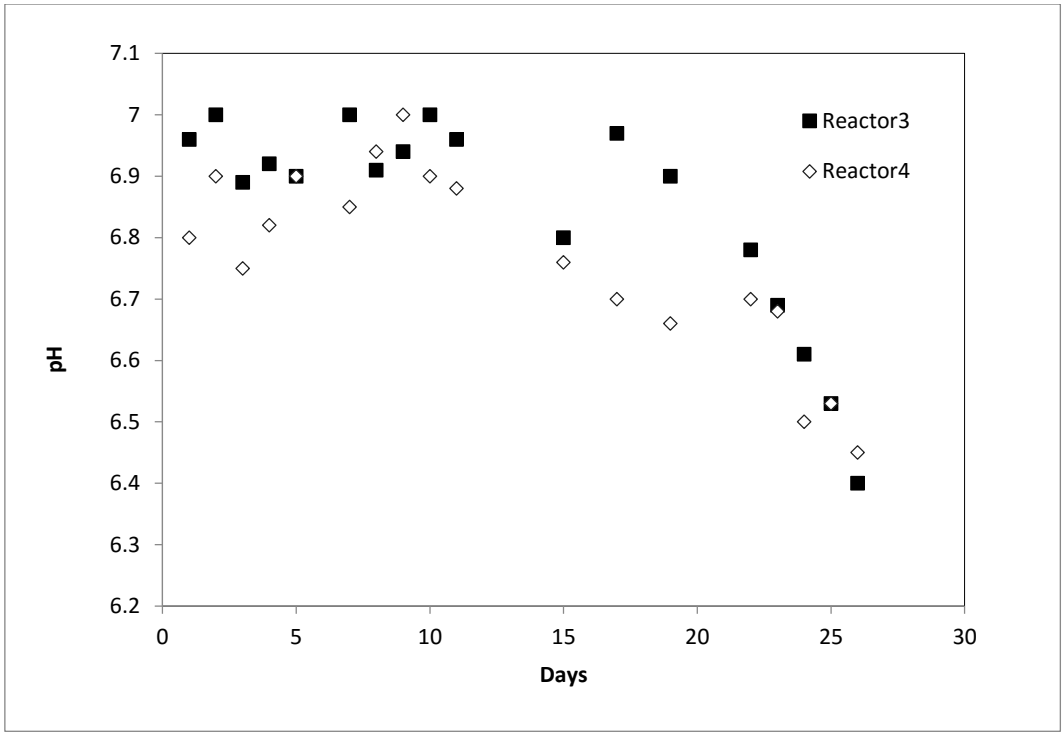

Figure 4-2: Experiment B: pH variation of Reactor 3 and Reactor 4

In experiment C, reactor 6 has a higher pH drop compared to reactor 5 (Figure 4-3) and the gas volume yields in reactor 6 was slightly higher than the reactor 5 (Figure 4-5). In reactor 5, effluent fresh from the milking shed was used, while reactor 6 used effluent collected from the effluent pond. It is possible that effluent from the pond was higher in methane producing bacteria than the effluent fresh from the shed, hence the higher gas production and acidification.

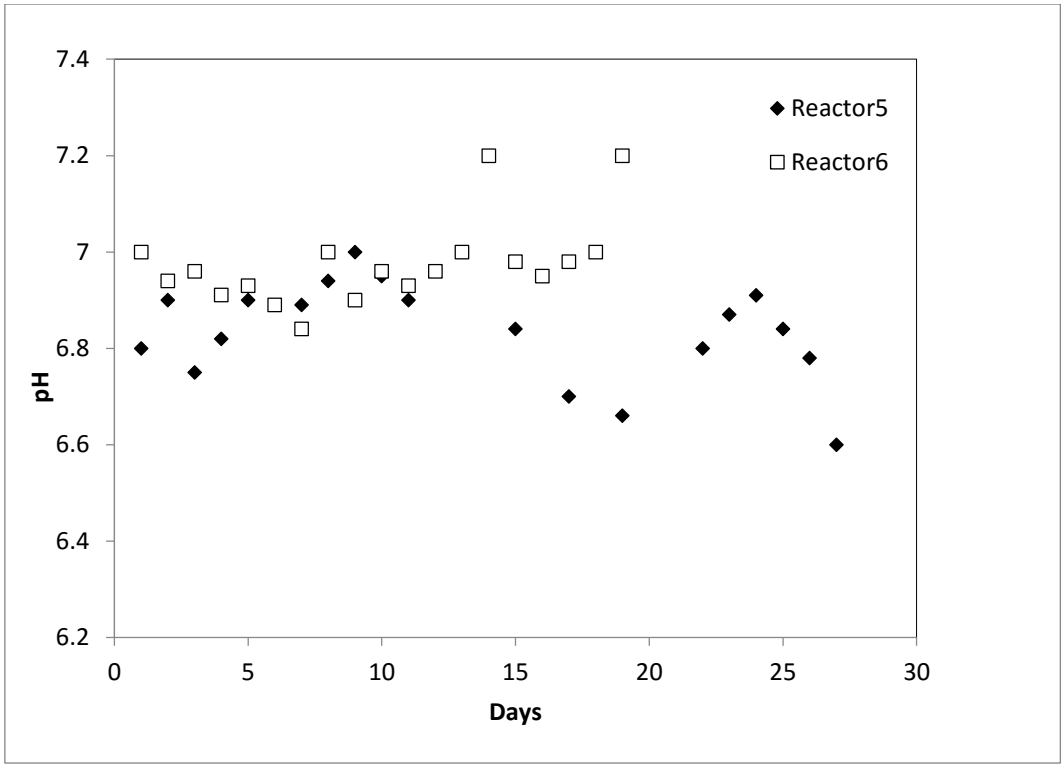

Figure 4-3: Experiment C: pH variation of Reactor 5 and Reactor 6

In experiment D for the three stage bio-digester, pH in reactor 7 has dropped by day 14 and has slightly more acidification compared to reactor 8 possibly because of the slightly higher temperatures (42-48 ºC in reactor 7 compared to 37-43 ºC in reactor 8). The biogas output in reactor 7 is higher (3717 ml) than the reactor 8 (1707 ml) and reactor 9 (863 ml) (Table 4-2) and gas production decreases as reactor pH drops. For reactor 9, the pH drops to as low as 5.2 which could be because it has been dosed with effluent from the subsequent reactors. Reactor 9 is also operating at a lower temperature of 32-37ºC (Figure 4-10).

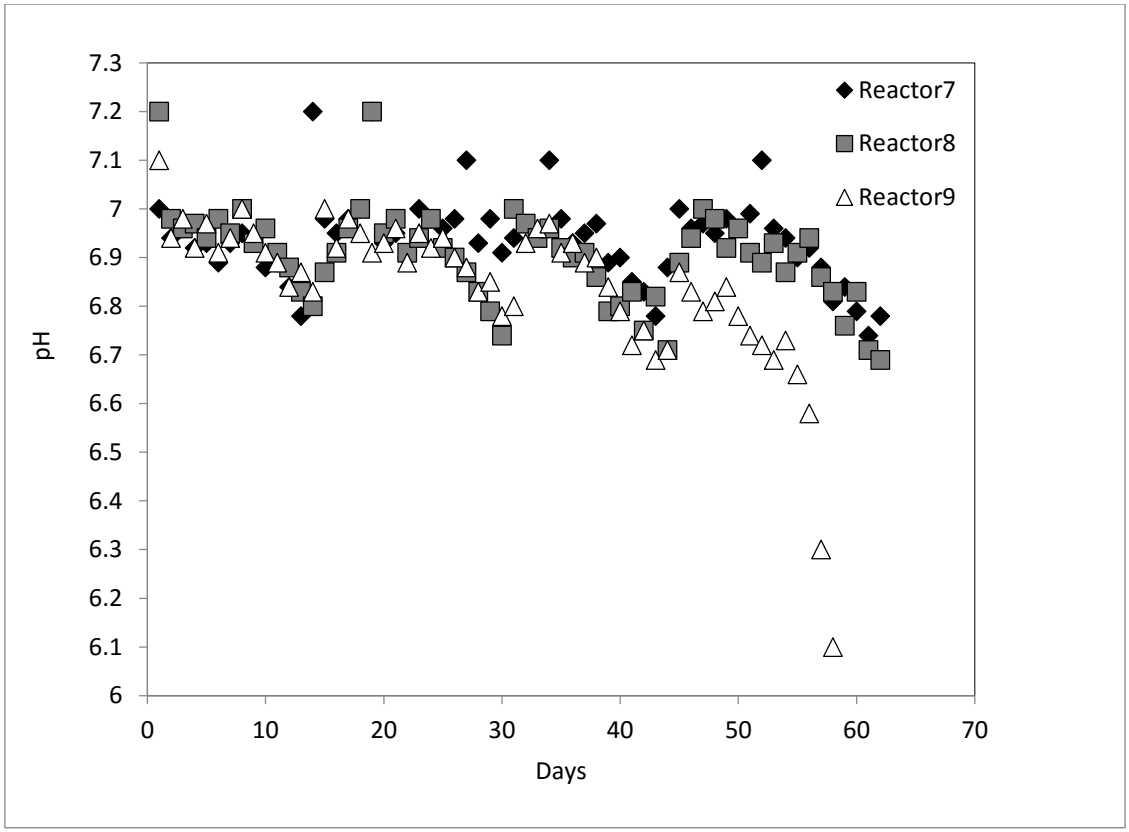

Figure 4-4: Experiment D: pH variation of Reactor 7, reactor 8, reactor 9

4.2 Gas volume in comparison with pH

The pH condition in anaerobic digestion affects bacteria activity to convert organic matter to biogas. Literature pH values for optimal gas production range between 6.9 – 7.3 (Metcalf and Eddy, 2003); 6.4-7.6 (Anderson and Yang, 1992); and 6.5-8.5 (Speece, 1996). A low pH value inhibits the activity of microorganisms involved in the biogas production especially methanogenic bacteria and accumulation of methanogenic bacteria in the digesters (Vicenta et al., 1984; Speece et al., 1996).

The gas volume increased in the first 10-15 days (Figure 4-5). However, after day 15 gas production decreased. Gas production was completely stopped at day 19 in reactors 1 and 2. pH of effluent decreased generally and a downward trend is noted for the reactors. At pH 6.2 and 6.3 in reactors 1 and 2 respectively, the gas production was lowest.

From Figure 4-5, in reactors 3 and 4 a definite relation is observed between pH and gas volume. As the pH is 6.8-7.1 showed highest volume of gas production. As a pH drop

is observed gas production also had a downward trend. It can be concluded that neutral pH (7) is most favorable for methane production. The same relation between pH and gas production can be seen for reactors 5 and 6 in the Figure 4-5. The highest volume of gas is observed between pH 7-7.2 in both reactors while the lowest gas volume is recorded between pH of 6.6-6.7.

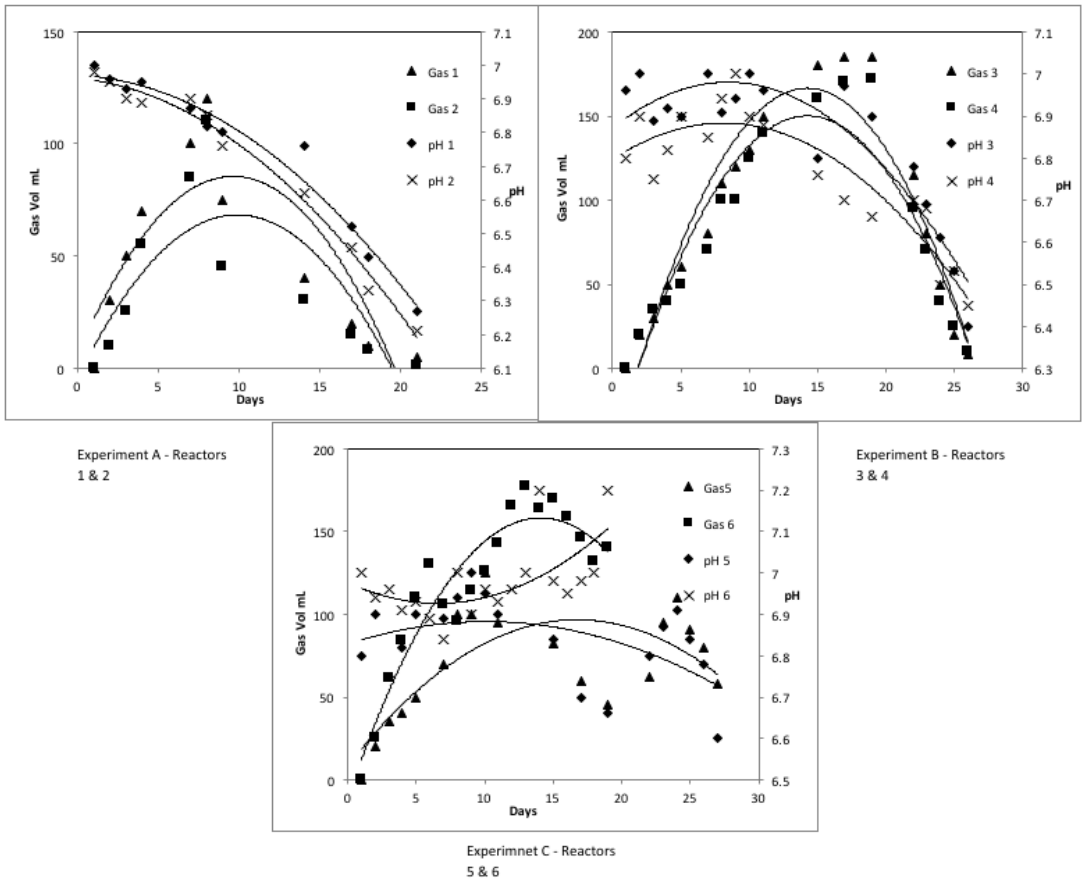

Figure 4-5: Gas volume(mL) in comparison with the pH changes in Experiments A, B and C (Reactors 1-6)

The cumulated produced biogas from organic fraction of dairy waste, in Reactor 7 of the three stage coupled mesophilic reactor with temperature (T=40-45°C) is presented in Figure 4-6. Total biogas production from dairy effluent was calculated after the reactors had been run for 62 days. Biogas production was lowest at pH 6.7-6.75 and maximum gas production was observed at pH of 7.05-7.15.

The final values of biogas volumes for reactor 7 with each effluent batch addition are 855 mL, 766 mL, 741 mL and 1355 mL, accumulating to a total volume production of 3717 mL over 62 days and a pH between 6.7-7.15.

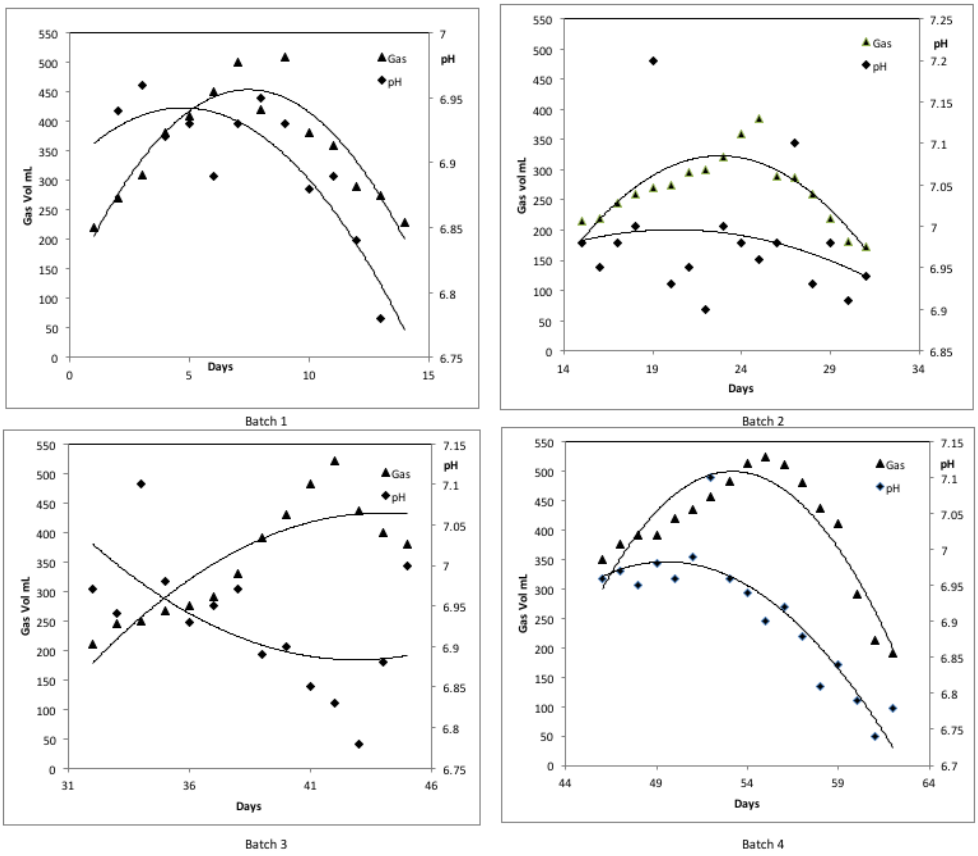

Figure 4-6: Gas volume (mL) in comparison to pH changes in Reactor 7, with batch addition of new effluent

The cumulated produced biogas from organic fraction of dairy waste, in Reactor 8 of the three stage coupled mesophilic reactor with temperature (T=37-41°C) was presented in Figure 4-7. Total gas volume production is 1707 mL for a HRT of 62 days and the lowest biogas production is at pH of 6.65-6.7 and maximum of gas production is observed at pH of 7-7.05. The cumulative biogas production in Reactor 9 with the temperature range of (T=32-37°C) was 863 mL and a pH between 5-7.05 (Figure 4-8). Biogas production for Reactor 9 was the lowest at pH of 5-6 and maximum gas production was at pH of 7-7.05 (Figure 4-8). Total cumulative gas production results from reactors 7, 8 and 9 confirm the results of articles that state starting with pH of between 6.5 and 8.5 gives the best biogas yields (Vedrenne et al 2005).

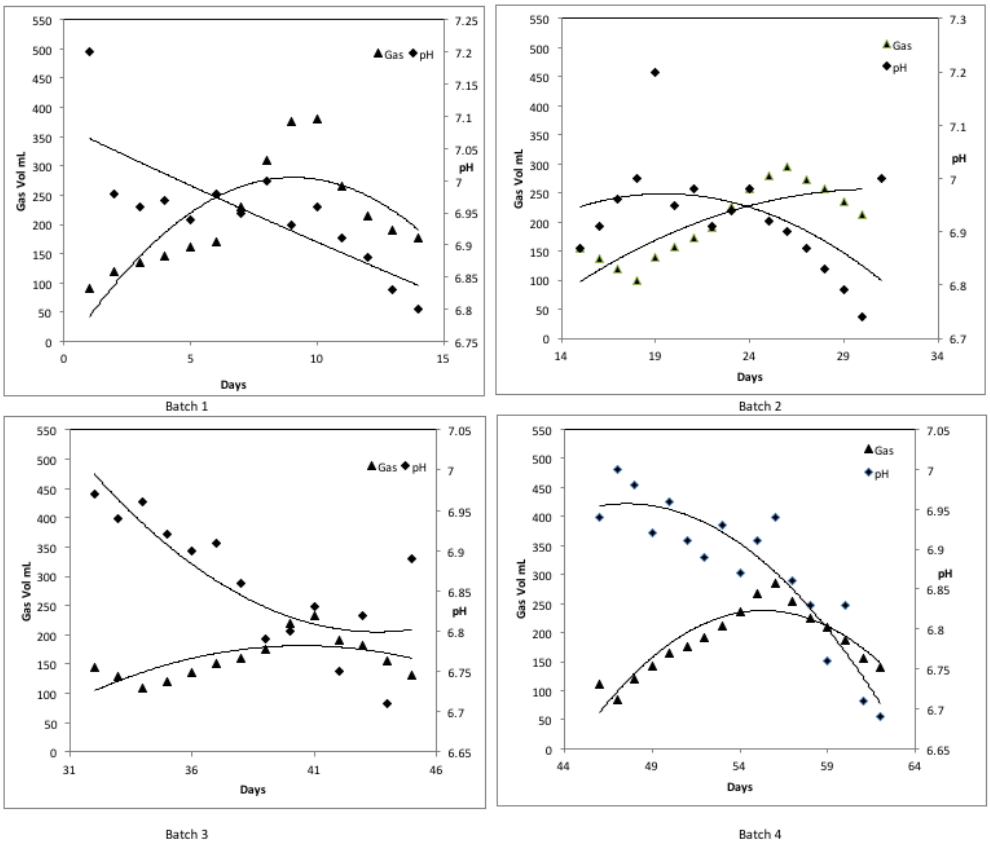

Figure 4-7: Gas volume (mL) in comparison to pH changes in Reactor 8, with batch addition of new effluent

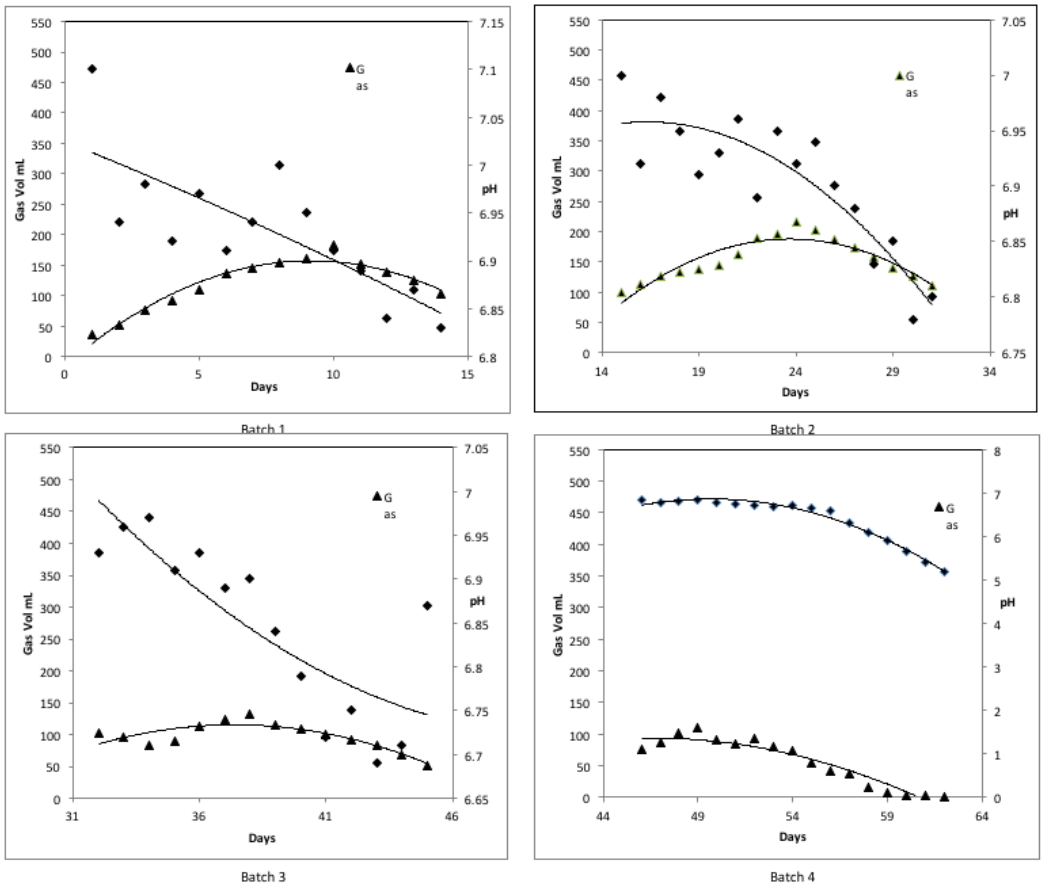

Figure 4-8: Gas volume (mL) in comparison to pH changes in Reactor 9, with batch addition of new effluent

4.3 Temperature

For experiments A, B, C (reactors 1-6) temperature was kept constant and monitored every day to record the data. Minimal trend of fluctuations is noted in the temperatures in the mesophilic temperature range (35-43^{0}C).

