# ANAEROBIC CO-DIGESTION OF DAIRY MANURE AND POTATO WASTE

A Dissertation

Presented in Partial Fulfillment of the Requirements for the

Degree of Doctorate of Philosophy

with a

Major in Environmental Science

in the

College of Graduate Studies

University of Idaho

by

SAI KRISHNA REDDY YADANAPARTHI

August 2014

Major Professor: Dr. Lide Chen

# AUTHORIZATION TO SUBMIT DISSERTATION

This dissertation of Sai Krishna Reddy Yadanaparthi, submitted for the degree of Doctor of Philosophy with a Major in Environmental Science and titled "Anaerobic Co-digestion of Dairy Manure and Potato Waste," has been reviewed in final form. Permission, as indicated by the signatures and the dates below, is now granted to submit final copies to the college of Graduate Studies for approval.

Major Professor: ________________________________ Date: __________________
Dr. Lide Chen

Committee
Member: ________________________________ Date: __________________
Dr. Jon H. Van Gerpen

________________________________ Date: __________________
Dr. Howard Neibling

________________________________ Date: ________________
Dr. Amber Moore

Department
Administrator: ________________________________ Date: __________________
Dr. Jan Boll

Discipline's
College Dean: ________________________________ Date: __________________
Dr. Larry Makus

Final Approval and Acceptance

Dean of the College
of Graduate Studies:________________________________ Date: __________________
Dr. Jie Chen

# ABSTRACT

Dairy and potato are two important agricultural commodities in Idaho. Both the dairy and potato processing industries produce a huge amount of waste which could cause environmental pollution. To minimize the impact of potential pollution associated with dairy manure (DM) and potato waste (PW), anaerobic co-digestion has been considered as one of the best treatment process. The purpose of this research is to evaluate the anaerobic co-digestion of dairy manure and potato waste in terms of process stability, biogas generation, construction and operating costs, and potential revenue. For this purpose, I conducted 1) a literature review, 2) a lab study on anaerobic co-digestion of dairy manure and potato waste at three different temperature ranges (ambient (20-25˚C), mesophilic (35-37˚C) and thermophilic (55-57˚C) with five mixing ratios (DM:PW-100:0, 90:10, 80:20, 60:40, 40:60), and 3) a financial analysis for anaerobic digesters based on assumed different capital costs and the results from the lab co-digestion study. The literature review indicates that several types of organic waste were co-digested with DM. Dairy manure is a suitable base matter for the co-digestion process in terms of digestion process stability and methane ($CH_4$) production (Chapter 2). The lab tests showed that co-digestion of DM with PW was better than digestion of DM alone in terms of biogas and $CH_4$ productions (Chapter 3). The financial analysis reveals DM and PW can be used as substrate for full size anaerobic digesters to generate positive cash flow within a ten year time period. Based on this research, the following conclusions and recommendations were made:

- ► The ratio of DM:PW-80:20 is recommended at thermophilic temperatures and the ratio of DM:PW-90:10 was recommended at mesophilic temperatures for optimum biogas and $CH_4$ productions.

- ► In cases of anaerobic digesters operated with electricity generation equipment (generators), low cost plug flow digesters (capital cost of $600/cow) operating at thermophilic temperatures are recommended.
  - The ratio of DM:PW-90:10 or 80:20 is recommended while operating low cost plug flow digesters at thermophilic temperatures.
- ► In cases of anaerobic digesters operated without electricity generation equipment (generators), completely mixed or high or low cost plug flow digesters can be used.
  - The ratio of DM:PW-80:20 is recommended for completely mixed digesters operated at thermophilic temperatures;
  - The ratio of DM:PW-90:10 or 80:20 is recommended for high cost plug flow digesters (capital cost of $1,000/cow) operated at thermophilic temperatures;
  - All of the four co-digested mixing ratios (i.e. DM:PW-90:10 or 80:20 or 60:40 or 40:60) are good for low cost plug flow digesters (capital cost of $600/cow) operated at thermophilic temperatures. The ratio of DM:PW-90:10 is recommended for positive cash flow within the ten year period if the low cost plug flow digesters are operated at mesophilic temperatures.