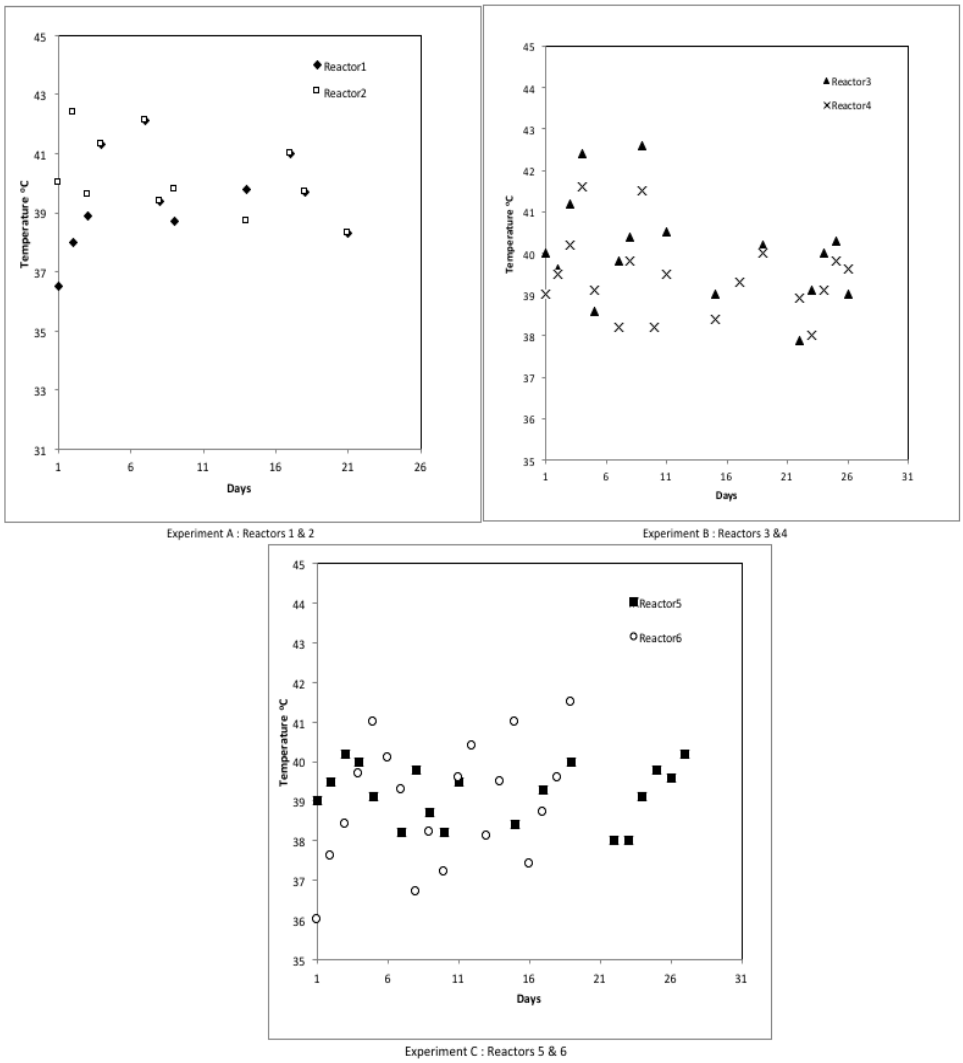

Figure 4-9: Temperature variation of Reactor 1 to 6

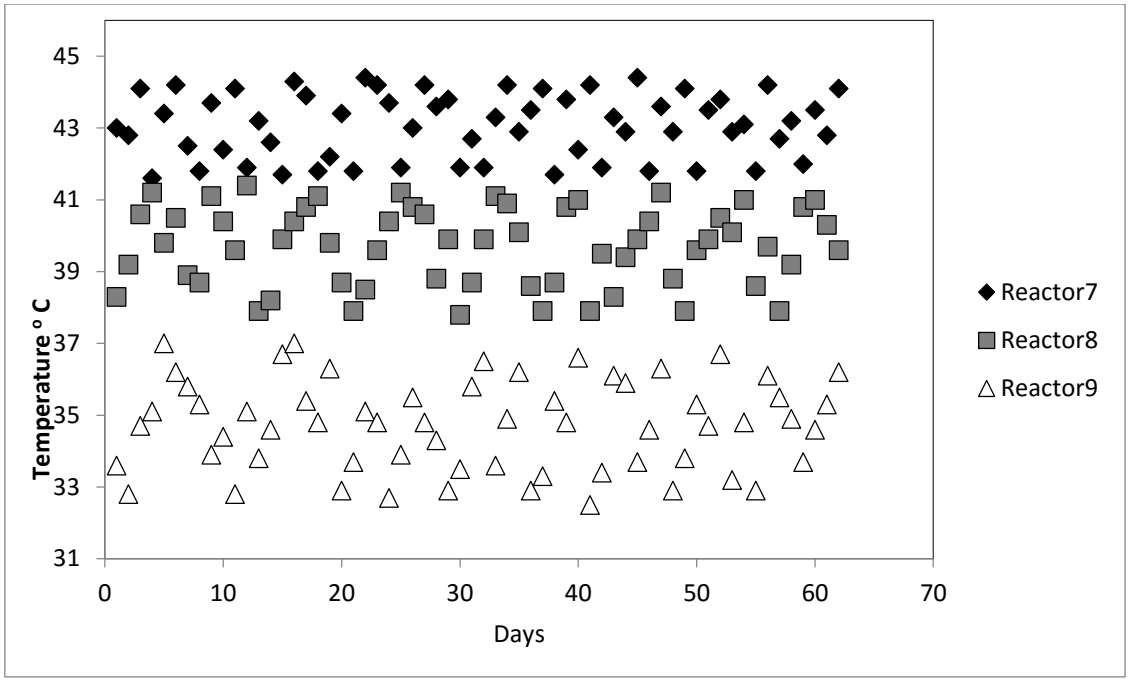

Figure 4-10: Temperature variation of Reactor 7 to Reactor 9

Temperatures in experiment D (reactors 7, 8 and 9) were maintained at the temperatures specified for the experiment, 43-47^{o}C for reactor 7, 37-42^{o}C for reactor 8, and 32-37^{o}C for reactor 9. Fluctuations were minimal and within the conditions specified in the experimental conditions.

4.4 Gas volume

In experiment A it is observed that under the same conditions and weight of the total solids to liquid content, the total gas volume produced in reactor 1 is 520 ml and in reactor 2 is 384 ml (Figure 4-11). Fluctuation in the gas volume may be because of the difference in readily digestible content in the reactors. Reactor 2 has more grass clippings than reactor 1 which are less digestible than dissolved solids. The aim of the experiment was to observe the gas volume produced by controlling all the parameters (pH and temperature) and gas analysis was not done for these experiments.

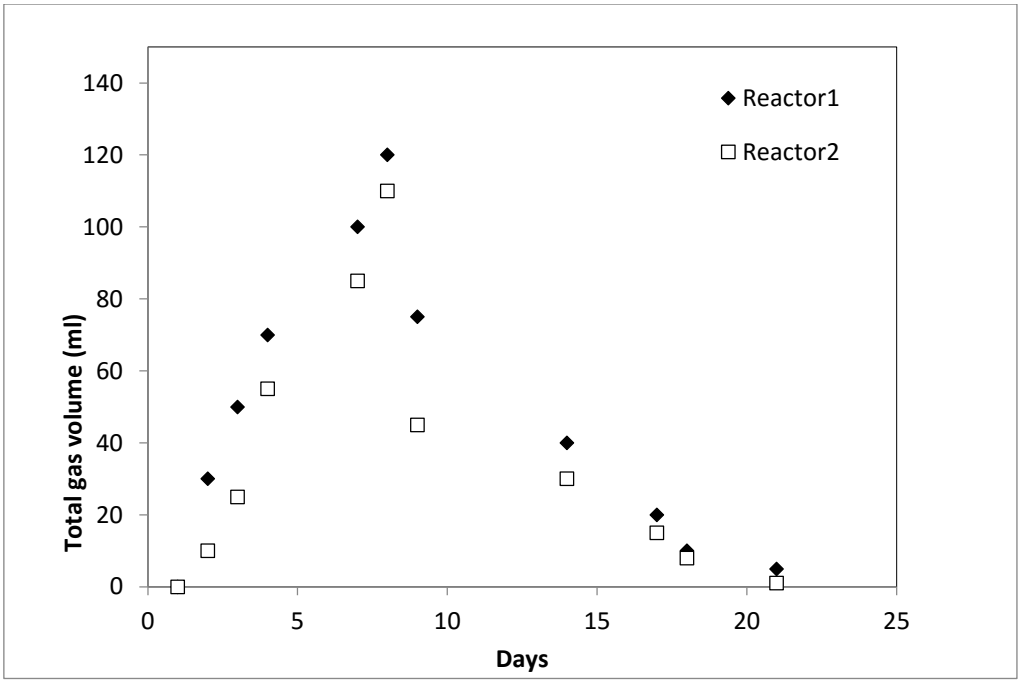

Figure 4-11: Experiment A: Reactor 1 and Reactor 2, Total gas volume (ml)

In experiment B the reactors were under the same operating conditions as experiment A and with the same total solids to liquid ratio. Each reactor was dosed with an additional 200 ml of effluent 15 days into the experiment. Total gas volume produced in reactor 3 is 1573 ml and 1422 ml in reactor 4 (Figure 4-12). The digestion process in both the reactors is similar without much fluctuation and the new influent was used to maintain the pH when a pH drop was observed.

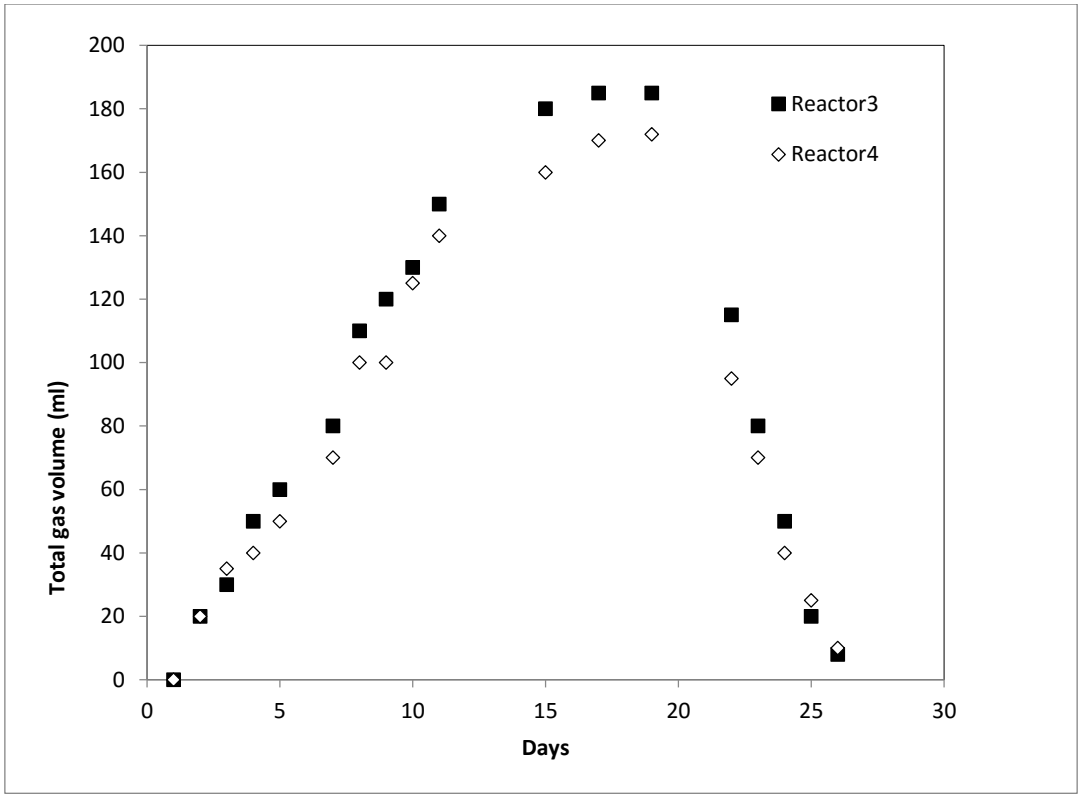

Figure 4-12: Experiment B: Reactor 3 and Reactor 4, Total gas volume (ml)

In experiment C the reactors are set up with effluents from two different farms. Reactor 5 has the sample from farm 1 which does not have an effluent pond. The effluent is collected from the gravity separator and is fresh from the milking shed with the wash down water. Fresh effluent is added on days 4 and 19 to maintain pH as a pH drop was observed on those days (Figure 4-3). Total gas volume produced for reactor 5 was 1318 ml while reactor 6 had a total gas volume of 2248 ml. In reactor 5 the effluent is fresh organic material (<2 week old) so the organic matter available for digestion probably lower. In reactor 6 the effluent used is acquired from the effluent pond which was visibly thicker in appearance than the other effluents, had a total solids of 23.2 g/L, and probably had a higher methanogenic bacteria population.

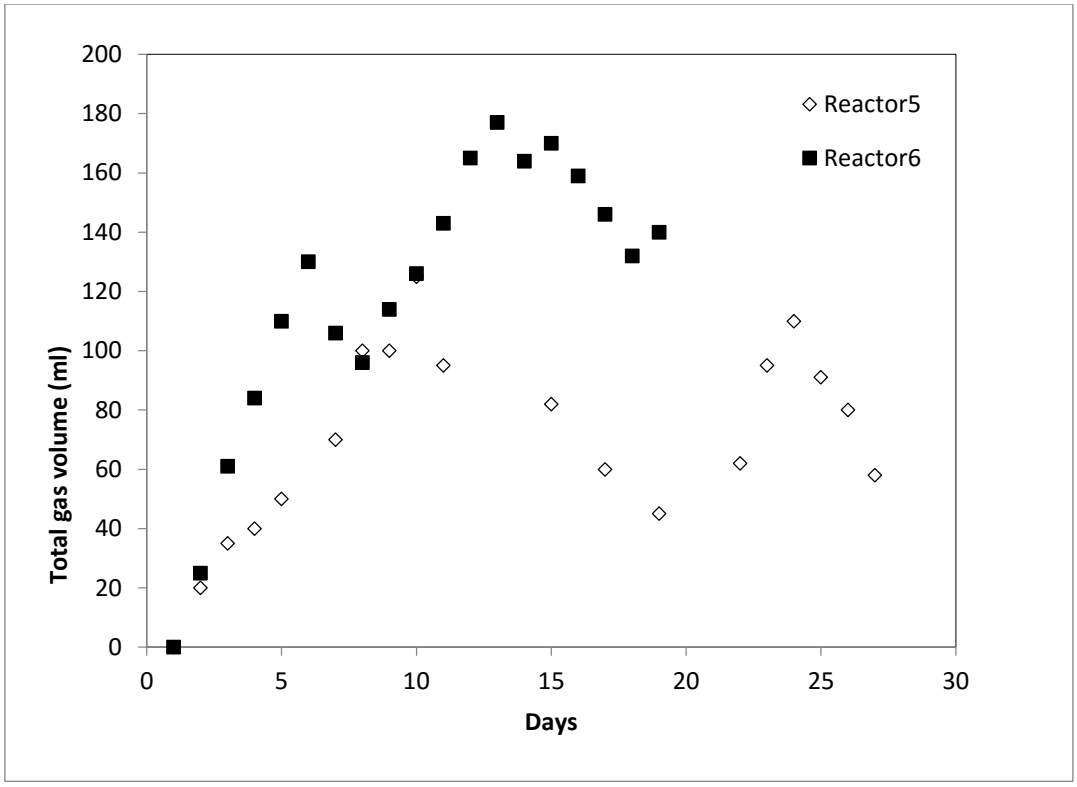

Figure 4-13: Experiment C: Reactor 5 and Reactor 6, Total gas volume (ml)

In experiment D, in reactor 7 total gas volume produced was 21.3L which is higher than reactor 8 which had a total gas volume of 13.7 L and reactor 9 with a gas volume of 6.6 L. Reactor 7 was operating at a higher temperature (40-45^{0}C) compared to reactor 8 and 9 (Figure 4-10) so the gas volume was higher.

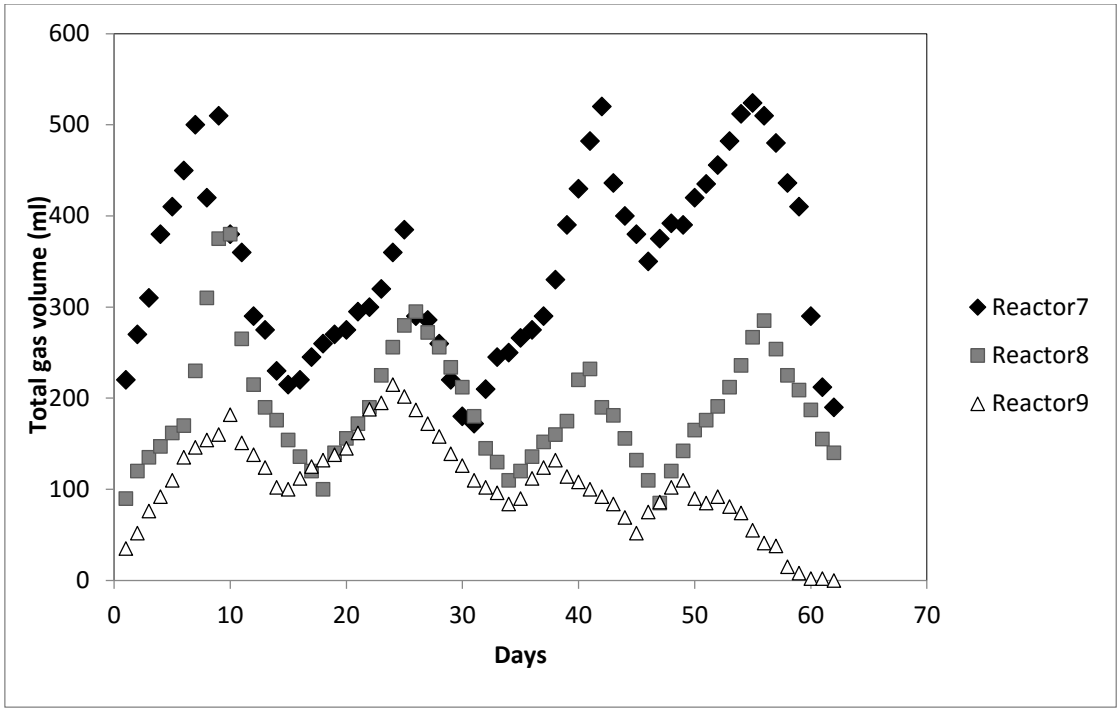

Figure 4-14: Experiment D: Reactor 7, Reactor 8 and Reactor 9, Total gas volume (ml)

4.5 Gas composition analysis

Volume of CH_4 and CO_2 in the gas produced from reactors 7-9 was found using gas chromatography. Volume of gas present in the gas sample was calculated from peak areas and a calibration standard. Total CH_4 and CO_2 present in the biogas as shown in Figure 4-14 and Table 4-2. Total CH_4 gas volume in reactor 7 (3717 ml) is higher than in the reactor 8 (1707 ml) and reactor 9 (855 ml). This is because of the higher temperature (42-47^{o}C) and mixing in the reactor compared to reactor 8 and 9.

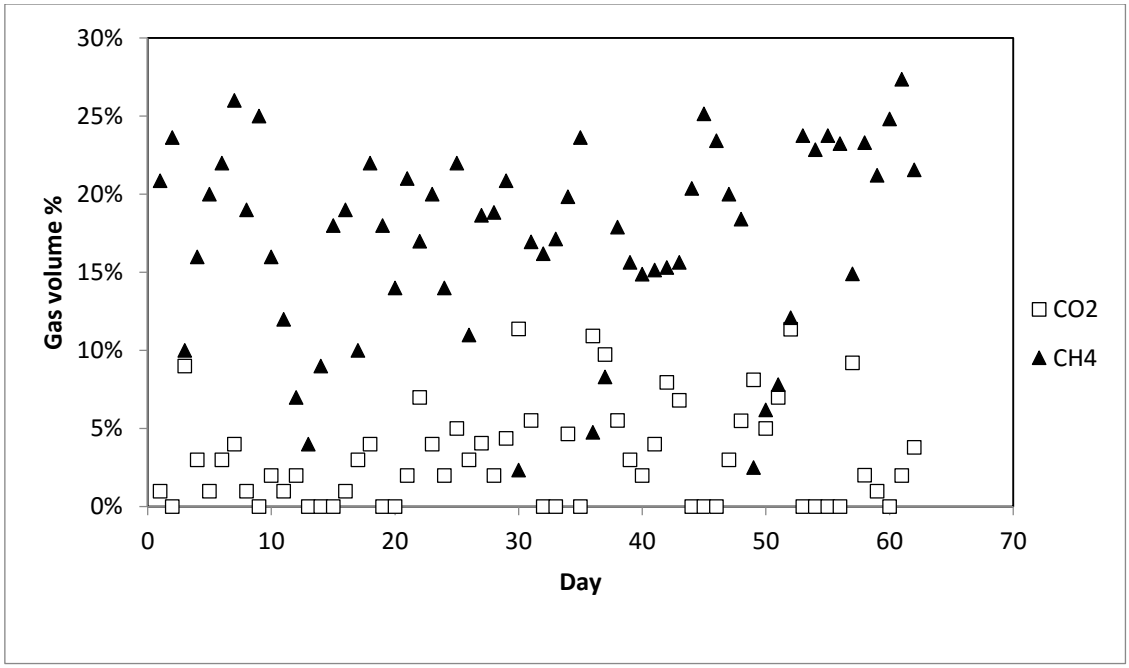

Figure 4-15: CH_4 and CO_2 gas volume percentage for reactor 7

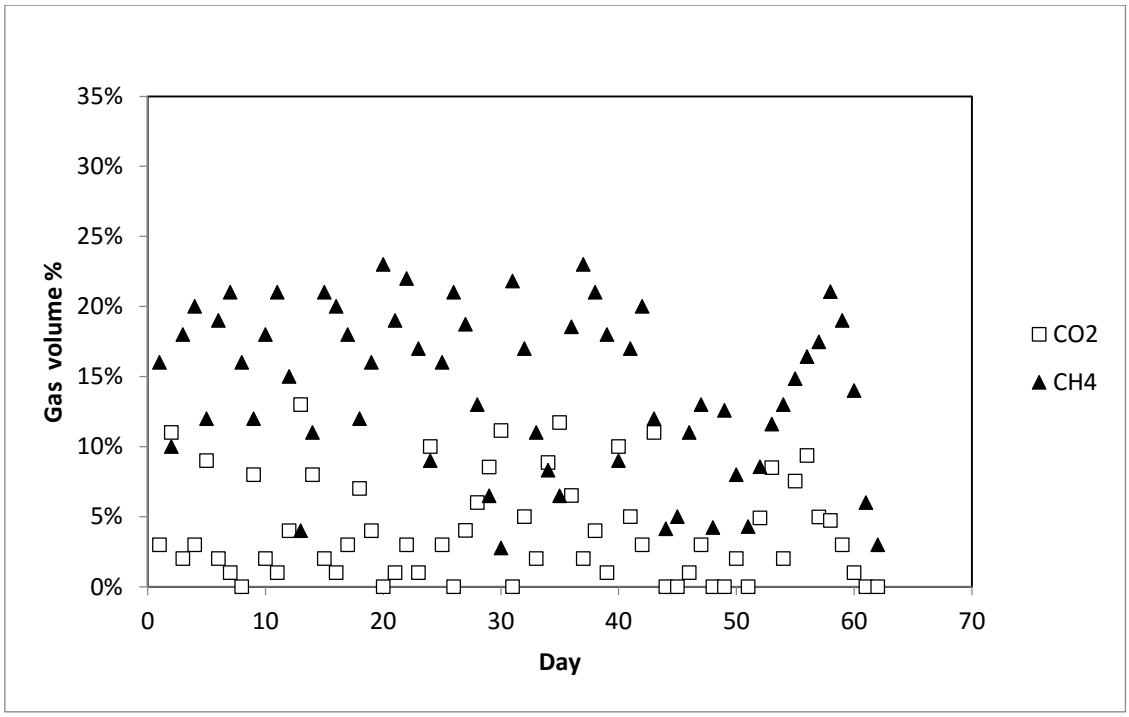

Figure 4-16: CH_4 and CO_2 gas volume percentage for reactor 8

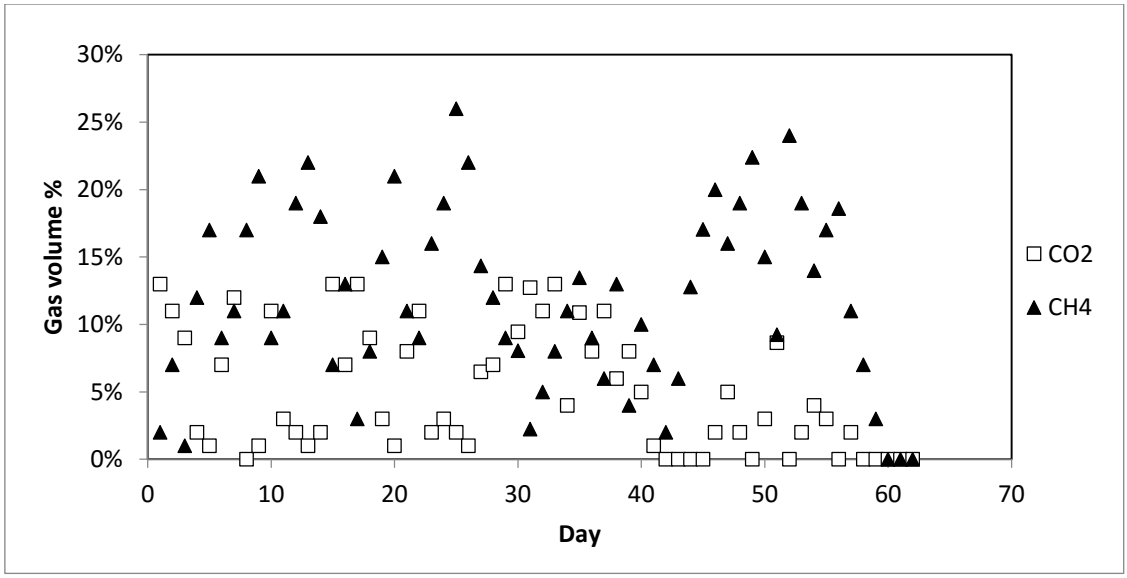

Figure 4-17: CH_4 and CO_2 gas volume percentage for reactor 9

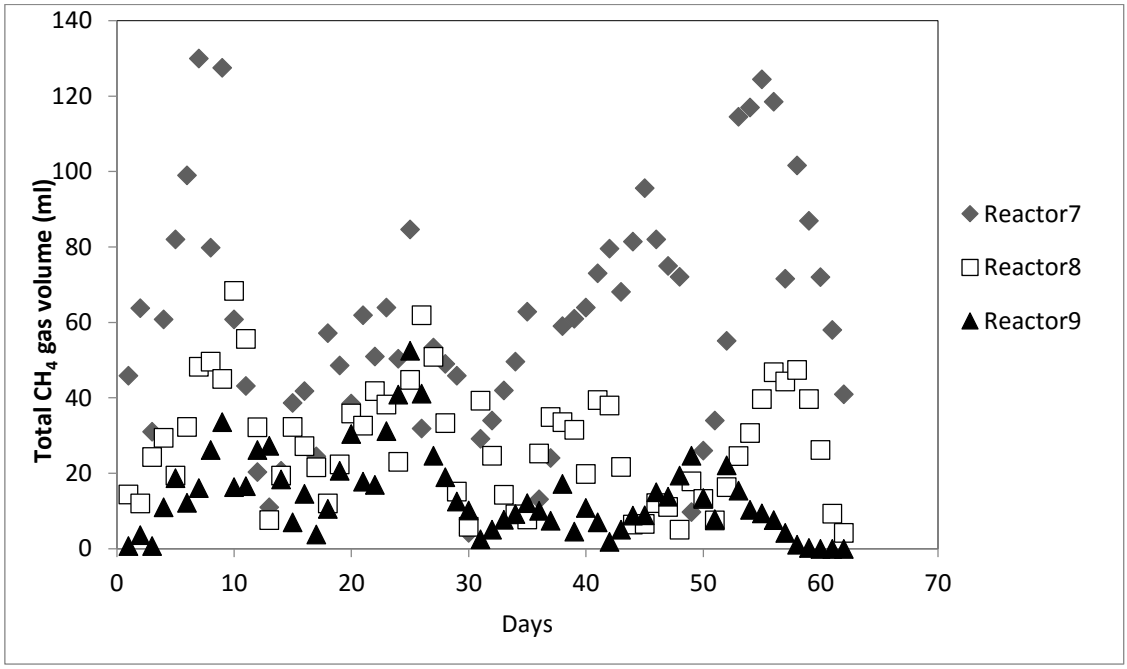

Figure 4-18: Total CH_4 gas volume experiment D (reactors 7, 8 and 9)

From the tabulated data (Table 4-1 and Figure 4-18) methane produced generally increased in reactor 7 when new effluent was added, particularly after the fourth addition of effluent. By the end of the experiment it is noted that the methane production in the digester 9 has decreased. Reactors 8 and 9 produced lower volumes

of CH4 than reactor 7 because they were operating at lower temperatures and were being dosed with effluent taken from 7 and 8, which would have lower digestible content after being in the previous reactor. Also the maximum pH drop is observed in reactor 9 dropping to 5.2, also likely due to being dosed with effluent from reactor 8.

Table 4-2: Total CH_4 gas volume experiment D

Effluent change	Reactor 7 CH_4 gas volume(ml)	Reactor 8 CH_4 gas volume(ml)	Reactor 9 CH_4 gas volume(ml)
1st batch of effluent	855	439	209
2nd batch of effluent addition (500ml)	766	519	372
3rd batch of effluent addition (500ml)	741	346	109
4th batch of effluent addition (500ml)	1355	403	173
Total 3ltr (62 days HRT)	3717	1707	863

Actual gas composition is presented in Table 4-3. Once nitrogen gas volume was subtracted from total gas volume, all the reactors produced biogas with methane percentages ranging from 58% up to 90%. Reactor 7 consistently had the highest methane percentage; 80 to 90% compared with 73 to 80% for Reactor 8 and 58-87% for Reactor 9 respectively. The typical methane content of full-scale digesters is reported as being between 65 and 70% (Tchobanoglous *et al.*, 2003). The average

methane content and carbon dioxide of biogas collected from each stage of three stage mesophilic coupled bench scale reactor is shown in Table 4-4 below.

Table 4-3: Average methane and CO_2 content of total biogas volume with batch addition of new effluent from the three stage mesophilic coupled bench scale reactors in experiment D

Effluent in	Reactor 7		Reactor 8		Reactor 9	
	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
Batch 1	17%	2%	15%	4%	14%	5%
Batch 2	17%	3%	16%	4%	14%	7%
Batch 3	16%	4%	14%	5%	9%	6%
Batch 4	18%	3%	13%	4%	17%	3%

Table 4-4: Average methane and CO_2 content of total biogas volume with batch addition of new effluent in experiment D after subtracting nitrogen

Effluent in	Reactor 7		Reactor 8		Reactor 9	
	CH_4	CO_2	CH_4	CO_2	CH_4	CO_2
Batch 1	90%	10%	78%	22%	74%	26%
Batch 2	84%	16%	80%	20%	68%	32%
Batch 3	80%	20%	73%	27%	58%	42%
Batch 4	84%	16%	77%	23%	87%	13%

Table 4-5: Literature values for volumetric gas production rates of different reactor configurations fed with dairy effluent and gas production from this study.

Researcher	System	Feed	Temperature (oC)	HRT (days)	Organic loading (kg VS/m3/day)	CH4 production (m3/kgVSadded/day)	CH4 production (m3/m3 reactor/day)
Safely and Westerman (1992b)	Lagoon	Screened	10.6 -15	67	0.14	0.32	0.044
Hernandez & Rodriguez(1992)	Anaerobic Filter	Screened and settled	Not reported	0.5	16.30	0.17	2.800
(Vartak et al., 1997)	Anaerobic filter (polyester matting)	Unscreened	10	33	0.12	0.08	0.013
(Lo & Liao, 1986)	CSTR	Screened	22	10	2.94	0.06	0.180
(Lo & Liao, 1986)	Fixed film reactor	Screened	12	1	28.70	0.01	0.300
(MAF, 1994)	Typical dairy farm anaerobic pond	Unscreened	Ambient	50-120	0.15	0.13	0.020
This study	Reactor (7)		40-45	62	0.22	0.09	0.020
	Reactor (8)		37-41	62	0.16	0.06	0.009
	Reactor (9)		32-37	62	0.07	0.07	0.005
	3 Stage bench scale methanogenic reactor			62	0.45	0.07	0.034

Table 4-4 above shows the operating conditions and methane production achieved in previous studies and the present study. Reactor 7 has equivalent gas production to typical anaerobic dairy pond. Reactor 8 had comparable volumetric CH_4 production with the anaerobic filter (polyester matting) (Vartak et al., 1997) despite it having much shorter hydraulic residence times. The highest volumetric CH_4 production of all the studies was 2.8 m^3CH_4/m3reactor /day (Hernandez & Rodriguez, 1992), although, the temperature range was not specified for that study and an assumption is made that it may be in the mesophilic temperature range. Lo and Liao (1986) reported that the volumetric CH_4 in the CSTR and fixed film reactors as 0.18 m^3CH_4/m^3reactor/day and 0.3 m^3CH_4/m^3reactor/day which can be recorded as high volumetric CH_4 production. This may be attributable to the significantly higher organic loading rates that were used in those studies: 2.9 and 28.7 kg VS/m3/day respectively in comparison of 0.45 kg VS/m3/day used in this study. The fixed film reactors of Lo and Liao had a very short HRT (1 day) and a very low specific methane yield (0.01 m3/kgVSadded) compared with that of Safely and Westerman (1992b) who had a 67 day HRT and a high 0.322

m3/kgVSadded specific methane yield. The specific methane yields achieved in reactors 7, 8 and 9 in this study appear be similar to or slightly lower than those reported in the literature with the exception of Safely and Westerman (1992a) and Hernandez & Rodriguez (1992). The total volumetric production of CH_4 of 0.034 m^3CH_4/m^3reactor/day from the three stage coupled mesophilic reactor reported in this study is similar or higher than those reported in the literature with the exception of Hernandez & Rodriguez (1992) and Safely and Westerman (1992b).

From the bio-digestion experiment a total volumetric CH_4 production of 0.034 m^3CH_4/m^3reactor/day was produced from the three stage mesophilic reactor in similar notes to the volumetric methane yield by different researchers as in the literature.

Based on the assumption for producing methane generator efficiency for electricity is about 33% and boiler efficiency for heat generation is about 40% and energy value of 1 kg methane to be 14.31 kWh, 1kg of methane can produce 4.66 kWh electricity and 5.72 kWh of heat, a typical farm of 250 cows would produce 548 kWh/day electricity and 665 kWh/day heat from using methane from the digesters using dairy shed effluent. A typical 250 cow farm consumes 1285 kWh/day total energy 40% is from heat and rest is electricity (Rockhill Farms limited , Huntly). So by having installed plug-flow anaerobic digesters it could potentially meet 130% of total energy needs and 113% of total energy needs by using a three stage mesophilic digester (Appendix 13).

5 Life cycle assessment (LCA) for Dairy farm

This chapter presents a description of terminology used for the LCA of the dairy farm, general NZ conventional farm description and various resource and operational inputs for the dairy farm. A methodology for the LCA analysis is derived by defining goal and scope and system boundaries. GHG emissions are estimated for the inputs methane emissions and nitrous emissions based on per-hectare of farm and per-ton of milk solids. Economic and mass allocations are given to edible and non-edible by products of a dairy cow and a cost analysis for having installed energy recovery by different digesters is included in the sections of this chapter.

Terminology used for LCA

Life cycle assessment (LCA) is a technique to assess environmental impacts based on economic and mass balance associated with all the stages of a product's life from cradle to grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use) (*ISO 14040* et al., 2010).

Carbon footprint: is the total amount of greenhouse gas (GHG) emissions associated with a product, along its supply-chain, and sometimes includes emissions from consumption, end-of-life recovery and disposal. It is usually expressed in kilograms or tons of carbon dioxide equivalent (CO_2-eq.) (GHG Emissions from Dairy Sector FAO, 2010).

CO_2-equivalent emission: is the amount of CO_2 emissions that would cause the same time- integrated radiative forcing, over a given time horizon, as an emitted amount of a long-lived GHG or a mixture of GHGs. The CO_2 equivalent emission is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) for the given time horizon (GHG Emissions from Dairy Sector, FAO 2010). The CO_2 equivalent emission is a standard and useful metric for comparing emissions of different GHGs, but does not imply the same climate change responses (IPCC, 4 AR 2007).

Dairy herd: for the purposes of this assessment includes milking animals, replacement stock and surplus calves that are fattened for meat production (GHG Emissions from Dairy Sector, FAO 2010).

Geographic information system: is a computerized system organizing data sets through the geographical referencing of all data included in its collections (GHG Emissions from Dairy Sector, FAO 2010).

Mixed farming systems: are those systems in which more than 10% of the dry matter fed to livestock comes from crop by-products and/or stubble or more than 10% of the value of production comes from non-livestock farming activities (Seré and Steinfeld, 1996).

Milking cows: are defined as all females at reproductive age, comprising both specialized and non-specialized dairy animals actually milked during the year (GHG Emissions from Dairy Sector, FAO (2010).

Capital cost assessment are fixed, one-time expenses incurred on the purchase, building, construction, materials, equipment, labor used in the production of products or rendering of services. It is the total cost needed to bring a project to a commercially operable status.

5.1 Introduction

Life Cycle Assessment (LCA) is a key tool for evaluating the resource inputs and environmental emissions throughout the life cycle of a product so that the most effective options for improvement defined (Ledgard et al., 2012). Life Cycle Assessment (LCA; Guinée et al., 2002) is a key tool for evaluating whole-system environmental efficiency. This starts from the extraction of raw materials and includes all aspects of processing and transportation.

Proponents of biogas argue that the CO_2-neutral nature of fuels produced from energy crops and manure mean minimal negative impact on the environment, but others claim that this benefit is not always as significant as expected (Jury & Benetto et al., 2009), questioning the sustainability of these bioenergy pathways, (Cherubini et al., 2010, Petrou et al., 2009, Sheenan et al., 2009) because the conversion of biomass to

bioenergy has input and output flows that may affect its overall environmental performance (Cherubini et al., 2011). To obtain a concrete analysis of the sustainability of bioenergy chains, researchers have increasingly made use of LCA to capture complexity and inter-dependencies, providing a comprehensive and objective picture of the situation (Blengini et al., 2011).

Though LCA of bioenergy chains can be useful for evaluating the whole system from "cradle to grave", as observed by Cherubini and Strømman (Cherubini et al., 2011) and by Muench and Guenther (Muenchet al., 2013), there is the risk that methodological assumptions might distort the results or render comparisons nearly impossible. Moreover, many LCAs do not fulfill the ISO 14040-14044 guidance required (Muenchet al., 2013). There are uncertainties linked to the data used to account for the environmental impacts associated the inputs and output for the system (normally from commercial databases), the approach used to model those impacts and the assumptions that underlie them (Battiniet al., 2014).

Studies in the literature researched bioenergy production and its environmental sustainability, using the LCA methodology, define the parameters for evaluating the inventories of the agricultural activity, energy production, transport and management of residuals, apply these parameters to specific case studies and compare energy production from renewable systems with that from conventional ones (Blengini et al., 2011).

Polsch et al. (2010, 2012) conducted an attributional LCA of multiple biogas production and utilization pathways against specific base scenarios and reported that to minimize the environmental damage associated with feedstock type in all impact categories considered and simultaneously maintain a positive energy balance, co-digestion of residues from agriculture (cattle manure and straw) and the food industry residues with municipal solid waste (MSW) is most appropriate for both small and large-scale biogas plants and co-digestion reduced the climate change impacts by almost 30%.

Jury et al (2009) from their attributional LCA study compared the climate change impact of biomethane production and injection into the grid against natural gas importation and reported that the lower impact of the biomethane system depended

mainly on the biogas yield, the amount of readily available nitrogen in the digestate and the type of agricultural practices.