# ACKNOWLEDGMENTS

I would like to express my gratitude to my major professor Dr. Lide Chen for giving me the opportunity to study at the University of Idaho (UOI), and for his support and guidance through my Ph.D. study. I would like to thank Ms. Chris Dixon and Dr. Jon H. Van Gerpen for their great and unforgettable support throughout my studies. I would like to thank Dr. Jan Boll, head of the Environmental Science Program, for giving me an opportunity to pursue a Ph.D. in the Environmental Science Program. I also would like to thank my dissertation committee members, Dr. Howard Neibling, and Dr. Amber Moore, for serving on my committee and their valuable suggestions and comments.

I would like to thank the United States Department of Agriculture (USDA) and UOI for providing financial support for this research through an Agriculture and Food Research Initiative (AFRI) grant under the USDA-National Institute of Food and Agriculture (NIFA) and through a seed grant from UOI. I am very grateful to Dennis Brauer, plumbing supervisor at College of Southern Idaho, for using his valuable time to construct the huge anaerobic digesters without any charge. I would like to thank both Dr. Jon H. Van Gerpen and Dr. Lide Chen for getting additional funding to purchase Gas Chromatography (GC) which was the main and most valuable equipment used for the project. I would like to thank Dr. Howard Neibling, and C. Wilson Gray for their help on economic analysis.

I would like to thank the office staff—Laura Baxter, Kathy Garofano and Linda Brandon for their patient support. I would like to thank present and previous lab mates—Dr. Gopi Krishna Kafle, Ron Roemer, David Graybill, Megan Satterwhite and Sara Zglobicki for their unconditional support, help and friendship during my Ph.D. studies.

Finally, yet importantly, I am sincerely grateful to my family members and my wife's family for their love and support, especially my parents always encourage and support me when I have difficulties. Without their support, it would have been impossible for me to complete my study.

Thank you every one!

# DEDICATION

To my loving parents and my wife

## TABLE OF CONTENTS

**CHAPTER 3 - ANAEROBIC CO-DIGESTION OF DAIRY MANURE WITH POTATO WASTE 61**

## LIST OF FIGURES

# LIST OF TABLES

# CHAPTER 1 - INTRODUCTION

## 1.1 Background

Dairy manure (DM) is a common waste on dairy farms. Handling, storage and disposal of DM is a challenging task. United States Department of Agriculture (USDA) has estimated that a total of about 120 billion dry kilograms of dairy manure is produced annually from 67,000 dairy farms in the United States (USDA-Economic Research Service, 1997 and USDA-National Statistics Service, 2009). At present, most of the manure is applied on cropland to supply crop nutrients and to improve the physical condition of the soil. As the size and regional concentrations of confined dairy operations increase, there is a growing concern about environmental problems (odors, ammonia and greenhouse gases) relating to the handling of DM. In efforts to minimize the pollution problems associated with dairy activities, anaerobic digestion (AD) of DM has been recognized as one of the best solution to handle DM. Anaerobic digestion is the biological treatment process that can minimize dairy manure associated environmental concerns such as odor and greenhouse gas (GHG) emissions, and is capable of simultaneously generating renewable energy, and biogas, from dairy wastes. Anaerobic digestion is a series of biological processes in which microorganisms break down biodegradable materials in the absence of free oxygen. One of the end products is biogas which is a mixture of methane ($CH_4$) and carbon dioxide ($CO_2$) with traces of hydrogen sulphide ($H_2S$), ammonia ($NH_3$) and water vapor (Sterling *et al.,* 2001). The generated biogas ($CH_4$) can be used for generating electricity (used for cooking and heating), direct vehicle fuel and producing chemicals (Cantrell *et al.,* 2008).

The $CH_4$ content of biogas ranges between 55% and 70% (Deublein & Steinhauser, 2008). Methane can be used in dairy farms as a replacement fuel for either natural gas or electricity. Besides odor control or generating biogas, minimizing GHG emissions has been identified as a major reason to build and optimize existing AD systems on dairy farms (Cuéllar & Webber, 2008). Methane is a major GHG, which is 20 times more efficient than $CO_2$ at trapping heat in the atmosphere (National Greenhouse Gas Inventories Programme, 1996). In the United States, manure management is estimated to contribute two million tons of $CH_4$, equivalent to 8% of the US emissions of anthropogenic activities (US-EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2010, 2010). Currently, most dairy farms in the United States stay away from adopting AD systems on dairy farms because of low biogas production rates (Lazarus, 2008) and high initial costs. Anaerobic digesters operate based on dairy manure as the only feedstock have a bad reputation due to low biogas production per unit mass of manure resulting in a long-term return on investment (Tafdrup, 1995). Additional negative factors are high capital investment, low benefits and high operational costs. However, co-digestion of DM with other types of waste such as agricultural waste or municipal solid waste have been considered as one of the potential strategies to enhance biogas production and make AD more economically competitive (Li *et al.,* 2009a; Li *et al.,* 2009b; Zhang *et al.,* 2013; Yue *et al,* 2013).