Research from these studies indicates that the LCA methodology must carefully consider all life cycle steps and subsystems in evaluating the environmental sustainability of bioenergy chains. Blengini et al. (2011) reported that there is no single dominating item or aspect, but rather, several of them play an important role in the overall sustainability Polsch et al. (2010) highlight that selection of feedstock resources and biogas conversion and that the utilization methods are crucial for sustainable biogas production.

5.2 Methodology

5.2.1 Goal and scope of research

The purpose of this study is to quantify the main sources of GHG emissions from the New Zealand dairy farm sector, and to assess the products to total emissions from the dairy sector.

This involves estimating the GHG emissions for:

- Major dairy cattle products and related services;
- Dairy production systems in New Zealand;

LCA assessment was done using calculation methods, modeling approaches, data and parameters for each production system within the dairy sector with reference to farm level or national level emissions. This assessment follows the attributional approach, which estimates the environmental impacts under current conditions and allocates impacts to the various co-products of the production system. This is in contrast to the consequential LCA approach, which considers potential consequences of changes in production technologies, and relies on a system expansion analysis to allocate impacts of co-products (Thomassen et al., 2008b).

LCA assessment methodology was developed based on the following documents:

- Environmental management – Life Cycle Assessment- Requirements and guidelines - BS EN ISO 14044 (ISO, 2006).

- British Standards Institute PAS2050; 2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services (BSI, 2008).

5.2.2 Functional unit

Dairy-cattle production systems produce a mix of goods and services:

- Edible products: meat and milk.
- Non-edible products and services: meals, leather (hide), manure, urea, waste.

In this assessment, the functional units used to report GHG emissions are kg of carbon dioxide equivalents (CO_2–eq.) per ton of milk solids and carcass weight at the farm gate.

5.2.3 System boundary

The assessment encompasses the entire production chain from feed production through to the final processing of milk and meat, analysis of operation inputs and their impacts, analysis of outputs of main products and by-products and impacts based on mass and economic basis.

The study covers the life cycle of the dairy cattle farm from “cradle to grave”, which can be divided into the following parts:

Cradle to farm-gate: includes all processes in livestock production up to the point where the animals or products leave the farm, i.e. production of farm inputs, and dairy farming, investigating impacts of operation feed inputs for production. The system boundary for cradle to farm-gate is presented in Figure 5-1.

Carbon dioxide emissions from resource use:

- Direct energy sources. All types of fuel used on farm, diesel used by contractors and in transportation, and electricity used by the farm.
- Electricity including the energy inputs to deliver resources to the farm.
- Fertilizers, agrichemicals and purchased feed including manufacture and delivery

- Limestone quarrying and processing, and carbon emissions from the reaction with the soil.

Methane and nitrous oxide emissions from:

- Resource inputs
- Methane emissions from ruminant animals
- Nitrous oxide emissions from direct and indirect inputs of synthetic fertilizer, direct and indirect emissions from animal excreta and effluent, and indirect emissions from leaching.

Farm-gate to grave: includes the analysis of impacts based on economic and mass basis of the products from the livestock production. The system boundary for farm-gate to grave is presented in Figure 5-1 below.

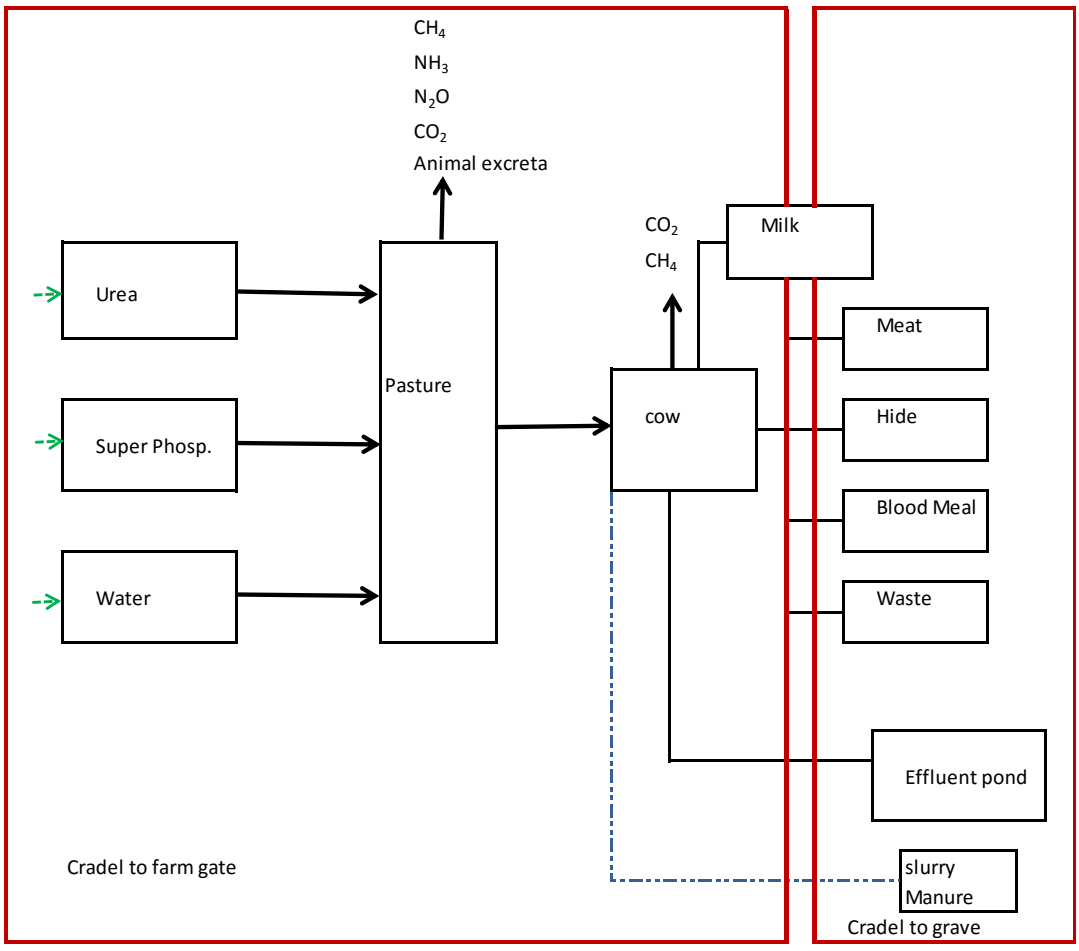

Figure 5-1: System boundary as defined for this assessment

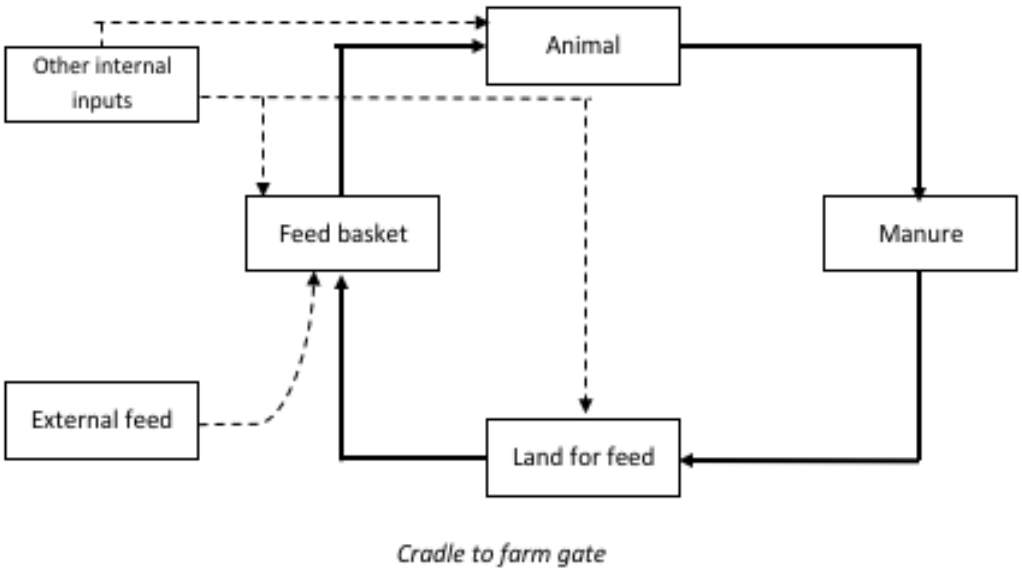

Figure 5-2: Livestock production systems (Adapted from Greenhouse gas Emissions from Dairy Sector – A lifecycle assessment FAO, 2010).

To calculate greenhouse gas emissions, a simplified description of livestock production systems, derived from Oenema et al. (2005); Schils et al. (2007a); and Del Prado and Scholefield (2008), was developed (Figure 5-2).

- "Land for feed" is the land used for feed production, on the farm itself or nearby (with negligible emissions related to the transport of feed to the animal rearing site).
- "External feed" originates from off-site production. It includes by-products from the food industry and feed crops produced and transported over longer distances. In most situations, the external feed is concentrate feed.
- "Manure" is shown partly outside the 'cradle-to-farm gate' system boundary, to illustrate situations where manure is used as a fertilizer for food crops, either on- or off- farm, or where manure is used as fuel.
- "Other external inputs" refers to the inputs into production such as energy, fertilizer, pesticides, etc.

The following emission sources of major greenhouse gas are included:

Cradle to farm gate (GHG Emissions from Dairy Sector, FAO, 2010):

- Processes for producing products grass, feed crops, crop residues, by using products, and concentrates, including: nitrogen fertilizer; operating inputs; application of FDE, manure, chemical fertilizers and supplements; direct and indirect emissions (N_2O); Nitrogen losses due to leaching;
- Enteric fermentation by ruminants (CH_4).
- Direct and indirect emissions from manure storage (CH_4 and N_2O).

Farm gate to grave

- Production and processing of edible products: meat and milk.
- Production and processing of non-edible products and services: meals, leather(hide), manure, urea, waste and capital.
- By products such as urea, manure.

5.2.4 Allocation of emissions

Dairy cows produce different products and by products in their lifetime which include milk, meat, hide, manure, blood meals. In LCA specific techniques are used to allocate GHG emissions to each of these goods and services. The ISO recommends avoiding allocation by dividing the main process into sub-processes, or by expanding the product system to include additional functions related to the co-products (ISO, 2006).

5.2.4.1 Milk and meat

In NZ dairy farms cows contribute to production of dairy products and meat (milked cows, reproduction bulls and replacement stock) or are only used to producing meat (fattened calves). For this research, GHG emission are allocated based on total milk solids. Emissions related to the production of calves, are allocated to milk. Emissions are allocated to the other parts of the slaughtered animal such as hide, bloodmeal, wastes as these are utilized and represent an economic yield.

5.2.4.2 Manure

Manure is a by-product of milk production and the emissions related to manure are allocated as follows:

- Emissions related to manure storage (FDE ponds, slurry, solid manure) are attributed to the farm livestock system.
- Emissions from manure applied by irrigation or nutrient supplement on the farm land used for feed.
- Emissions from manure discharged into the environment. Emissions are solely attributed to livestock activities. The discharge causes environmental impacts such as NH_3 volatilization, nitrate leaching, surface water pollution by direct discharge and runoff.

5.2.4.3 Emissions related to operational inputs

Emissions from operational inputs mostly come from the use of energy, whether electricity or fossil fuels, water, labour. Energy consumption in dairy farms was acquired by literature review and average energy consumption for products was calculated. Data on GHG emissions from electricity and other sources of energy, were sourced from (MfE 2014).

Table 5-1: Summary of the allocation techniques used in this study

Products	Source of emissions	Allocation technique
Milk	All system related emissions	Total milk solids (ton MS)
Meat	All system related emissions	Protein content, carcass weight
Manure	Emissions from storage	Livestock system, storage method
	Emissions from application	when crop or crop residue is used for feed in the livestock system
Grass and feed crops	Emissions related to cultivation and application of manure and chemical fertilizer	Livestock system
Crop residues, by- products and concentrate components	Emissions related to cultivation, application of manure and chemical fertilizer, processing, transport, land use change	Economic allocation
Capital functions such as hide, meals, wastes		Economic allocation

5.2.4.4 Economic allocation

Many studies use economic allocation of impacts including Thomassen et al., (2008) where they used 90% and 91% allocation to milk for organic and conventional farms respectively; and Cederberg and Flysjö (2004) used 90% allocation to milk.

In this study, economic allocation been used and it has been averaged at 80% for conventionally produced milk (Table 5-8).

5.2.5 Assumptions

A number of assumptions are made considering the complex and varied interactions within livestock production systems. The main assumptions and methodological choices made in this study are summarized below:

- The farming of dairy is simplified to a model consisting of three modules: (i) feed production (within or external to the farming system being assessed), (ii) animal feeding and performance, and (iii) manure management.
- The herd model assumes a constant total herd count (no herd dynamics e.g. calving, bobby calves, cull cows or attrition, are considered).

Table 5-2: Overview of data sourced for the life cycle assessment

Data groups	Data collection approach and resources
Herd (animal parameters)	Literature review and reports, Dairy NZ (2014)
Manure management	Literature review and reports, Dairy NZ (2014), Craggs et al.,2006 , AgResearch (2011)
Feed information	Literature review and reports, Dairy NZ (2014)
Milk production	Literature review and reports, DCANZ (2015), Dairy NZ (2014)
Non edible products	Literature review and reports
Carbon footprints, LCA	Literature review and reports, Ledgard et al 2012, Craggs et al., 2014
LCA of local and imported fertilizers used on NZ farms	Literature review and reports, Ledgard et al.,2011

5.2.6 Farm research data

Data was collected for producing a resource use inventory based on farm main products and milk solids. This is discussed in the following sections:

5.2.6.1 Fertilizers, agrichemicals

Literature review and data has been used to develop fertilizer use in their different nutrient components for the conventional farm use. Table 5-3 shows the average energy costs of manufacturing each nutrient component based on Ledgard and Boyes (2008) and Wells (2001). These are average figures taken from a range of different fertilizer production methods. Urea is the predominant form of nitrogen and has been

used as the basis for all nitrogen applications in this study. New Zealand specific LCA of local and imported fertilizer study by Ledgard and Boyes (2011) reported GHG emissions from various fertilizers covering the cradle to NZ port stage using data from a detailed LCI database and NZ fertilizer companies. GHG emissions used in this study are shown in the Table 5-3.

Table 5-3: Energy Requirements to Manufacture Fertilizer Components

Component	Energy use (MJ/kg)	GHG($kgCO_2e$/kg)
N (urea-N)[1]	51	4.02[a]
P[1]	39	3.18
K[1]	10	0.74
S[2]	5	0.32
Mg[2]	5	0.32
Lime stone[1]	0.6	0.43

[1]Ledgard and Boyes (2008), [2] Wells (2001), [a] includes manufacture and field emissions of once applied to the soil.

5.2.6.2 Feed and purchased feed

Purchased feed included hay, silage, barley and straw the resource cost and GHG emissions of this purchased feed are acquired from literature review and data collected which is shown in Table 5-4 below. In addition to the purchased feed, replacement and winter grazing stock are often grazed off the farms. Accounting for this, the resource inputs and GHG emission is about 640 $kgCO_2e$/ha for NZ conventional farms (Barber et al.,2010).

Table 5-4: Purchased Feed – Energy and GHG Emissions (Adapted from Barber et al., 2010)

Feed	Energy (MJ/tDM)	GHG($kgCO_2e$/MJ)	GHG ($kgCO_2e$/t DM)
Grain (barley)	3350	0.070	235
Silage	1695	0.102	170
Hay	1640	0.102	170

5.2.7 Greenhouse gas emissions – animal and field emissions

Methane (CH_4) emissions from dairy farm are mainly from enteric fermentation and CH_4 is exhaled or belched by the animal. Anaerobic decomposition of manure produces methane which accounts for less than 2% of total methane emissions. NH_3 volatilization, nitrate leaching and nitrous oxide (N_2O) emissions occur from both direct and indirect sources. For this study to estimate N_2O emissions direct sources included emissions from soil by application of nitrogen fertilizer and other synthetic fertilizers, FDE irrigation, animal manure excreted while grazing and indirect sources included N_2O emissions from NH_3 volatilized and nitrate leaching, nitrogen content of soil and excreta. Atmospheric reduction of ammonia (NH_3) and oxides of nitrogen (NO_X) are included in indirect sources.

Animal and field emissions like methane emissions, direct and indirect N_2O emissions are from various literature reports (Craggs , Heubeck , Pratt (2015); Hawke & Summers (2006); Barber et al., 2010).

Specific data is presented in the Results and Discussion in Table 5-7 in the on-farm GHG emissions impact analysis.

5.3 Results and Discussion

5.3.1 Life cycle inventory

5.3.1.1 Farm description

Table 5-5 below represents the average farm area and farm production intensity for conventional NZ farm. Literature values of the total affective area, average number of cows per farm, stocking rate and milk solids production are obtained from New Zealand Dairy Statistics (Dairy NZ, 2014). Literature values for main milking platform was obtained from GHG assessment for Lincoln university dairy farm report (2006) and also from GHG emissions report (2010). From the literature values a comparison of average conventional dairy farm is carried out to get the present values for this study.

Table 5-5: Summary of NZ conventional farm description

Average NZ conventional farm area (ha)			
Total affective area	Main milking platform	Run-off	Grazing-off
141	118	23	26
Average NZ conventional farm production intensity			
Number of cows milked per farm	Stocking rate cows/ha	Production of milk solids	
		kgMS/ha	kgMS/cow
402	2.81	1160	413

5.3.1.2 Farm resource inputs and impact assessment

Farm resource inputs include direct energy such as fuel and electricity, fertilizer, agrichemicals and purchased feed and other consumables are tabulated as the inventory of resource inputs as well as their impacts for the whole farm in Table 5-6. These values are based on the literature values from the GHG assessment for Lincoln university dairy farm report (2006) and also from the GHG emissions report of Organic and Conventional NZ dairy farms (2010) farm resource inputs. The emissions are tabulated for GHG emissions per hectare and also GHG emissions per ton of milk solids.

Key resources having the largest impact for this analysis are electricity (0.47 $kgCO_2e$/ha); nitrogen fertilizers (0.25 $kgCO_2e$/ha); nutrients such as ammonia and urea (use and production) 0.057 $kgCO_2e$/ha, phosphorus (0.08 $kgCO_2e$/ha); and feed (1.16 $kgCO_2e$/ha). GHG emissions per unit of production of milk solids were 12,163 kgCO2e/tMS for conventional farm systems. Methane emissions including emissions from enteric fermentation and at farm gate (deposition of excreta and manure, FDE storage and land application) were 7440 kgCO2e/tMS and are the largest contributor for the GHG emissions. Nitrous oxide emissions (both direct and indirect emissions) accounted to 3165 kgCO2e/tMS which were the second largest contributor for total GHG emissions. Fertiliser and agro chemical use had emissions of 794 kgCO2e/tMS

and direct energy 765 kgCO2e/tMS at farms also contributed significantly to the GHG emissions.

From LCA analysis of NZ dairy farming the emissions per-ton of milksolids (MS) and kg of meat, are mostly affected by digestibility, milk yield per cow and manure management. In NZ due to extensive farming practices higher enteric methane emissions are observed per ton of milk solids comparatively to intensive farming systems. In contrast, the fraction of methane coming from manure storage is relatively high 15 to 20 percent, compared to less than 5 percent in the extensive systems (NZ dairy farming scenario). So study from literature review suggests improving of feed digestibility for extensive farming systems would achieve significant reductions in methane emissions per ton of milksolids, through a direct reduction of emissions and through the improvement of milk yields (Kristjanson and Zerbini, 1999). Anaerobic digestion of manure to produce biogas and manure management has significant potential to reduce methane emissions.

Methane emissions are most significant contributor to total greenhouse gas emissions at 61% of total farm GHG emissions on a per-hectare and per-ton of milk solids basis (Figure 5-3 and Figure 5-5). It should be noted that GHG emissions due to methane have been converted to CO_2 equivalent by multiplying methane emissions by a factor of 21 (IPCC – Intergovernmental Panel on Climate Change, 2007). Therefore, reducing methane emissions to reduce overall greenhouse gas emissions is worthwhile for more sustainable dairy farming with lower environmental impacts. From this study (Figure 5-9) 46.1% of CH_4 emission from the FDE ponds can be captured and 1.1% of N_2O emissions from the FDE ponds can be minimized.

Potential mitigation measures of reducing CH_4 emissions is by covering the FDE ponds, treatment of CH_4 accumulated under the cover by biofilters (Pratt et al. 2013), or it can be combusted, either with or without energy recovery (Heubeck & Craggs 2010). (Energy Efficiency and Conservation Authority dairy-farm biogas feasibility studies). Another potential mitigation solution is to irrigate the FDE on a daily regular basis instead of differed irrigation (Craggs and Chung et al., 2015).