Dairy manure remains the primary substrate for co-digestion due to its abundance and its unique properties such as high water content, good buffering capacity and the presence of almost all the essential nutrients and trace elements required for digestion (Li *et al.,* 2009c). Co-digestion of manure with other waste offers a number of advantages for managing manure and other agricultural wastes. For example, co-digestion of manure mitigates GHG emissions, produces energy, saves costs related to waste treatment, improves the fertilizer value of the digestate and increases the biogas production of the co-substrate wastes (Li *et al.,* 2009a; Li *et al.,* 2009b; Zhang *et al.,* 2013; Yue *et al,* 2013). However, there are limitations on the quantity and quality of co-substrate that can be used because the variation in the mixing ratio of co-substrate leads to decrease or increase in biogas production (Li *et al.,* 2010). The variation in the ratio of mix to co-substrate can also cause excessive scum from flotation, process inhibition and operational instability (Carucci *et al.,* 2005; Lehtomäki *et al.,* 2007). The amount of co-substrate that optimizes the biogas production without any process inhibition due to increase in volatile fatty acid (VFA) concentrations differs for different types of co-substrate used. For this purpose a literature review on anaerobic co-digestion of DM with different types of organic wastes has been carried out (Chapter 2). Based on this literature review, the optimum mixing ratio and C/N ratio of co-substrates used with DM are the important parameters which influences the co-digestion process. Additionally the parameters such as the type of reactor, the type of process (batch or continuous), the temperature of digestion process, and the characteristics of substrate used for the co-digestion process influence the digestion process in terms of biogas production (Chapter 2). This literature review also revealed that different types of organic matter can be co-digested with DM to improve the efficiency of the digestion process and to improve the biogas production. For my experiments, potato waste has been co-digested with DM to determine the efficiency of the digestion process in terms of biogas production at three different temperature ranges (ambient, mesophilic and thermophilic) (Chapter3).

Potato waste includes, for instance, skins and tubers with defects and mechanical damages that are rejected in the process of potato chip production. Since PW has a high moisture content, it is an eligible feedstock for AD. Nevertheless, because of its high soluble organic compounds, the AD of potato by-products as a single substrate is considered unstable. The literature contains some studies on AD of potato tuber and its industrial by-products (Kaparaju *et al.,* 2005; Parawira *et al.,* 2004, 2005). Many authors have reported unstable process conditions when treating potato by-products in mesophilic conditions. In fact, potato by-products contain high amounts of soluble substances that can be easily degraded to volatile fatty acids which can inhibit the methanogenic microorganisms in single stage anaerobic digesters. To overcome this problem, some studies used pig manure as a co-substrate (Kaparaju *et al.,* 2005).

Another study reports the results of the batch AD of potato waste alone and in combination with sugar beet leaves (Parawira *et al.,* 2004). In this case, the authors obtained an improved $CH_4$ yield when applying the co-digestion compared to the digestion of the single substrate. The authors studied the AD of solid PW in two double-stage mesophilic AD systems. The first consisted of a solid-bed reactor connected to an upflow anaerobic sludge blanket reactor (UASB), while the second was a solid-bed reactor connected to a methanogenic reactor packed with a wheat straw biofilm. The configuration with the packed straw bed had a greater speed of degradation compared to an UASB system. The $CH_4$ yield was the same for both systems (Parawira *et al.,* 2005).

The anaerobic treatment of potato processing solid waste was also studied in laboratory scale completely stirred tank digesters (CSTR) under thermophilic conditions (55˚C). A kinetic study to find simple model equations for the design of completely stirred tank digesters (CSTR) was carried out (Linke, 2006). It showed that an increase in the organic loading rate (OLR) caused a decrease in both biogas yield and $CH_4$ content.