Table 5-6: Total GHG emission for conventional farm

Resource Inputs	Unit	Conventional (Quantity / ha)	In Farm Conventional ($kgCO_2e$/ha)	In Farm Conventional ($kgCO_2e/CH_4$ kg)
Direct Energy				
Diesel	litres	36.7	98.4	0.06
Petrol	litres	12.8	30.1	0.02
Oil	litres	0.5	0	0.00
Contractors	litres	6.4	0	0.00
Electricity	kWh	778	759.6	0.47
Digester equip	kWh	323	315.4	0.20
Consumables				
Nitrogen	kg	99	397	0.25
Phosphorus	kg	41	131	0.08
Potassium	kg	50	37	0.02
Sulphur	kg	46	14	0.01
Magnesium	kg	12	4	0.00
Compost	kg	0	0	0.00
Lime	kg	400	173	0.11
Transport of Lime	kg		1.5	0.0009
Ammonia & Urea production	kg	57	53.6	0.0332
Transport of Urea to NZ	kg	41	38.8	0.0240
Agrichemicals	litres	1	12	0.01
Minerals	kg	5		
Production of Minerals		5	4	0.00237
Local transport of Minerals		5	0	0.00015
Shipping of Minerals		5	1	0.00064
Purchased feed	kg DM	158	153	0.09
Grazing-off	ha off	0		
water	litres	81760	14	0.0088
Dry matter	kg	15000	1876	1.16
Animal and Field Emissions				
Methane		7965	8634	5.35
Nitrous Oxide – excreta & effluent direct		2008	2177	1.35
Nitrous Oxide – excreta & effluent indirect		774	839	0.52
Nitrous Oxide – N fert direct & indirect		606	657	0.41
Nitrous Oxide – compost direct		0	0	0.00
Total		**110194**	**16420**	**10**

Water Heating 24%
Refrigeration 17%
Milk pump 3%
Vaccum pump 15%
Water pumping 22%
Effluent pumping 9%
Lighting 2%
Other 8%

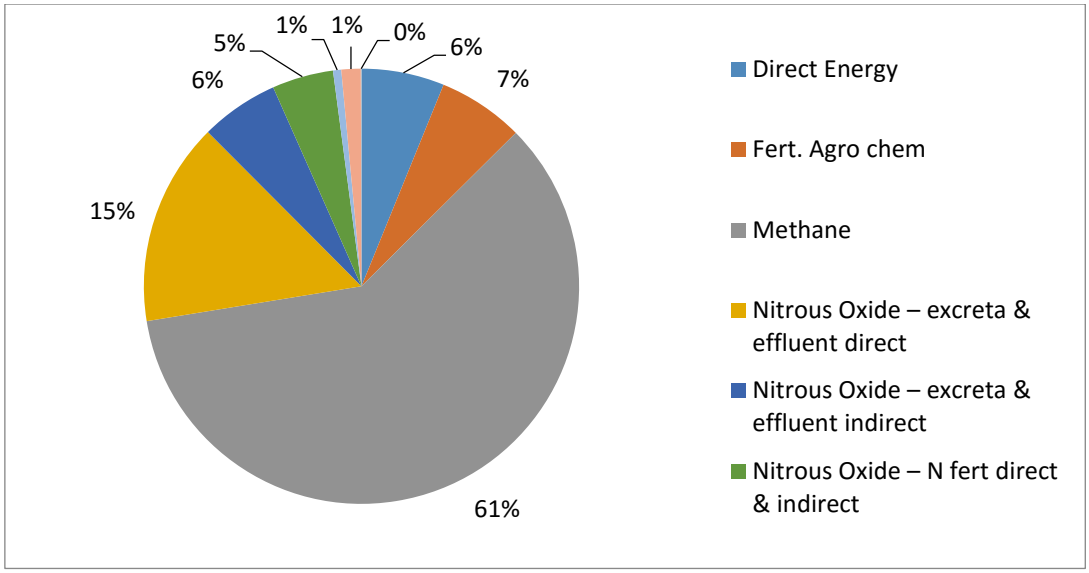

Figure 5-3: GHG emission profile for conventional farm

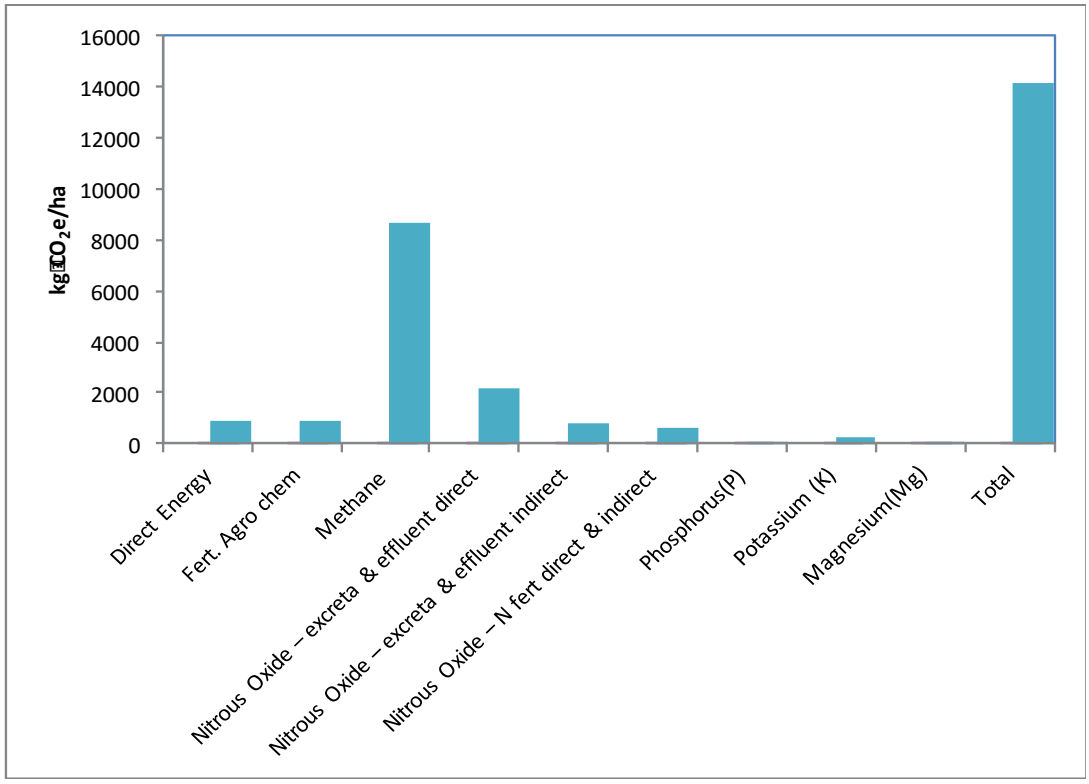

Figure 5-4: GHG emission per hectare of conventional farm

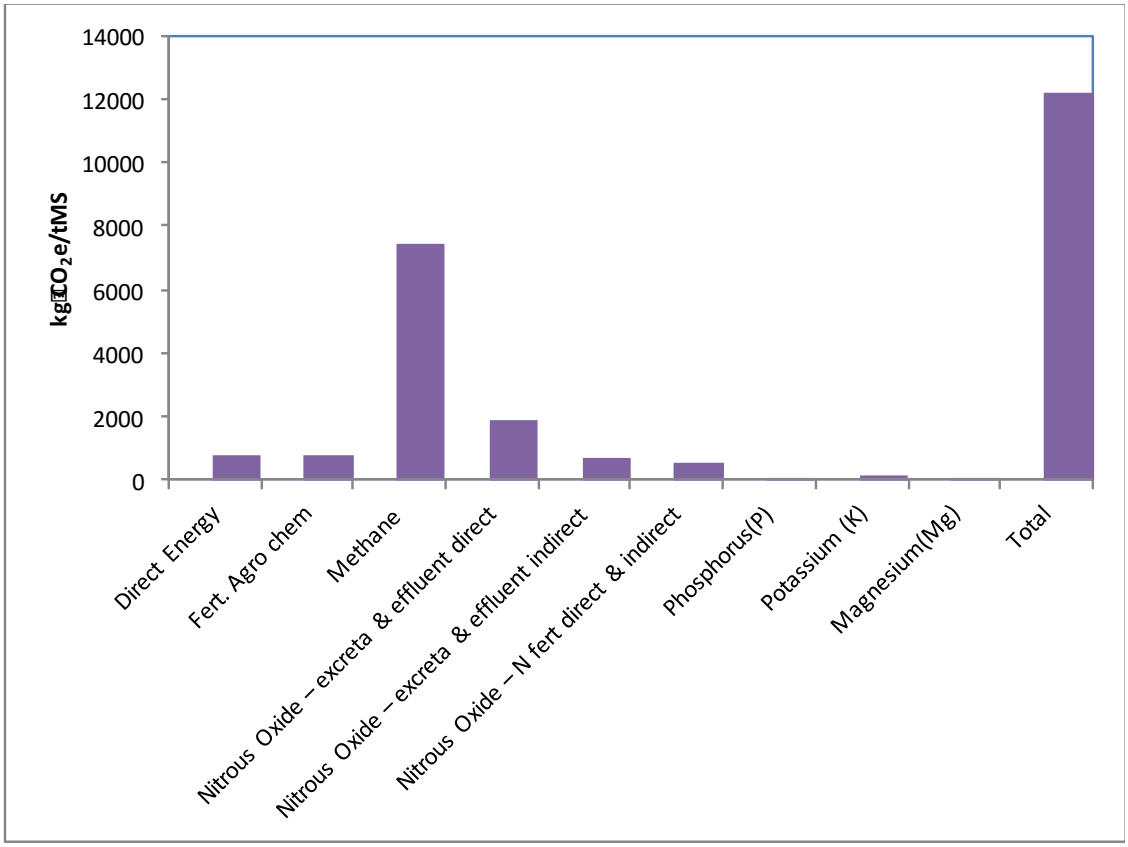

Figure 5-5: GHG Emission per ton of milk solids

5.3.2 Economic and mass allocation

Economic allocation has been given for edible products which are meat and milk and non-edible products and services which include meals, leather (hide), manure, urea, waste and capital. Literature value for the economic allocation of edible and non-edible products are sourced from various reports (Anderson & Ridler (2010) ; Optimizing resource allocation MAF,2007; Barber et al., 2010). Based on the literature values and the assumption such as average life time of dairy cow with average weight of 450kg to be 4.8 years (2.5 lactations) and economic value of $4.6/kgMS (MS-milk solids), the data for the present study was tabulated and presented in Table 5-8. Figure 5-6 shows the economic allocation percentage profile for various products and Figure 5-7 shows the economic allocation values for the products.

Table 5-7: Economic allocation per dairy cow (over life time and after slaughter) include $ percentage in table

Output	Unit	Weight	%wt	Value($)	%($)
Milk/Milk solids kgMS/cow/LT	kgMS	1764	80%	8114.4	82
Meat	kg	284	13%	1395	14
Hide	kg	31	1%	157.5	2
Tallow	kg	15.8	1%	78.75	1
Blood/Inedible raw matter	kg	67.2	3%	2.36	0
Paunch/Manure	kg	36	2%	180	2
Losses	kg	16	1%	0	0

Of the total GHG emissions for a dairy farm allocated on an economic basis, 82% can be allocated to milk products, 14% to meat products and the remainder to the byproducts such as hide, tallow, blood, and offal. This is very similar to a mass basis, therefore allocating impacts on the basis of economic value will show little difference. However, this will depend on the type of farm and its main products, for example for a cattle farm, the majority of impact should be allocated to the meat products.

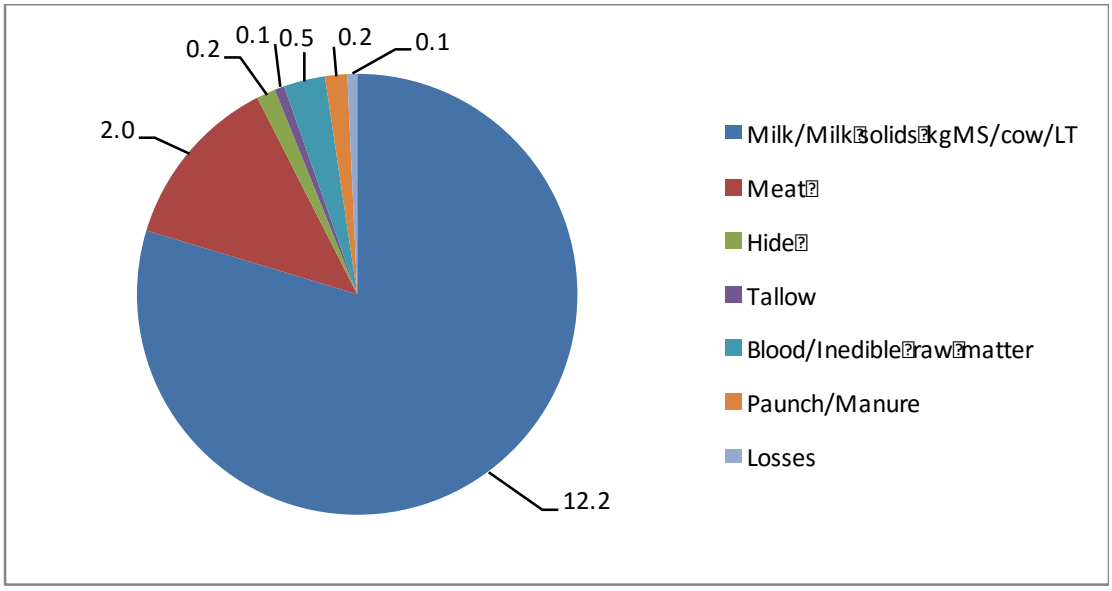

Figure 5-6: GHG emissions per kg of product

From the GHG emissions allocation per kg of product of the dairy farm, 80% is allocated to milk products, 13% for meat and the remainder to the byproducts. This is again similar to allocations based on economic and mass basis.

5.3.3 GHG emissions from FDE collection and storage

From literature review total greenhouse gas (GHG) emissions are noted as 81,104 $ktCO_2$ –e/year of which 49% is reported from agriculture sector. Of the total 49% of agriculture emissions 76% is accounted from dairy sector (MfE, 2014) which is 29,902 $ktCO_2$ –e/year. Figure 6-3 shows a comparison of GHG emissions in the current New Zealand scenario. According to the most recent inventory (MfE 2014), emissions from manure management account for nearly 2% of the emissions from the agricultural sector and from this study manure management (dairy shed effluent digestion and biogas capture) accounts for 1.8% of the emissions reduction which can be seen in the figure 6-3.

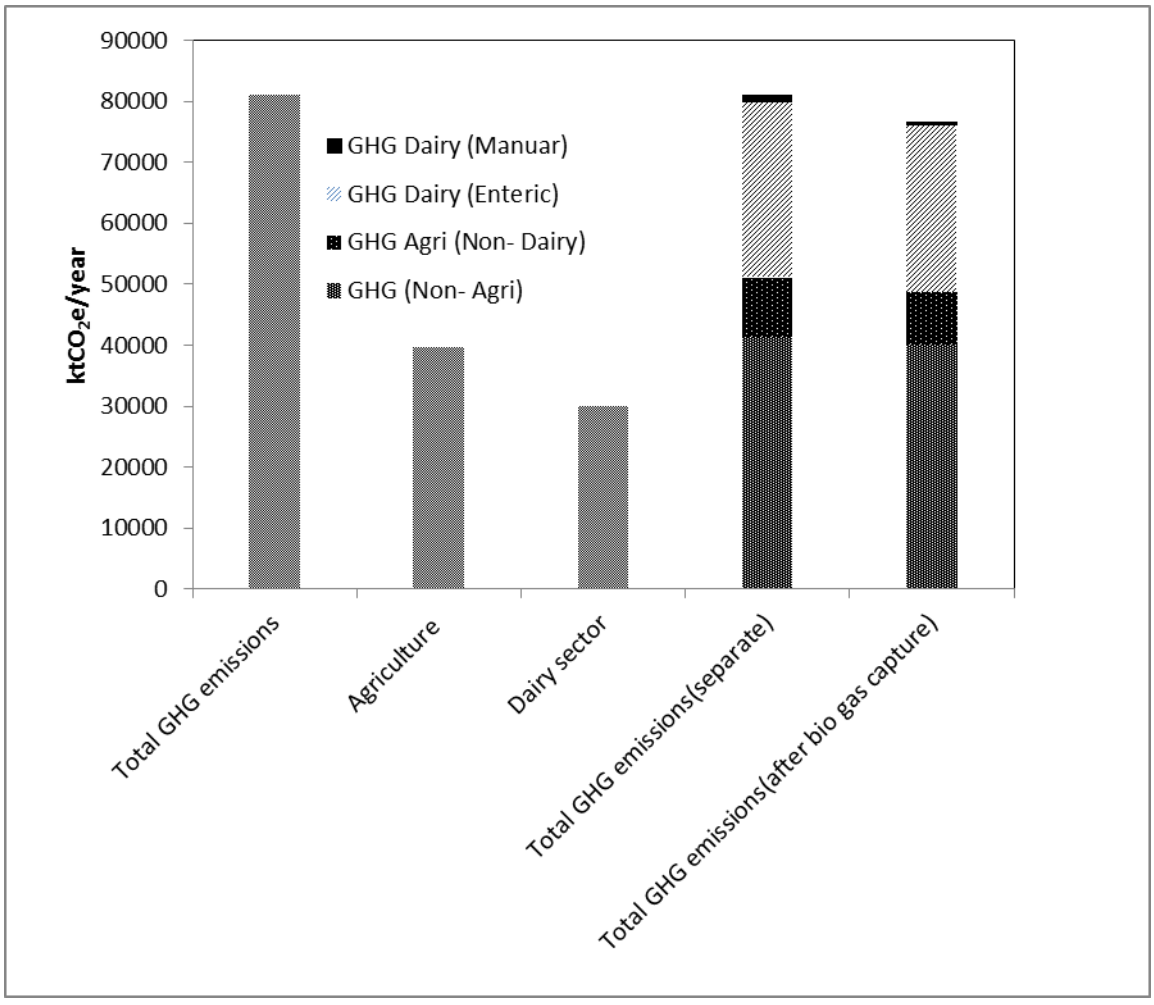

Figure 5-7: GHG emissions profile for New Zealand before and after capturing the total dairy manure.

But due to the increase in FDE collection, storage and application, it is necessary to look at the GHG emission estimates from FDE. The estimates of GHG of FDE are

expressed as CO_2-equivalents, based on conversion factors of 21 kg CO_2-e/kgCH_4 and 310 kg CO_2-e/kgN2O. Assuming that 6% of the excreta from New Zealand's lactating cow population is collected at the milking shed (Ledgard & Brier 2004) and subsequently kept in FDE ponds, CH_4 emissions from these ponds were estimated to be 579 Gg CO_2-e/year (Chung et al., 2013) with ±20% variation. The amount of N in ponds was then 2.94 × 107 kg N/year. Applying the emission factor of 0.001, the resulting N_2O emissions from ponds were 4.61 × 104 kg N_2O/year, equivalent to 14.3 Gg CO_2-e/year (MfE 2014). Also using literature values from MfE 2014, N_2O emissions from direct and indirect emissions of land irrigation is 143 Gg CO_2-e/year which equals to nearly 25% of CH_4 emissions from FDE ponds which can be accounted as N_2O emission as the second largest contributor to total GHG emissions from FDE. Similar emissions occur by any application of manure to land and so minimizing these emissions is not avoidable while the CH_4 emissions from FDE ponds are a consequence of storage practice and in principle avoidable (Craggs and Chung et al., 2015).

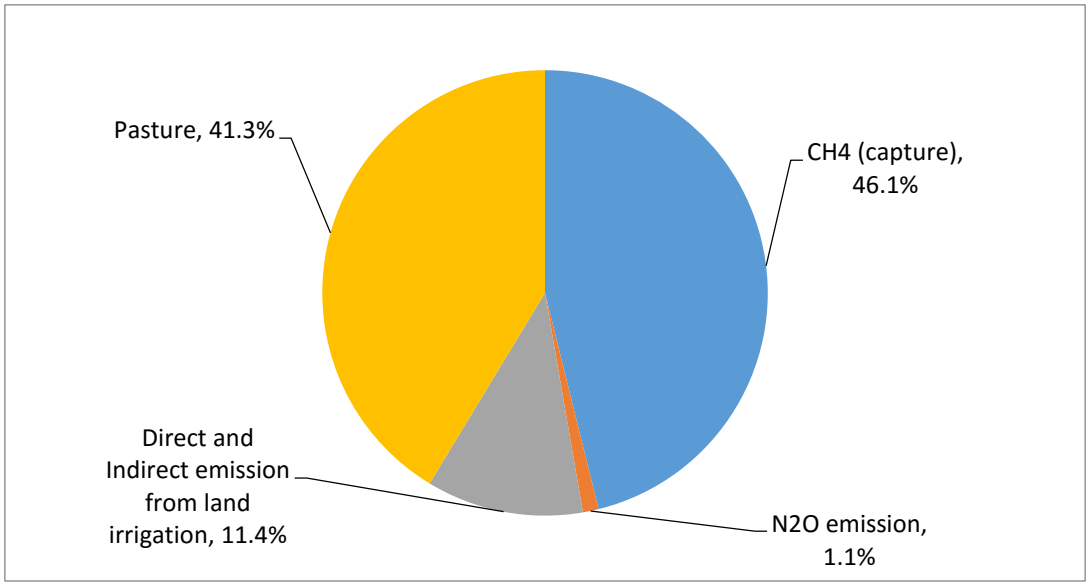

Figure 5-8: GHG emissions profile of dairy manure

5.3.4 Emissions from FDE application to land

N_2O emissions can be related to the readily available N content (i.e. ammonium-N content) of slurries and manures and the N_2O emission factors ranged from 0.01%–

1.2% (Chadwick et al. 2011). The proportion of total N in the available form for land applied cattle slurry from literature review was 45% ± 2%. This is similar to the available N proportion in FDE (47% ± 6% of total N;), calculated using available New Zealand data (Barton & Schipper 2001; Bhandral et al. 2007; Li, Shi, Luo & Zaman et al. 2014).

The application of FDE on to soils increases N_2O production in two ways: firstly by adding nitrogen (N) and available carbon (C) and secondly by increasing soil moisture thus enhancing anaerobic conditions within the soil (Barton & Schipper et al.,2001). Bhandral et al. (2007) found that water irrigation alone increased N_2O emission above the non-irrigated treatment by 0.014 kg N/ha in autumn and 0.029 kg N/ha in winter, and the application of untreated FDE increased N_2O emission above that of the water-only application by 0.24 kg N/ha in autumn and 0.052 kg N/ha in winter. Thus, Bhandral et al. (2007) illustrated that FDE irrigation increases N_2O emission by both increasing soil moisture and providing a source of C and N to the soil microbial communities.

Ammonia (NH_3) emissions ranged from 1%–3.1% of the total N applied as fresh FDE and 0.4%–2% of the total N applied as stored FDE. The observed difference in NH_3 emissions from fresh and stored FDE were attributed to the greater proportion of total N as NH_4^+ and higher pH of the fresh material (Li, Shi, Luo & Houlbrooke et al. 2014; Li, Shi, Luo & Zaman et al. 2014). NH_3 emissions were greater in the summer compared with spring and winter applications, suggesting the high temperatures decrease the solubility of NH_3 and lower soil moisture content in summer, produces a relatively high NH_4^+ concentration in the soil, leading to greater NH_3 volatilization (Li, Shi, Luo & Houlbrooke et al. 2014). The total nitrogen (TN) content of FDE ranged from 138–1200 mg N/L, while for slurries with a similar dry matter TN ranged from 1100–3900 mg N/L (Heubeck, Pratt, & Craggs et al., 2015).

Larger nitrogen leaching losses are observed when FDE is applied to wet soils due to reduced interactions between the soil and the FDE which reduces N retention within the soil (Cooke et al. 1979; Macgregor et al 1979; Di et al. 1998; Houlbrooke et al. 2008). Nitrate leaching losses of 31.4 and 31.1 kg N/ha occurred from ‘water-only’ irrigated plots and deferred FDE applications, respectively in comparison with the 36.7

kg N/ha found when non-deferred irrigation was used thus proving the importance of soil moisture conditions on leaching. New Zealand studies of leaching losses from FDE irrigation are most likely of order 1%–5% of applied N (Heubeck, Pratt, & Craggs et al., 2015).

Emissions from FDE application to pasture (expressed in CO_2 equivalent) are significantly smaller than those from the FDE ponds. Capturing emissions from FDE irrigation is more difficult to achieve than those from the ponds. FDE pond system is more feasible to capture the emissions as the area is considerably small in comparison and already controlled. Houlbrooke et al. (2004) concluded that because 80-98% of the nutrients applied as the FDE were trapped by the soil land treatment, a considerable reduction in the quantity of nutrients reaching freshwater bodies, land treatment could have considerable positive effects on improved water quality. Nitrous oxide leaching is minimal when soils are dry. Best practice for application of FDE is to avoid during periods of saturated soils to keep N leaching to a minimum.

5.3.4.1 General conclusions from LCA

Methane emissions from enteric fermentation, excreta, manure and FDE irrigation and storage ponds contribute to 60% of the total GHG emissions of a farm. Management of dairy shed effluent will only reduce GHG emissions by 1.8%. In addition, spray irrigation will impact on GHG emissions due increased moisture, C and N content, increasing N_2O emissions. Hence from an environmental sustainability point of view, collecting and digesting diary shed effluent will have little significant impact on overall GHG emissions. Therefore, collecting and digesting dairy effluent is only of value if it results in economic benefits for the farm. This aspect is discussed in the next section under cost analysis.

5.3.5 Cost analysis using desktop analysis for energy recovery for different digesters

For this research a desktop study has been done to analyze the optimum conditions for energy recovery with either a covered anaerobic pond, heated plug flow digester or a three stage continuous stirred heated bio-digester system. For each technology estimates are made of: the potential energy yield (as useable electricity and heat),

potential methane production (Farm Use Total and Total Potential electricity and heat generation), capital and operating costs, and the return on investment based on the payback period. Calculations and tables are shown in Appendix 1 and Appendix 9. In these calculations it was assumed that 1kg of methane can produce 4.66 kWh electricity and 5.72 kWh of heat (Rockhill farms, Huntly). SCENZ data was used to estimate equipment and capital costs using SCENZ (2004), and a Lang factor for equipment was 4; biogas plant and construction was 4.3; was used to calculate total capital investment. SCENZ data collected was from 2012, it was assumed there would be little change in cost due to inflation. The cost index for year 2004 as compared to year 2016 has increased by an average 2.2 % per year which is an average $100 per year for equipment, construction and main biogas plant installation items which contributes a 15-25% variation. Given that the cost estimation method using SCENZ has an error of plus or minus 30-50%, this was considered acceptable.

From the analysis, covered anaerobic ponds have higher capital costs (Appendix 1) and are not economic resulting in longer payback time (Figure 5-9). Reduced volume of wash down water would result in reduced size and cost for the pond (Appendix 9). The ratio of pond size to cost was approximately 1:3 which implies that reducing the volume of wash down water by 25% for the covered anaerobic pond option would reduce the cost by 75%. Covered anaerobic ponds are not a sustainable solution for the present NZ conventional farms (small [250-400 cows], medium [400-600 cows] and large [700->1000 cows]) because of the high operating cost and payback period. For a 250 cow dairy farm having an installed anaerobic pond digester (Figure 5-10).

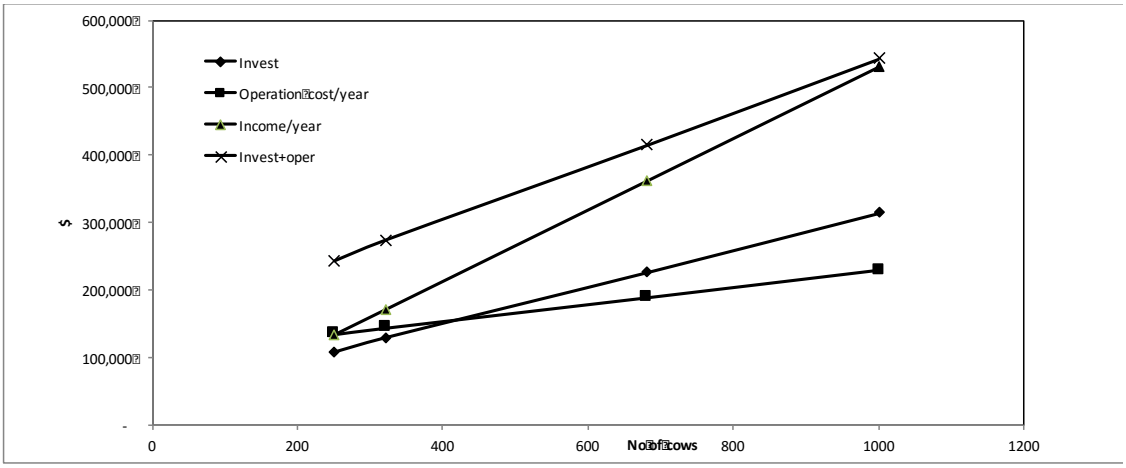

Figure 5-9: Cost analysis for anaerobic digester

Reducing the waste volume and having more solids content by using scrape system and replacing wash down system for the heated plug flow digester would lower the capital cost investment for larger farms (>600 cows). Heated plug flow digester systems are suitable and recommended for medium (400-600 cows) to large (>700 cows) conventional farms (Appendix 2).

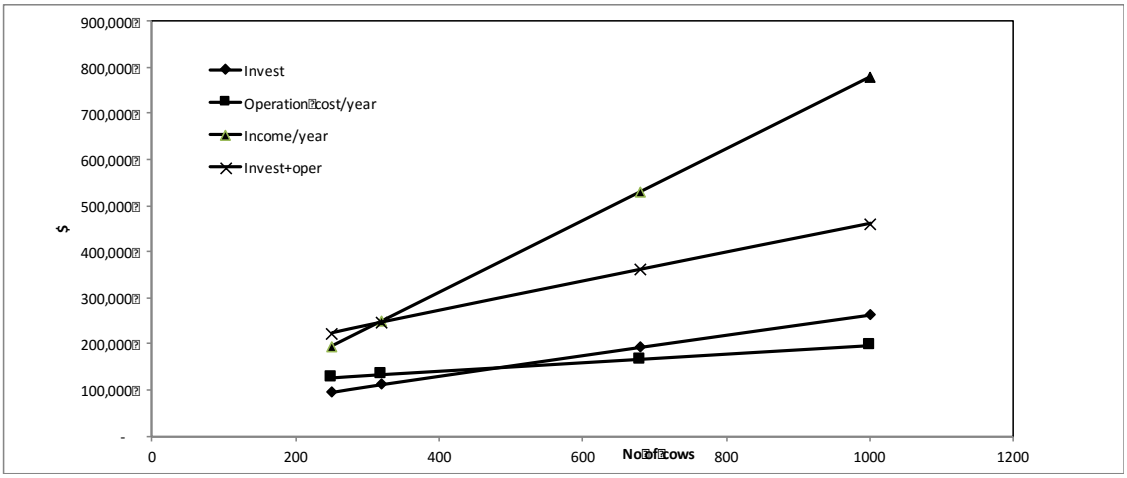

Figure 5-10: Cost analysis for plugflow reactor

From the data and the desktop study it is observed that by using the present system of plug-flow or three stage coupled methanogenic reactors, more biogas with higher methane gas volume could be produced (Appendix 2 and 10; Figure 5-10). This study recommends having multistage bio-digestion with optimum conditions (thermophilic and mesophilic) to generate more biogas in reduced time. From the experimental data and desktop analysis of having a three stage mesophilic batch digester higher volume of biogas and methane can be produced but the operational cost of the digester is more in comparison with the plug-flow digester for the same farm size. But if the energy generated could be used as integrated heat for the operation of the digester the operational cost would be reduced (Appendix 3-8 and 11; Figure 5-11).

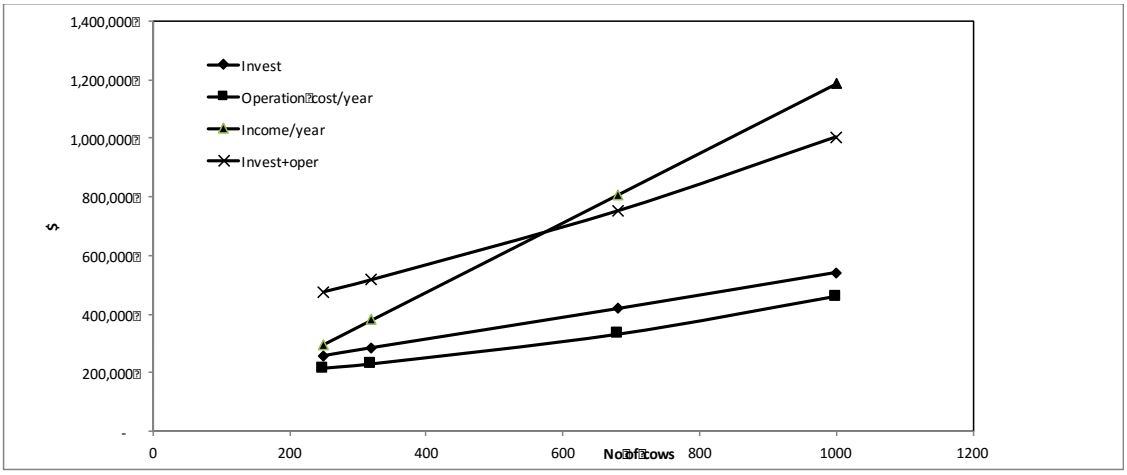

Figure 5-11: Cost analysis for three stage coupled mesophilic biodigester

This highlights an area that should be clarified by future research to whether the variations in gas production can be attributed to the operating parameters and the feasibility of maintaining the operating parameters within optimal range in the bio-digesters. Research suggests study of enhanced energy recovery in the thermophilic digester and integrated heat usage to maintain the higher temperature so operating costs could be reduced.

6 Conclusion

This study evaluated the economic feasibility and environmental impact of using a bio-digester to produce methane for energy production from a NZ conventional dairy farm.

Using locally supplied dairy shed effluent, it was found that 1 L reactors had peak gas production over 15 days, after which pH dropped and gas production dropped. Optimal pH was 7 and maximum gas production was 1.25L/L reactor.

A three stage digester was set up and run for 62 days, the first stage operating at 42-47oC followed by progressively cooler stages. This was fed every 15-20 days with 500 of fresh effluent into the first digester. Maximum gas production was from the first digester 21.3L in comparison with reactor 8 gas production of 11.7L and 6.6L production from reactor 9. Total volumetric methane production was 0.09 m^3/kgVS/day 0.06 m^3/kgVS/day and 0.07 m^3/kgVS/day respectively from reactors 7, 8 and 9. Gas composition was typically 17% CH_4 and 3% CO_2 in reactor 7, 15% CH_4 and 4% CO_2 in reactor 8 and 13% CH_4 and 5% CO_2 in reactor 9 (the remainder being nitrogen gas). But considering just biogas the reactors produced an average of 74 % CH_4 and 25% CO_2 .A typical digestor would produce 65-70% CH_4.

Based on the assumption for producing methane, generator efficiency for electricity is about 33% and boiler efficiency for heat generation is about 40% and energy value of 1 kg methane to be 14.31 kWh, 1kg of methane produces 4.66 kWh electricity and 5.72 kWh of heat, a typical farm of 250 cows would produce 548 kWh/day electricity and 665 kWh/day heat from using methane from the anaerobic digesters using dairy shed effluent. A typical 250 cow farm consumes 1285 kWh/day total energy 40% is from heat and rest is electricity (Rockhill Farms limited, Huntly). So by having installed plug-flow anaerobic digesters it could potentially meet 130% of total energy needs and 113% of total energy needs by using a three stage mesophilic digester (Appendix 13).

A life cycle assessment was carried out for a typical NZ farm. Methane emissions from enteric fermentation, excreta, manure and FDE irrigation and storage ponds contribute to 60% of the total GHG emissions of a farm. Management of dairy shed effluent will only reduce GHG emissions by 1.8%. In addition, spray irrigation will

impact on GHG emissions due increased moisture, C and N content, increasing N_2O emissions. Hence from an environmental sustainability point of view, collecting and digesting diary shed effluent will have little significant impact on overall GHG emissions. Therefore, collecting and digesting dairy effluent is only of value if it results in economic benefits for the farm.

An economic analysis was conducted on installing a digester system. The anaerobic digester systems for 250 cow farm would have a capital cost of $107,745 per year, an operating cost of $134,828 per year, and generate revenue of $132,819 per year, but would not be able to pay back the capital cost. For a 250 cow farm a plug flow digester would have a capital cost of $95,658 per year, operating cost $127,018 per year, generate revenue $194,722 per year, and the resulting payback period is 2 years. A three stage digester for a 250 cow farm would have a capital cost of $259,608 an operating cost of $215,920 per year, generate revenue of $296,389 per year, a payback period of 3 years. But for a large farm size of 600-1000 cows therefore a multi stage digester would be worthwhile. For large dairy farms, CH_4 capture with energy recovery can already be cost effective based on the energy value alone.

6.1.1.1 Recommendations

This study was carried out on small scale in the lab, therefore the findings should be verified using a larger scale system, for example in 1-2 m^3 digester.

Effluent collected for the study was from the top surface of the effluent pond, therefore a large amount of the solids may have settled out. The usual depth of standard effluent ponds being 4 meters, in future effluent collection should be from deeper depth of the pond for further experiments.

Three stage mesophilic digester was set up with effluent from a single farm, but further research has to be done by experimenting with multiple three stage digesters dosed with effluents from different farms to verify the reproducibility of the results.

7 References

Ahring, B. (2003). Perspectives for anaerobic digestion Biomethanation I (Vol. 81, pp. 1-30): Springer

Amon, T., Amon, B., Kryvoruchko, V., Zollitsch, W., Mayer, K., & Gruber, L. (2007). Biogas production from maize and dairy cattle manure--Influence of biomass composition on the methane yield. Agriculture, Ecosystems & Environment, 118(1-4), 173-182

Anderson, K., Yang, G.1992. Determination of bicarbonate and total volatile acid concentration in anaerobic digesters using a simple titration. Water Environ. Res. 64, 53–59. Angelidaki, I., & Ahring, B. K. (2000). Methods for increasing the biogas potential from the recalcitrant organic matter contained in manure. Water Science and Technology, 41(3), 189-194

Angelidaki, I., Ellegaard, L. (2003). Codigestion of manure and organic wastes in centralized biogas plants - Status and future trends. Applied Biochemistry and Biotechnology, 109(1-3), 95-105

Annual report, NRCE India, 2004 APHA (1998).

Eaton, A., Clesceri, L., Greenberg, A., Standard Methods for the Examination of Water and Wastewater. Washington DC: American Public Health Association. American Water Works Association, Water Environment Federation

Argelier, S., Delgenes, J.-P., & Moletta, R. (1998). Design of acidogenic reactors for the anaerobic treatment of the organic fraction of solid food waste Bioprocess and Biosystems Engineering, 18(4), 309-315

Atkins, P. W. (1998). Chemical Equilibrium Physical Chemistry (6 ed., pp. 215-242) Oxford: Oxford University Press

Banister, S. S., & Pretorius, W. A. (1998). Optimisation of primary sludge acidogenic fermentation for biological nutrient removal Water SA, 24(1), 35-41

Barber, A., 2010 On-farm Greenhouse Gas Emissions from 23 Surveyed Organic and Conventional NZ Dairy Farms

Basset-Mens, C., Eco-efficiency of intensification scenarios for milk production in New Zealand. Ecological Economics, 68 (6), 1615-1625

Basset-Mens C., Ledgard S. and Carran A., 2005. First Life Cycle Assessment of Milk Production from New Zealand Dairy Farm Systems. AgResearch Ltd. www.anzsee.org/anzsee2005papers/Basset-Mens_LCA_NZ_milk_production.pdf

Barnes, S., & Keller, J., (2003). Cellulosic waste degradation by rumen-enhanced anaerobic digestion. Water Science and Technology, 48(4), 155-162

Biofuel Technology Handbook (Rutz & Janssen et al., 2007)

Verma, M., Godbout, S., Brar, S., Solomatnikova, O., Lemay, S., Larouchel, J., Biofuels Production from Biomass by Thermochemical Conversion technologies, International Journal of Chemical Engineering

Biogas handbook Rutz and Seadi 2008 Birchall, S., C. Dillon, et al. (2008). Effluent and Manure Management Database for the Australian Dairy Industry

Bouman, R., Jesen , S., Wake, M., Process Capital Cost Estimation for New Zealand , SCENZ 2004

Broughton, D Alistair (2009). Hydrolysis and Acidogenesis of Farm Dairy Effluent for Biogas Production at Ambient Temperatures

Bryant, M., Varel, V., Frobish, R., Isaacson, H. (Eds.). (1976) Seminar on Microbial Energy Conversion: Gottingen

Burke, D. A. (2001). Dairy Waste Anaerobic Digestion Handbook. Olympia WA: Environmental Energy Company

Burke, D. A. (1997). Anaerobic Digestion of Sewage Sludge Using Anoxic Gas Flotation. 8th International Conference on Anaerobic Digestion, Sendai Japan.

Burke, D. A. (1997). Anaerobic Treatment Process for the Rapid Hydrolysis and Conversion of Organic Materials to Soluble and Gaseous Components. USA. Burke, D. A. (2000). Anaerobic Treatment Process with Removal of Inorganic Material. US006113786A. United States

Western Environmental Engineering: Castrillon, L., Vazquez, I., Maranon, E., & Sastre, H. (2002). Anaerobic thermophilic treatment of cattle manure in UASB reactors. Waste Management & Research, 20(4), 350

Characterization of Dairy manures and slurries "The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure." Bioresource Technology 99(1): 1-6

Chen, T. H., & Shyu, W. H. (1996). Performance of four types of anaerobic reactors in treating very dilute dairy wastewater. Biomass & Bioenergy, 11(5), 431- 440

Chen, Y., Cheng, J. J., & Creamer, K. S. (2008). Inhibition of anaerobic digestion process: A review. Bioresource Technology, 99(10), 4044-4064

Cheng, K. J., Akin, D. E., & Costerton, J. W. (1977). Rumen bacteria: Interaction with particulate dietary components and response to dietary variations

Federation Proceedings, 36(7), 193-197

Chugh, S., Chynoweth, D. P., Clarke, W., Pullammanappallil, P., & Rudolph, V(1999). Degradation of unsorted municipal solid waste by a leach-bed process. Bioresource Technology, 69(2), 103-115

Chynoweth, D., & Pullammanappallil, P. (1996). Anaerobic digestion of municipal solid wastes Microbiology of solid waste. (Vol. 113). Boca Raton, FL: CRC Press

Craggs, R. J. (2006). Potential Energy Recovery by Anaerobic Digestion of Dairy Farm Waste (Sustainable Farming Fund Report No. 03/029): NIWA

Craggs, R. J. (2007). Biogas power made easy. NIWA Climate-Energy Solutions Update, (20). Retrieved from http://www.niwa.co.nz/ourscience/ energy/publications/all/csu/2007-20/power

Craggs, R. J., Sukias, J. P., Tanner, C. T., & Davies-Colley, R. J. (2004). Advanced pond system for dairy-farm effluent treatment. New Zealand Journal of Agricultural Research, 47(4), 449-460

Dairy Waste Handbook, 2000 Demirel, B., & Scherer, P. (2008). The roles of acetotrophic and hydrogenotrophic methanogens during anaerobic conversion of biomass to methane: a review[10.1007/s11157-008-9131-1]. Reviews in Environmental Science and Biotechnology, 7(2), 173-190

Demirel, B., & Yenign, O. (2002). Two-phase anaerobic digestion processes: a review. Journal of Chemical Technology & Biotechnology, 77(7), 743-755

Demirer, G. N., & Chen, S. (2005). Two-phase anaerobic digestion of unscreened dairy manure. Process Biochemistry, 40(11), 3542-3549

Demirer, G. N., & Chen, S. (2008). Anaerobic biogasification of undiluted dairy manure in leaching bed reactors. Waste Management 28(1), 112-119

Dencamp, H., Verkley, G. J. M., Gijzen, H. J., & Vogels, G. D. (1989). Application of Rumen Microorganisms in the Anaerobic Fermentation of an Organic Fraction of Domestic Refuse. Biological Wastes, 30(4), 309-316

Dexcel (2006). Managing Farm Dairy Effluent. Dairying and the Environment (DEC Manuals 2006), from http://www.dexcel.co.nz/main.cfm?id=364&nid=133 D J Houlbrooke, 2008

Duff, S., & Murray, W (1996) Best practice management of Farm Dairy Effluent in the Manawatu-Wanganui region. Prepared for Horizons Regional Council. Bioconversion of forest products industry waste cellulosics to fuel ethanol : A review. Bioresource Technology, 55(1), 1-33

Energy Revolution: A sustainable New Zealand Energy Outlook, Greenpeace 2013,www.greenpeace.org/newzealand/PageFiles/493408/TheFutureisHereModelling.pdf

Erickson, L. E. and D. Y.-C. Fung (1988). Handbook on Anaerobic FermentationsNew York, Basel

FAO 2006a. Livestock's long shadow: environmental issues and options. Rome: Food and Agricultural Organization.