Anaerobic digestion of potato by-products as a single substrate is a challenging process due to the high biodegradability of PW which can lead to rapid and strong acidification inside the reactor with consequent inhibition of the methanogenic bacteria activity. Until now, no studies have been performed to determine the digestion efficiency of mixing PW with DM. This study opens the doors for dairy farmers in the Pacific Northwest who are eagerly looking for disposing PW and treating DM to minimize the impact of pollution caused by PW and DM.

The economic feasibility for dairy farms to convert cow manure mixed with other types of organic waste into electricity has gained more attention in recent years due to higher biogas production which apparently leads to a quicker payback period. Anaerobic digesters are quite capital intensive and require a thorough economic analysis to assess economic feasibility prior to construction. The economic analysis can be carried out using a discounted cash flow analysis and pro-forma financial statements. The U.S. EPA AgStar program has produced an AD system evaluation tool called FarmWare 3.1. The tool is available as a free download at: http://www.epa.gov/agstar/tools/project-dev/farmware.html. The FarmWare 3.1 tool requires that the user input information regarding the dairy farm and biogas system. It then estimates capital costs, electricity generation potential, and profitability, among other things. A similar tool (spreadsheet-based tool) was designed by Enahoro and Gloy, 2008. It has a slightly different set of inputs and gives the user more flexibility to alter a wider variety of parameters than FarmWare 3.1. The spreadsheet-based tool designed by Enahoro and Gloy is available as a free download at: http://www.agfinance.aem.cornell.edu/ad-systems.html.

To evaluate the results obtained from the co-digestion of DM and PW study (Chapter 3), an economic analysis was performed (Chapter 4). The results obtained in co-digestion were incorporated into the spreadsheet-based tool to estimate the profitability of using PW as a co-substrate with DM. A wide range of herd sizes (1,000 to 10,000) were used for analysis to estimate the payback period. This spreadsheet-based tool is limited to checking for profitability within a ten year time period.

## 1.2 Objectives

The overall goal of this research was to investigate the effect of temperature and mixing ratios on anaerobic co-digestion of DM and PW in terms of biogas and $CH_4$ production.

The specific objectives of this research were to:

1. Conduct a literature review of studies on the anaerobic co-digestion of dairy manure with different types of organic waste.
2. Investigate the effects of mixing potato waste with dairy manure at three different temperature ranges (ambient, mesophilic and thermophilic).
3. Evaluate (using economic analysis) the obtained results from the laboratory co-digestion study and to determine the feasibility of mixing potato waste with dairy manure on farm based anaerobic digesters.

## 1.3 Dissertation Organization

This dissertation is divided into five chapters.

1. ***Chapter 1,*** a general introduction on dairy manure, potato waste and economic analysis.
2. **C*hapter 2***, a literature review of anaerobic co-digestion of dairy manure with different types of organic wastes.
3. **C*hapter 3***, a lab-scale study on anaerobic co-digestion of dairy manure (DM) and potato waste (PW) which was studied under a batch digestion process.
4. **C*hapter 4,*** an economic analysis of dairy based anaerobic digestion systems. The analysis was performed using the data obtained in laboratory experiments for anaerobic co-digestion of DM and PW.
5. ***Chapter 5,*** Overall conclusions and recommendations for future research.

## 1.4 References

Cantrell, K. B., Ducey, T., Ro, K. S., & Hunt, P. G. (2008). Livestock waste-to-bioenergy generation opportunities. *Bioresource Technology, 99,* 17, 7941-53.

Carucci, G., Carrasco, F., Trifoni, K., Majone, M., and Beccari, M. (2005). Anaerobic digestion of food industry wastes: effect of co-digestion on methane yield, *J. Environ. Eng.* 131, 1037–1045.

Cuéllar, A. D., & Webber, M. E. (2008). Cow power: the energy and emissions benefits of converting manure to biogas. *Environmental Research Letters, 3,* 3, 34002.

Deublein, D., & Steinhauser, A. (2008). *Biogas from waste and renewable resources: An introduction*. Weinheim Germany: Wiley-VCH.

Dixon, J. E., J. E. Ojala, L. E. Sandval, and S. L. Hafez. (1987). Disposal of cull and waste potatoes. Current Information Series – Cooperative Extension Service, Univ. Idaho, Moscow. No. 814.

Kaparaju P., Rintala J., (2005). Anaerobic co-digestion of potato tuber and its industrial by-products with pig manure, *Resources Conservation & Recycling*, *43*, 175-188.

Lazarus, W. F. (2008). Farm-based anaerobic digesters as an energy odour control technology: background policy issues, in USDA Agricultural Economic Report 843, 2008. Reterived from http://www.usda.gov/oce/reports/energy/AnerobicDigesters0308.pdf on May 7th, 2012.

Lehtomäki, A., Huttunen, S., & Rintala, J. A. (2007). Laboratory investigations on co-digestion of energy crops and crop residues with cow manure for methane production: Effect of crop to manure ratio. *Resources, Conservation and Recycling, 51,* 3, 591-609.

Li, R., Chen, S., & Li, X. (2010). Biogas production from anaerobic co-digestion of food waste with dairy manure in a two-phase digestion system. *Applied Biochemistry and Biotechnology, 160,* 2, 643-54.

Li, R., Chen, S., Li, X., Saifullah, L. J., He, Y., & Zhu, B. (2009a). Anaerobic Codigestion of Kitchen Waste with Cattle Manure for Biogas Production. *Energy & Fuels : an American Chemical Society Journal, 23,* 2, 2225.

Li, R., Li, X., & Chen, S. (2009b). Anaerobic co-digestion of kitchen waste and cattle manure for methane production. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 31,* 20, 1848-1856.

Li, X., Li, L., Zheng, M., Fu, G., & Lar, J. S. (2009c). Anaerobic Co-Digestion of Cattle Manure with Corn Stover Pretreated by Sodium Hydroxide for Efficient Biogas Production. *Energy and Fuels, 23,* 5, 4635-4639.

National Greenhouse Gas Inventories Programme. Intergovernmental panel on climate change (IPPC-1996). Reterived from http://www.ipcc.ch/graphics/speeches/sbsta-19-statement-revision-1996.pdf on April 22nd, 2012.

Nelson, M. L. (2010). Utilization and application of wet potato processing coproducts for finishing cattle. *Journal of Animal Science, 88,* 13, 133-42.

Olsen, N., Nolte, P., Harding, G. and Ohlensehlen, B. (2001). Cull and waste potato management. University of Idaho, College of Agriculture, Cooperative Extention System CIS Bulletin # 814.

Pailthorp, R. E., J. W. Filbert, and G. A. Richter. (1987). Treatment and disposal of potato wastes. Pages 747–788 in Potato Processing. W. F. Talburt and O. Smith, ed. AVI Publ. Co., Westport, CT.

Parawira W., Murto M., Read J.S., Mattiasson B., (2005), Profile of hydrolases and biogas production during two stage mesophilic anaerobic digestion of solid potato waste, *Process Biochemistry*, *40*, 2945-2952.

Parawira W., Murto M., Zvauya R., Mattiasson B., (2004), Optimization of the anaerobic digestion of solid potato waste alone and in combination with sugar beet leaves, *Renewable Energy*, *29*, 1811-1823.

Smith, J. H. (1986). Decomposition of potato processing wastes in soil. *J. Environ. Qual.* *15*:13–16

Sterling, J. M. C., Lacey, R. E., Engler, C. R., & Ricke, S. C. (2001). Effects of ammonia nitrogen on H2 and CH4 production during anaerobic digestion of dairy cattle manure. *Bioresource Technology, 77,* 1, 9-18.

Tafdrup, S. (1995). Viable energy production and waste recycling from anaerobic digestion of manure and other biomass materials. *Biomass & Bioenergy, 9,* 303.

USDA, Potatoes summary. (2011). National Agricultural Statistics Service. Reterived from http://usda01.library.cornell.edu/usda/current/Pota/Pota-09-20-2012.pdf on June 6th, 2012.

USDA-Economic Research Service, 1997. Confined Animal and Manure Nutrient Data System.

USDA-National Agricultural Statistics Service, 2009. Farms, Land in Farms, and Livestock Operations.