FAO. 2006b. World agriculture: towards 2030/2050. Food and Agriculture Organization, Rome. FAO. 2007. Gridded livestock of the world 2007. Food and Agriculture Organization, Rome.

FAO FertilizerStat. 2009. FAO fertilizer use statistics. http://www.fao.org/ag/agl/fertistat/. FAOSTAT. (2009). FAO Statistical Database. from Food and Agriculture Organization: http://faostat.fao.org/site/339/default.aspx

Funk, P. A., Armijo, C. B., Hanson, A. T., Samani, Z. A., Macias-Corral, M. A., Smith, G. B. et al. (2005). Converting gin and dairy wastes to methane

Ford, M., Fleming, R., Mechanical Solid-Liquid Separation of Livestock Manure Literature Review , 2002

Transactions of the Asae, 48(3), 1197-1201

Gavala, H. N., Angelidaki, I., & Ahring, B. K. (2002). Kinetics and Modeling of Anaerobic Digestion Process, Biomethanation I (pp. 57-93)

Ghanem, I. I. I., Guowei, G., & Jinfu, Z. (2001). Leachate production and disposal of kitchen food solid waste by dry fermentation for biogas generation

Renewable Energy, 23(3-4), 673-684

Gibson, C. (1995). Farm dairy effluent management. New Zealand Dairy Exporter, 72, 22-24

Glover, T. J. (1995). Pocket Ref

Guerrero, L., Omil, F., Mendez, R., & Lema, J. M. (1999). Anaerobic hydrolysis and acidogenesis of wastewaters from food industries with high content of organic solids and protein. Water Research, 33(15), 3281-3290

Hernandez, E. S., & Rodriguez, X. (1992). Treatment of Settled Cattle-Wastewaters by Downflow Anaerobic Filter. Bioresource Technology, 40(1), 77-79

Hickey, C. W., Quinn, J. M., & Daviescolley, R. J. (1989). Effluent Characteristics of Dairy Shed Oxidation Ponds and Their Potential Impacts on Rivers. New Zealand Journal of Marine and Freshwater Research, 23(4), 569-584

Hill, D. T., Taylor, S. E., & Grift, T. E. (2001). Simulation of low temperature anaerobic digestion of dairy and swine manure. Bioresource Technology, 78(2), 127-131

Hills, D. J. (1979). Effects of Carbon - Nitrogen Ratio on Anaerobic-Digestion of Dairy Manure. Agricultural Wastes, 1(4), 267-278

Hills, D. J., & Kayhanian, M. (1985). Methane from settled and filtered flushed dairy wastes. Transactions of the Asae, 28(1), 865-869

Hobson, P. N., & Wheatly, A. D. (1993). Anaerobic Digestion: Modern Theory and Practice. London: Elsevier Applied Science

Houlbrooke, D. J. (2008). Best practice management of Farm Dairy Effluent in the Manawatu-Wanganui region

Hwang, S., Lee, Y., & Yang, K. Y. (2001). Maximization of acetic acid production in partial acidogenesis of swine wastewater. Biotechnology and Bioengineering, 75(5), 521-529

Howell & Weber 2015, http://www.biodiesel.org/reports/19950101_gen-263.pdf,

Steve Howell And J. Alan Weber IEA Bioenergy Task 37. Country Reports of Member Countries, Istanbul, April 2011. International Energy Agency. Accessed June 3, 2011

Initiatives in Good Governance, Ministry of New and Renewable Energy (MNRE), 2012

Mousdale (2010)., Introduction to Biofuels

Jain, S., Lala, A. K., Bhatia, S. K., & Kudchadker, A. P. (1992). Modelling hydrolysis controlled anaerobic digestion. Journal of Chemical Technology and Biotechnology, 53, 337-344

Jensen, P. D., Hardin, M. T., & Clarke, W. P. (2008). Measurement and quantification of sessile and planktonic microbial populations during the anaerobic digestion of cellulose. Water Science and Technology, 57(4), 465- 469

Jensen, P. D., Hardin, M. T., & Clarke, W. P. (2009). Effect of biomass concentration and inoculum source on the rate of anaerobic cellulose solubilization. Bioresource Technology, 100(21), 5219-5225

Jiang, W. Z., Kitamura, Y., & Li, B. (2005). Improving acidogenic performance in anaerobic degradation of solid organic waste using a rotational drum fermentation system. Bioresource Technology, 96(14), 1537-1543

J Laubach, S Heubeck, C Pratt, K Woodward, B Guieysse, TJ van der Weerden, ML Chung, AN Shilton & RJ Craggs (2015) Review of greenhouse gas emissions from the storage and land application of farm dairy effluent, New Zealand Journal of Agricultural Research, 58:2, 203-233, DOI: 10.1080/00288233.2015.1011284

Kalia, A., Singh, S. (2001). Effect of mixing digested slurry on the rate of biogas production from dairy manure in batch fermenter. Energy Sources, 23(8), 711-715

Kashyap, D.., Dadhich, K., & Sharma, S., (2003). Biomethanation under psychrophilic conditions: a review. Bioresource Technology, 87(2), 147-153

Ledgard, S F., and Boyes, M., 2008. Fertiliser data for MAF GHG footprint projects

Prepared by AgResearch, Ruakura Research Centre, Hamilton, NZ

Lehtomaki, A., Huttunen, S., Lehtinen, T. M., & Rintala, J. A. (2007). Anaerobic digestion of grass silage in batch leach bed processes for methane production

Bioresource Technology, In Press, Corrected Proof

LIC (2006). Dairy Statistics 2005/2006: Livestock Improvement

LIC (2008). Dairy Statistics 2007/2008: Dairy NZ and Livestock Improvement Corporation

Li, X., Swan, J. E., Nair, G. R. and Langdon, A. G. (2015), Preparation of volatile fatty acid (VFA) calcium salts by anaerobic digestion of glucose. Biotechnology and Applied Biochemistry, 62: 476–482. doi:10.1002/bab.1301 Linke, B. (1997). A model for anaerobic digestion of animal waste slurries

Environmental Technology, 18(8), 849-854

Livestock Population in India by Species,' National Dairy Development Board, http://www.nddb.coop/English/Statistics/Pages/Population-india-species.aspx

Lo, K. V., & Liao, P. H. (1986). Psychrophilic anaerobic digestion of screened dairy manure. Energy in Agriculture, 5(4), 339-345

Loehr, R. C. (1974). Agricultural Waste Management- Problems, Processes, and Approaches. New York and London, Academic Press. Longhurst, R. D., Roberts, A. H. C., & O'Connor, M. B. (2000). Farm dairy effluent: A review of published data on chemical and physical characteristics in New Zealand. New Zealand Journal of Agricultural Research, 43(1), 7-14

Lusk, P. D. (1995). Anaerobic Digestion of Livestock Manures: A Current Opportunities Casebook. Washington, D.C., U. S. Department of Energy

Luo, J., Ledgard, S F., Lindsey, S B., and Sun, W., 2008a. Nitrous oxide emissions from dairy farms: sources and management options to reduce emissions. Luo, J., Ledgard, S. F., and Lindsey, S.B., 2008b. A test of a winter farm management option for mitigating nitrous oxide emissions from a dairy farm. Soil Use and Management, June 2008, 24, 121–130

Luostarinen, S. A., & Rintala, J. A. (2005). Anaerobic on-site treatment of black water and dairy parlour wastewater in UASB-septic tanks at low temperatures. Water Research, 39(2-3), 436-448

Lusk, P. (1998). Methane Recovery from Animal Manures The Current Opportunities Casebook. United States

MAF (1994). Dairy shed wastewater treatment ponds. Wellington: Ministry of Agriculture and Fisheries

Marchaim, U. (1992). Biogas processes for sustainable development. Available from http://www.fao.org/docrep/T0541E/T0541E00.HTM Mason, I. G., & Mulcahy, J. (2003). Volatile fatty acid production from farm dairy wastewater. Transactions of the Asae, 46(3), 819-824

Mathias Gustavsson, 'Biogas Technology- Solution in search of its Problems,' Gotenborg University, 2000 http://www.ted-biogas.org/assets/download/Gustavsson2000.pdf Mattocks, R., Kintzer, B., & Wilkie, A. C. (2008, November 27th, 2008). The AgSTAR Handbook 2. Retrieved May 2008, 2008, from http://www.epa.gov/agstar/pdf/handbook/full_pdf.pdf Mawson, A. J. (1986). Factors Influencing the Rate and Stability of the Anaerobic Digestion Process. Unpublished PhD, Massey University, Palmerston North

McCarty, P., & Mosey, F. (1991). Modelling of anaerobic digestion processes (a discussion of concepts). Water science and technology, 24(8), 17-33

McDougall, E. I. (1948). Studies on ruminant saliva, The composition and output of sheep's saliva. Biochemistry Journal., 43, 99-109

Merry, R. J., & McAllan, A. B. (1983). A comparison of the chemical composition of mixed bacteria harvested from the liquid and solid fractions of rumen digesta. British Journal of Nutrition, 50, 701-709

Metcalf and Eddy (2014) Wastewater Engineering Treatment and Resource Recovery, Chapter 13, Processing and Treatment of Sludges, 13-9 Anaerobic Digestion Metcalf and Eddy. 2003. Wastewater Engineering: Treatment, Disposal, and Reuse, 4th ed., McGraw-Hill, Singapore. Milk production in India, NDDB, 2008, Department of Animal Husbandry, Dairying & Fisheries, Ministry of Agriculture, GoI Miron, Y., Zeeman, G., Van Lier, J. B., & Lettinga, G. (2000). The role of sludge retention time in the hydrolysis and acidification of lipids, carbohydrates and proteins during digestion of primary sludge in CSTR systems. Water Research, 34(5), 1705-1713

Moller, H. B., Sommer, S. G., & Ahring, B. (2004). Methane productivity of manure, straw and solid fractions of manure. Biomass & Bioenergy, 26(5), 485-495

Moletta, R., D. Verrier, et al. (1986). "Dynamic modelling of anaerobic digestion." Water Research 20(4): 427-434

Monod, J. (1949). The Growth of Bacterial Cultures. Annual Review of Microbiology, 3(1), 371-394

Morris, G. R. (1976). Anaerobic fermentation of animal wastes: a kinetic and empirical design fermentation. Cornell University

Myint, M. T., & Nirmalakhandan, N. (2009). Enhancing anaerobic hydrolysis of cattle manure in leachbed reactors. Bioresource Technology, 100(4), 1695- 1699

Myint, M. T., Nirmalakhandan, N., & Speece, R. E. (2007). Anaerobic fermentation of cattle manure: Modeling of hydrolysis and acidogenesis. Water Research, 41(2), 323-332

Noike, T., Endo, G., Chang, J. E., Yaguchi, J. I., & Matsumoto, J. I. (1985)

Characteristics of Carbohydrate Degradation and the Rate-Limiting Step in Anaerobic Digestion Biotechnology and Bioengineering 27(10), 1482-1489

NZ Ministry of Agriculture and Fisheries (1994). Dairy shed wastewater treatment ponds. MAF Agriculture Policy Technical Paper, (94/17). Retrieved from http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resourceuse/ resource-management/dairy-shed-wastewater/ NZ Ministry of Agriculture and Forestry (2005). Stand-off and Feed pads Design and Management Guidelines

Ong, H. K., Greenfield, P. F., & Pullammanappallil, P. C. (2002). Effect of mixing on biomethanation of cattle-manure slurry. Environmental Technology, 23(10), 1081-1090

Oswald, W. J., Green, F. B., & Lundquist, T. J. (1994). Performance of Methane Fermentation Pits in Advanced Integrated Waste-Water Pond Systems. Water Science and Technology, 30(12), 287-295

Pain, B. F., West, R., Oliver, B., & Hawkes, D. L. (1984). Mesophilic anaerobic digestion of dairy cow slurry on a farm scale: First comparisons between

digestion before and after solids separation. Journal of Agricultural Engineering Research, 29(3), 249-256

Park, J. B., & Craggs, R. J. (2007). Biogas production from anaerobic waste stabilisation ponds treating dairy and piggery wastewater in New Zealand

Water Science and Technology, 55(11), 257-264 Pena Varon, M., & Mara, D. (2004). Waste stabilisation ponds. Delft, from www.irc.nl/redir/content/download/13614/186208/file/TOP13_WSP.pdf Pin-Jing, H., Fan, L., Li-Ming, S., Xiu-Jiang, P., & Duu-Jong, L. (2006). Enzymatic hydrolysis of polysaccharide-rich particulate organic waste. Biotechnology and Bioengineering, 93(6)

Potential Energy Recovery by Anaerobic Digestion of Dairy Farm Waste, Craggs 2006 Ann. C. Wilkie (2015) Feedstocks for biogas production Rajeshwari, K. V., M. Balakrishnan, et al. (2000). "State-of-the-art of anaerobic digestion technology for industrial wastewater treatment." Renewable and Sustainable Energy Reviews 4(2): 135-156

Raskin, L., Poulsen, L. K., Noguera, D. R., Rittmann, B. E., & Stahl, D. A. (1994)

Quantification of methanogenic groups in anaerobic biological reactors by oligonucleotide probe hybridization. Appl. Environ. Microbiol., 60(4), 1241-1248

Rico, C., J. L. Rico, et al. (2011). "Anaerobic digestion of the liquid fraction of dairy manure in pilot plant for biogas production: Residual methane yield of digestate." Waste Management 31(9-10): 2167-2173

Safley, L. M., & Westerman, P. W. (1990). Psychrophilic anaerobic digestion of animal manure: Proposed design methodology. Biological Wastes, 34(2), 133-148

Safley, L. M., & Westerman, P. W. (1992a). Performance of a Dairy Manure Anaerobic Lagoon. Bioresource Technology, 42(1), 43-52

Safley, L. M., & Westerman, P. W. (1992b). Performance of a Low-Temperature Lagoon Digester. Bioresource Technology, 41(2), 167-175

Saggar, S., Bolan, N. S., Bhandral, R., Hedley, C. B., & Luo, J. (2004). A review of emissions of methane, ammonia, and nitrous oxide from animal excreta deposition and farm effluent application in grazed pastures. New Zealand Journal of Agricultural Research, 47(4), 513-544

Sakar, S., Yetilmezsoy, K., & Kocak, S. (2009). Anaerobic digestion technology in poultry and livestock waste treatment – a literature review. Waste Management & Research, 27(1), 3-18

Scandrett, J. (2005). Alternative Dairy Effluent Application Methods

Schurz, J. (1978.). Paper presented at the Bioconversion of cellulosic substances into energy, chemicals, and microbial protein, New Delhi,

Schafer, P.L., and J.B. Farrell (2000a) "Turn Up the Heat," Water Environ. Technol.,12, 11, 27-32 Schafer, P.L., and J.B. Farrell (2000b) "Performance Comparisons for Staged and High-Anaerobic Digestion Systems," Proceedings of WEFTEC 2000, Water Environment Federation, Alexandria, VA Southern-California-Edison (2005). The Dairy Farm Energy Management Guidebook. http://www.dairyfarmenergy.com/Chapter_PDFs/8%20_Waste_ Collection_Treatment.pdf

Speece, R. (1987). Nutrient Requirements. In D. Chynoweth & R. Isaaacson (Eds.), Anaerobic Digestion of Biomass. (pp. 109-128). New York: Elsevier Science Publishing Co

Speece, R.E. 1996. Anaerobic Technology for Industrial Wastewaters.Archae Press, USA, p.43, ISBN:0-9650226-0-9. Stroot, P. G., McMahon, K. D., Mackie, R. I., & Raskin, L. (2001). Anaerobic codigestion of municipal solid waste and biosolids under various mixing conditions--I. digester performance. Water Research, 35(7), 1804-1816

Stephan Bringezu et al., 2009 'Towards Sustainable Production and Use of Resources: Assessing Biofuels,' UNEP, 2009, hhtp://unep.fr/scp/rpanel/pdf/

Subramanian, R. S. (2001). "Flow through Packed Beds and Fluidized Beds." Retrieved 2/10/11, 2011, from http://web2.clarkson.edu/projects/subramanian/ch301/notes/packfluidbed.pdf

Sun, Y., & Cheng, J. (2002). Hydrolysis of lignocellulosic materials for ethanol production: a review. Bioresource Technology, 83

Syngas from Waste: Emerging Technologies Puigjaner et al., 2011 Tchobanoglous, G., Burton, F. L., & Stensel, H. D. (2003). Wastewater Engineering: Treatment and Reuse / Metcalf & Eddy (4th ed.): McGraw Hill

The Agstar Program. U.S. Farm Anaerobic Digestion Systems: A 2010 Snapshot. *U.S. EPA*. U.S. EPA. Accessed June 2, 2011

THE FUTURE OF NZ DAIRY FARMING SYSTEMS: SELF MANAGING COWS WITH ACCESS TO PARTIAL HOUSING Tom Pow1, Bob Longhurst2, Zoe Pow3 'The Importance of Cattle in Biogas Production', http://www.preservearticles.com/2012042130934/the-importance-of-cattle-in-biogas-production.html The National Biogas and Manure Management Programme (NBMMP), 2012 Tian Cheng, Z. and T. Noike (1994). "Influence of retention time on reactor performance and bacterial trophic populations in anaerobic digestion processes." Water Research 28(1): 27-36

Vanderholm, D. H. (1984). Agricultural Waste Manual: NZ Agricultural Engineering Institute

Vandeviviere, P., De Baere, L., & Verstraete, W. (2002). Types of anaerobic digester for solid wastes. In Mata-Alvarez (Ed.), Biomethanization of the Organic Fraction of Municipal Solid Wastes (pp. 111-137): IWA

VandeBerg, L. and K. Kennedy (1985). "Anaerobic downflow stationary fixed film reactor: Performace under steady-state and non-steady conditions." Water Science and Technology 17: 89-102

Vartak, D. R., Engler, C. R., McFarland, M. J., & Ricke, S. C. (1997). Attached-film media performance in psychrophilic anaerobic treatment of dairy cattle wastewater. Bioresource Technology, 62(3), 79-84

Vavilin, V. A., & Angelidaki, I. (2005). Anaerobic degradation of solid material: Importance of initiation centers for methanogenesis, mixing intensity, and 2D distributed model. Biotechnology and Bioengineering, 89(1), 113-122

Vavilin, V. A., Fernandez, B., Palatsi, J., & Flotats, X. (2008). Hydrolysis kinetics in anaerobic degradation of particulate organic material: An overview. Waste Management, 28(6), 939-951

VARIABILITY OF EFFLUENT QUALITY AND QUANTITY ON DAIRY FARMS IN NEW ZEALAND Stephan Heubeck, John Nagels and Rupert Craggs Vedrenne, F., Beline, F., Dabert, P., & Bernet, N. (2008). The effect of incubation conditions on the laboratory measurement of the methane producing capacity of livestock measurement wastes. Bioresource Technology, 99, 146-155

Vedrenne, F, Béline F, Bernet N.2005, Evaluation of the methane production of livestock wastes: Ultimate productivity and organic matter characterization, 4th international symposium on anaerobic digestion of solid waste, Copenhague, 218-225. Veeken, A., Kalyuzhnyi , S., Scharff, H., & Hamelers, B. (2000). Effect of pH and VFA on the hydrolysis of organic solid waste. Journal of Environmental Engineering ASCE, 126(12)

Vesvikar, M., & Al-Dahhan, M. (2006). Effect of Mixing and Scale on the Performance and Hydrodynamics of Anaerobic Digesters. Paper presented at the Bioenergy I: From Concept to Commercial Processes, Tomar, Portugal

Wang, Z., & Banks, C. J. (2000). Accelerated hydrolysis and acidification of municipal solid waste (MSW) in a flushing anaerobic bio-reactor using treated leachate recirculation. Waste Management & Research, 18(3), 215- 223

Wells, C. M. (2001). Total Energy Indicators of Agricultural Sustainability :Dairy Farming Case Study Final Report. : University of Otago

Wen, Z., Liao, W., & Chen, S. (2004). Hydrolysis of animal manure lygnocellulosics for reducing sugar production. . Bioresource Technology, 91(1), 31-39

Wilkie, A. C., Castro, H. F., Cubinski, K. R., Owens, J. M., & Yan, S. C. (2004)

Fixed-film anaerobic digestion of flushed dairy manure after primary treatment: Wastewater production and characterisation. Biosystems Engineering, 89(4), 457-471