USEPA (U.S. Environmental Protection Agency). (2013). Common manure handling systems. Ag 101. Retrieved from http://www.epa.gov/oecaagct/ag101/dairymanure.html on April 22nd, 2012.

US-EPA, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2010, 2010. Retrieved from http://epa.gov/climatechange/emissions/downloads12/US-GHG-Inventory-2012-Chapter-6-Agriculture.pdf on May 7th, 2013.

Van Buren, A. (ed.) (1979). A Chinese Biogas Manual – Popularizing Technology in the Countryside, trans. Cook, M., Interm. Tech. Publ. Ltd.

Yue, Z., Chen, R., MacLellan, J., Liu, Y., Liao, W., Yang, F., & Marsh, T. (2013). Effects of dairy manure and corn stover co-digestion on anaerobic microbes and corresponding digestion performance. *Bioresource Technology, 128,* 65-71.

Zhang, C., Xiao, G., Peng, L., Su, H., & Tan, T. (2013). The anaerobic co-digestion of food waste and cattle manure. *Bioresource Technology, 129,* 170-176.

# CHAPTER 2 - ANAEROBIC CO-DIGESTION OF DAIRY MANURE WITH DIFFERENT TYPES OF ORGANIC WASTE – A REVIEW

## 2.1 Abstract

Dairy manure (DM) is a common waste in dairy farming, and poses handling, storage and disposal challenges. With poor management, dairy manure produces odour, ammonia and releases greenhouse gases that contribute to global warming. Anaerobic digestion (AD) is a means to produce renewable energy and to reduce environmental impacts resulting from improper management of DM. To improve biogas production per unit volume, anaerobic co-digestion of DM is one of the methods used to enhance biogas production. The present work reviews the potential of AD for biogas production from DM and compares the operating and performance data for various anaerobic process configurations. It examines co-digestion effects of manure with different types of organic waste and the influences of several parameters on biogas and $CH_4$ yield. The comparison indicates that a variety of different operational conditions, various reactor configurations such as batch digesters, and continuously stirred tank reactor (CSTR) are suitable for the AD of DM.

These studies have demonstrated that combining different organic waste products results in a substrate that is better balanced and assorted in terms of nutrients. Pretreatment makes organic solids more accessible and degradable to microorganisms. Mathematical models are also useful to predict the co-digestion process performance and therefore can be used to choose the best substrate to mix.

## 2.2 Introduction

In the USA, DM is a common organic waste from dairy industry with an estimated production of 22 tons of DM/cow-year (USEPA, 2013). At present, most of the manure is applied on agricultural fields to supply crop nutrients and to improve the physical condition of the soil. As dairy size and density of cow numbers increase, there is a growing concern about environmental problems associated with the increased volume of DM per unit area. Anaerobic digestion of manure has been promoted in the last two decades as one method to mitigate GHGs emissions, odor nuisance and manure disposal challenges. Anaerobic digestion is a series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen. The AD process has several benefits including (1) reducing odor emissions; (2) reducing GHGs emissions; (3) killing pathogens; (4) reducing wastewater strength (oxygen demand); (5) converting organic nitrogen into plant available ammonia nitrogen; (6) preserving plant nutrients (e.g., N, P, K); and (7) producing biogas (Beddoes *et al.,* 2007; Kashyap *et al.,* 2003; Wilkie *et al.,* 2004).

Between 1990 and 2010, the $CH_4$ emissions in the USA increased by 64.0 percent from 31.7 teragrams of $CO_2$ equivalents (Tg $CO_2$ Eq.) to 52.0 Tg $CO_2$ Eq. mainly from dairy and swine manure (USEPA, 2012). Most dairy farmers in the United States are reluctant to adopt AD, citing low biogas production rates (Lazarus, 2008) and high costs associated with an AD plant. Biogas plants based on only DM have a bad reputation due to low biogas production per unit mass of manure and therefore a low return on investment (Tafdrup, 1995; Zhang, *et al.,* 2007). Additional problems include high capital investment and operational costs (Yiridoe *et al.,* 2009; Bekkering *et al.,* 2010; Schievano *et al.,* 2008). In the US, costs of generating electricity from AD processes ranged from 0.03 to 0.50$/kWh (Beddoes *et al.,* 2007), which is less competitive when compared with commercial electricity rate of $0.09 per kilowatt (Department of Energy, 2007). The use of some existing AD systems has been discontinued because the associated costs exceed the retail price of electricity. However, environmental benefits are paramount and AD offers a solution to some dairy farmers.