Wilkie, A. C. (2000). Anaerobic Digestion: Holistic Bioprocessing of Animal Manure . Gainesville, FL, University of Florida. Wilkie, A. C. (2000). “Reducing Dairy Manure Odor and Producing Energy.” BioCycle 41(9): 48-50 Wilkie, A. (2000). Fixed Film Anaerobic Digester. F. E. Office. Gainesville

Yadvika, Santosh, Sreekrishnan, T. R., Kohli, S., & Rana, V. (2004). Enhancement of biogas production from solid substrates using different techniques--a review. Bioresource Technology, 95(1), 1-10

Yatri R. Shah , Dhrubo Jyoti Sen 2011 Bioalcohol as green energy - A review Yu, H. Q., & Fang, H. H. P. (2001). Inhibition on acidogenesis of dairy wastewater by zinc and copper. Environmental Technology, 22(12), 1459-1465

Yu, H. W., Samani, Z., Hanson, A., & Smith, G. (2002). Energy recovery from grass using two-phase anaerobic digestion. Waste Management, 22(1), 1-5

Zeeman, G., Sutter, K., Vens, T., Koster, M., & Wellinger, A. (1988). Psychrophilic digestion of dairy cattle and pig manure: Start-up procedures of batch, fedbatch and CSTR-type digesters. Biological Wastes, 26(1), 15-31

8 Appendices

Appendix 1:Cost analysis for covering anaerobic digester

250 cows		Area(m2)			
Digester vol	1875	937.5			
	2008	2015			
A Digester	$	$	unit	Qty	cost
Labour	80	88	hr	32	2816
piping	20	22	/m		0
cover	40	44	/m2	937.5	41250
Gas meter	500	550		1	550
Gas pressure Reg	1000	1100		1	1100
					45716
320 cows		Area(m2)			
Digester vol	2400	1200			
	2008	2015			
A Digester	$	$	unit	Qty	cost
Labour	80	88	hr	40	3520
piping	20	22	/m		0
cover	40	44	/m2	1200	52800
Gas meter	500	550		1	550
Gas pressure Reg	1000	1100		1	1100
					57970
680 cows		Area(m2)			
Digester vol	5100	2550			
	2008	2015			
A Digester	$	$	unit	Qty	cost
Labour	80	88	hr	56	4928
piping	20	22	/m		0
cover	40	44	/m2	2550	112200
Gas meter	500	550		1	550
Gas pressure Reg	1000	1100		1	1100
					118778
1000 cows		Area(m2)			
Digester vol	7500	3750			
	2008	2015			
A Digester	$	$	unit	Qty	cost
Labour	80	88	hr	80	7040
piping	20	22	/m		0
cover	40	44	/m2	3750	165000
Gas meter	500	550		1	550
Gas pressure Reg	1000	1100		1	1100
					173690

Appendix 2: Cost analysis for covering plug flow digester

250 cows		Area(m2)			
Plug flow	333	416.6666667			
	2008	2015			
Plug flow	$	$	unit	Qty	cost
Labour	80	88	hr	24	2112
piping	20	22	/m		0
cover	40	44	/m2	416.666667	18333.3333
Gas meter	500	550		1	550
Gas pressure Reg	1000	1100		1	1100
					22095.3333
320 cows		Area(m2)			
Plug flow	1,067	533.3333333			
	2008	2015			
Plug flow	$	$	unit	Qty	cost
Labour	80	88	hr	24	2112
piping	20	22	/m		0
cover	40	44	/m2	533.333333	23466.6667
Gas meter	500	550		1	550
Gas pressure Reg	1000	1100		1	1100
					27228.6667
680 cows		Area(m2)			
Plug flow	2,267	1133.333333			
	2008	2015			
Plug flow	$	$	unit	Qty	cost
Labour	80	88	hr	40	3520
piping	20	22	/m		0
cover	40	44	/m2	1133.33333	49866.6667
Gas meter	500	550		1	550
Gas pressure Reg	1000	1100		1	1100
					55036.6667
1000 cows		Area(m2)			
Plug flow	3,333	1666.666667			
	2008	2015			
Plug flow	$	$	unit	Qty	cost
Labour	80	88	hr	48	4224
piping	20	22	/m		0
cover	40	44	/m2	1666.66667	73333.3333
Gas meter	500	550		1	550
Gas pressure Reg	1000	1100		1	1100
					79207.3333

Appendix 3: Cost analysis for covering three stage complete mix digester

250 cows		Area(m2)			
Complete	479	239.5833333			
Mix					
	2008	2015			
Complete	$	$	unit	Qty	cost
Labour	80	88	hr	20	1760
piping	20	22	/m	1000	22000
cover	40	44	/m2	240	10542
Gas meter	500	550		1	550
Gass pressure	1000	1100		1	1100
					35951.66667
320 cows		Area(m2)			
Complete	613	306.6666667			
Mix					
	2008	2015			
Complete	$	$	unit	Qty	cost
Labour	80	88	hr	24	2112
piping	20	22	/m	1000	22000
cover	40	44	/m2	307	13493
Gas meter	500	550		1	550
Gass pressure	1000	1100		1	1100
					39255.33333
680 cows		Area(m2)			
Complete	1,303	651.6666667			
Mix					
	2008	2015			
Complete	$	$	unit	Qty	cost
Labour	80	88	hr	24	2112
piping	20	22	/m	1000	22000
cover	40	44	/m2	652	28673
Gas meter	500	550		1	550
Gass pressure	1000	1100		1	1100
					54435.33333
1000 cows		Area(m2)			
Complete	1,917	958.3333333			
Mix					
	2008	2015			
Complete	$	$	unit	Qty	cost
Labour	80	88	hr	32	2816
piping	20	22	/m	1000	22000
cover	40	44	/m2	958	42167
Gas meter	500	550		1	550
Gass pressure	1000	1100		1	1100
					68632.66667

Appendix 4: Additional costs for three stage complete mix digester installation

Additional cost incurred for mix digester		
Mechanical	250	19000
Agitator	320	19000
	680	23000
	1000	31000
2X pumps	250	47882
	320	54009
	680	85519
	1000	113528
Heater	250	8554
	320	9266
	680	14256
	1000	17820
Civil	250	54240
Elec	320	54240
Plumbing	680	54240
Technical	1000	54240
Total	250	129676
	320	136515
	680	177015
	1000	216588

	Length(feet)
Copper tube for heater $9/foot	950.4
	1029.6
	1584
	1980

total hrs for two people	Total Hours	Pay/hr ($)
11520	72	80
9600	48	100
11520	72	80
21600	72	150

H_2S capture	5000	7330	10995
	6400	9383	14074
	13600	19938	29908
	20000	29321	43982
Water removal	0	0	0
	0	0	0
	0	0	0
	0	0	0
Generator cost	[illegible]28,910	[illegible]35,393	[illegible]45,590
1000$/kw	[illegible]32,805	[illegible]41,103	[illegible]54,155
	[illegible]52,836	[illegible]70,470	[illegible]98,205
	[illegible]70,641	[illegible]96,573	[illegible]137,360
Generator Controlling unit($)	2000	2588	3382
	2280	3033	4049
	3720	5320	7480
	5000	7353	10529
Blower($)	5000	6765	9147
	5840	8099	11148
	10160	14960	21440
	14000	21059	30588
Heat exchanger($)	519	1037	1266
	948	1165	1458
	1363	2821	3157
	2772	3137	4898
Civil cost (construction, of buildings for equipment and other added costs)$	20000	20000	20000
	22000	22000	22000
	24000	24000	24000
	26000	26000	26000
Consultation (Building oversee)	600	450	3600
	750	450	3600
	1050	750	3600
	1500	900	3600

Appendix 5: Total cost with additional costs for the installation of digester

Farm Size	A Digester	Plug flow	Complete Mix
250	₹107,745.26	₹95,658.47	₹259,607.91
320	₹128,992.69	₹112,461.64	₹286,256.08
680	₹225,507.22	₹193,296.24	₹419,239.59
1000	₹313,602.59	₹263,550.83	₹542,177.49

Appendix 6: Operation cost analysis for different digesters

Operation cost	Farm Size	A Digester	Plug flow	Complete Mix
Maintenance	250	3729	5468	8885
	320	4774	6999	14557
	680	10144	14872	65734
	1000	14918	21871	142158
Depriceation	250	₹21,549	₹19,132	₹51,922
	320	₹25,799	₹22,492	₹57,251
	680	₹45,101	₹38,659	₹83,848
	1000	₹62,721	₹52,710	₹108,435
Consumables	250	₹ 829	₹1,062	₹1,408
	320	₹ 965	₹1,256	₹1,698
	680	₹1,634	₹2,270	₹3,204
	1000	₹2,248	₹3,149	₹4,547
Electricity	250	5847	0	0
	320	7484	0	0
	680	15905	0	0
	1000	23389	0	0
Labour	250	70000	70000	105000
	320	70000	70000	105000
	680	70000	70000	105000
	1000	70000	70000	105000
Total	250	₹101,954.35	₹95,661.59	₹167,214.10
	320	₹109,022.18	₹100,746.56	₹178,505.95
	680	₹142,783.69	₹125,801.41	₹257,785.79
	1000	₹173,275.62	₹147,729.57	₹360,141.13

Appendix 7: Yearly consultation fee and total capital cost for the digester

Yearly Consultation fee	250	1500	1500	1500
	320	1500	1500	1500
	680	1500	1500	1500
	1000	1500	1500	1500
Total	250	103,454.35	97,161.59	168,714.10
	320	110,522.18	102,246.56	180,005.95
	680	144,283.69	127,301.41	259,285.79
	1000	174,775.62	149,229.57	361,641.13
Grand Total	250	211,199.61	192,820.06	428,322.01
	320	239,514.88	214,708.19	466,262.03
	680	369,790.91	320,597.65	678,525.38
	1000	488,378.22	412,780.40	903,818.62

Appendix 8: Total capital cost including insurance and other miscellaneous

	Insurance	633.60	578.46	1,284.97
		718.54	644.12	1,398.79
		1,109.37	961.79	2,035.58
		1,465.13	1,238.34	2,711.46
	Rates &	5,500	5500	5500
		6,000	6000	6000
		8,000	8000	8000
		10,000	10000	10000
Grand Total	Farm Size			
	250	217,333.21	198,898.52	435,106.98
	320	246,233.42	221,352.32	473,660.82
	680	378,900.28	329,559.44	688,560.96
	1000	499,843.35	424,018.74	916,530.07
	Investment	109,587.95	103,240.05	175,499.07
		117,240.73	108,890.68	187,404.74
		153,393.06	136,263.20	269,321.37
		186,240.76	160,467.91	374,352.59
	Pay	25,240.66	23,778.59	40,421.53
		27,003.28	25,080.07	43,163.69
		35,330.00	31,384.60	62,031.00
		42,895.60	36,959.51	86,222.14
	Operation	34,828.61	127,018.64	215,920.60
		44,244.01	133,970.75	230,568.43
		88,723.06	167,647.80	331,352.37
		229,136.35	197,427.42	460,574.73

Appendix 9: Summary of cost for anaerobic digester

A Digester				
Size cows	Invest ($)	Income/year ($)	Operation cost/year ($)	Invest+oper
250	107,745	132,819	134,828.61	242,574
320	128,993	170,009	144,244.01	273,237
680	225,507	361,269	188,723.06	414,230
1000	313,603	531,278	229,136.35	542,739

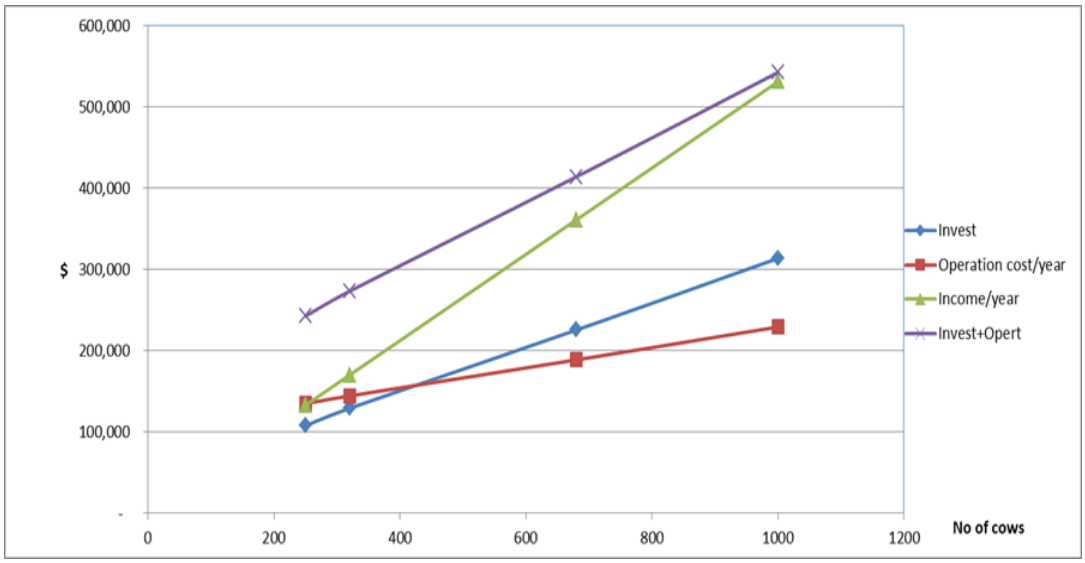

Figure 8-1: Cost analysis per herd size for anaerobic digester

Appendix 10: Summary of cost for plug flow digester

Plug flow				
Size cows	Invest ($)	Income/year ($)	Operation cost/year ($)	Invest+oper
250	95,658	194,722	127,018.64	222,677
320	112,462	249,244	133,970.75	246,432
680	193,296	529,643	167,647.80	360,944
1000	263,551	778,887	197,427.42	460,978

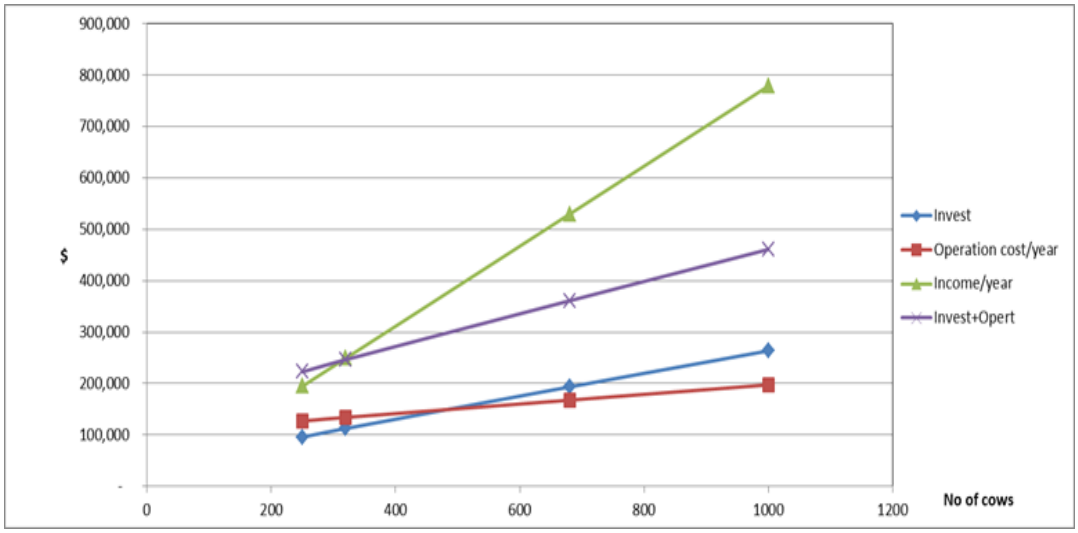

Figure 8-2: Cost analysis per herd size for plug flow digester

Appendix 11: Summary of cost for three stage complete mix digester

Mix				
Size cows	Invest ($)	Income/year ($)	Operation cost/year ($)	Invest+oper
250	259,608	296,389	215,920.60	475,529
320	286,256	379,378	230,568.43	516,825
680	419,240	806,178	331,352.37	750,592
1000	542,177	1,185,556	460,574.73	1,002,752

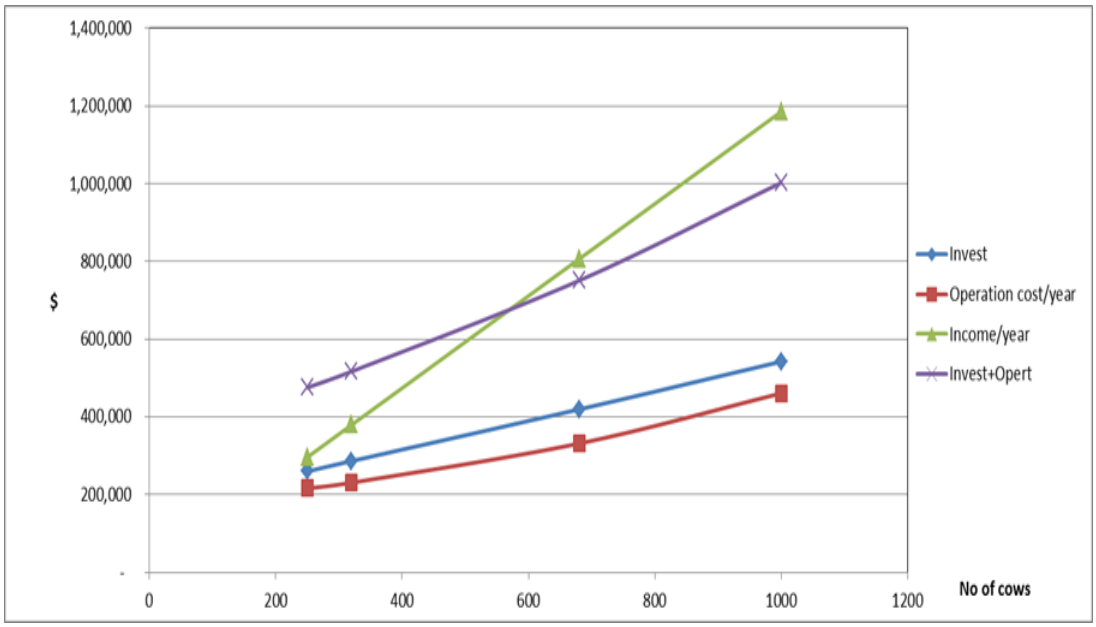

Figure 8-3: Cost analysis per herd size for three stage coupled methanogenic digester

Appendix 12 : Microbiological Species Involved in Biomethanation

Table 8-1: Species of hydrolysers and their respective substrates and products.

Species	**Substrate**	**Product**	**Enzymes**
Clostridium prefringens *C. bifermentans, C.histolyticum, C.sporogenes* (McInerney, 1988)	proteins	Peptides amino acids ammonia carbon dioxide	
Anaerovibrio lipolytica and *Syntrophomonas wolfei* (Cecchi and Mata-Alvarez, 1992).	Simple lipids (fats and oils) Complex lipids (e.g., phospholipids, glycolipids)	saturated and unsaturated long chain fatty acids, glycerol	esterase
Streptococcus bovis, Bacteriodes amylophilus, Selenomonas ruminatium, Succinomonas amylolytica, B.ruminocola and also a number of *Lactobacillus* species (Tsao 1984).	Starch: □ethyla and amylopectin.	Glucose maltose	α-amylase β-amylase Glucoamylase

(Chynoweth & Pullammanappallil, 1996**)**

Table 8-2 : Species of acetogens and their respective substrates

Species	substrate
Syntrophomonass wolfei, Syntrophobacter wolinii	propionate, butyrate, lactate, and ethanol

Table 8-3: Species of methanogens and their respective substrates.

Species	substrate
Methancoccales	H_2-CO_2 formate
Methanobacteriales	H_2-CO_2 formate
Methanogenium relatives	H_2-CO_2 formate
Methanosarcinaceae	acetate
Methanosarcina plus relatives	Methanol, □ethylamines; some use acetate and H_2-CO_2
Methanosarcina	acetate H_2-CO_2, methanol, and methylamines;
Methanosaeta	Use only acetate;

(Raskin *et al.*, 1994)

Appendix 13 : Electricity and heat generation by different digester systems for four herd size scenarios

Digester type	Heard size (no of cows)	Effluent(kg) /day	Digester Vol (m^3)	Bio gas (m3)/day	CH4 (m3)/day	Total Energy out(kwh)/day	Electricity (33% of total Energy) (kwh/day)	Hot water (40% of total Energy) (kwh/day)
Anaerobic Digester	250	1,160	1,875	276	180	1,686	556	674
	320	1,485	2,400	354	230	2,158	712	863
	680	3,155	5,100	751	488	4,586	1,513	1,834
	1000	4,640	7,500	1,105	718	6,744	2,226	2,698
PlugFlow Digester	250	1,160	833	439	263	2,472	816	989
	320	1,485	1,067	562	337	3,164	1,044	1,266
	680	3,155	2,267	1,193	716	6,724	2,219	2,689
	1000	4,640	3,333	1,755	1,053	9,888	3,263	3,955
Continuous complete mix Digester	250	1,160	479	658	395	3,708	1,224	1,483
	320	1,485	613	842	505	4,746	1,566	1,898
	680	3,155	1,303	1,790	1,074	10,085	3,328	4,034
	1000	4,640	1,917	2,633	1,580	14,832	4,894	5,933

Appendix 14: Energy cost saving for different digester systems for four herd size scenarios

Digester type	Heard size (no of cows)	Energy cost saving($)/year
Anaerobic Digester	250	(5,847)
	320	(7,484)
	680	(15,905)
	1000	(23,389)
PlugFlow Digester	250	56,968
	320	72,919
	680	154,952
	1000	227,871
Continuous complete mix Digester	250	155,764
	320	199,378
	680	423,678
	1000	623,056