In order to obtain higher biogas output from dairy operated AD systems, the simultaneous addition of a co-substrate, such as agricultural waste or organic municipal solid waste with DM, has been recognized as an alternative solution. This process (mixing two or more wastes and digesting) is known as anaerobic co-digestion (Li *et al.,* 2009b; Brown & Li, 2013; Zhang *et al.,* 2013). Substrates that produce more biogas per unit mass are co-digested with DM to maximize biogas production per unit volume of the reactor. In general, substrate that contains high concentrations of fats and lipids have higher $CH_4$ potential than those with high sugar or protein content (Gumisiriza *et al.,* 2009; Labatut, 2012). Lipids are composed of a mixture of fats, oil and grease (FOG). Although fats, oil and grease normally account for about 10-30% of the volatile solids in most wastes, over 50% of the COD reduction and biomethane production during AD comes from FOG degradation (Novak and Carlson, 1970). In some cases, longer residence times along with the mixing and pre-treatment of the substrate are required to exploit the benefits of co-digestion. Co-digestion of manure with other waste offers a number of advantages including dilution of potential toxic compounds, improved balance of nutrients, synergistic effects of microorganisms, increased load of biodegradable organic matter, and better biogas yield (Sosnowski *et al.,* 2003).

Optimum mixing ratio is a necessary and important parameter to maintain a stable process and to obtain the optimum biogas production. Incorrect mixing ratios (DM:Other organic waste) may lead to process inhibition, operational instability, and low biogas production (Carucci *et al.,* 2005; Lehtomäki *et al.,* 2007). Process inhibition results in decreased biogas production and a parallel effect of an increase in volatile fatty acids (VFA) concentration. Many studies have been undertaken to examine the factors that affect the co-digestion process of DM with other types of organic wastes interms of inhibition resulting from biological and chemical constituents in the co-substrate (Chen *et al.,* 2008). Research is being continued to determine the best operating parameters for the co-digestion process.

This review only addresses DM as main substrate. The objective of this review is to 1) summarize the types of substrate that were co-digested with DM, 2) to describe the several factors that influence co-digestion of DM with other types of organic substrate and 3) to briefly emphasize the mathematical models useful for the co-digestion process.

## 2.3 Dairy manure as an important base substrate

Increased manure production needs to be managed in an environmentally friendly way without creating soil, water and air pollution. The economic research service reports that there were 75,000 dairy farms in the US (USDA, 2007). These dairy farms generate a huge amount of DM. Untreated or poorly managed manure causes odors, water pollution and nutrient leaching (Yiridoe *et al.,* 2009; Cantrell *et al.,* 2008). When AD technology was unavailable, a large part of the manure was stored in anaerobic lagoons or left outside for a period of 6–9 months to decompose naturally (Lazarus, 2008). There is huge potential to use DM as the base substrate for AD and generate renewable energy, while reducing GHG emissions.

Dairy manure generally has moisture content around 75-80% and contains all the essential nutrients such as nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), manganese (Mn), copper (Cu), zinc (Zn), chlorine (Cl), boron (B), iron (Fe), and molybdenum (Mo) that are required for AD process (Seppala *et al.,* 2013). Dairy manure is rich in protein content but low in carbon content. The C/N ratio is generally low which, results in high concentration of ammonia when DM is digested as a sole substrate. Due to its high buffering capacity, DM can be mixed with other organic wastes (swine manure, poultry manure, food wastes and energy crops) to maintain a stable AD process and to obtain higher biogas production. The buffering capacity is determined by the amount of alkalinity present in the AD system. The bicarbonate ion ($HCO_3^-$) is the main source of buffering capacity to maintain the AD system's pH in the range of 6.5 – 7.6. In a typical manure-only digester with a pH 7.4, the bicarbonate alkalinity is about 5,500 mg/L as $CaCO_3$ (Labatut and Gooch, 2012). Such alkalinity usually provides enough buffering capacity to withstand moderate shock loads of volatile fatty acids. In fact, cow manure can play an important role in co-digestion operations by increasing the pH and buffering capacity of the influent mixture when high-strength, easily degradable agricultural waste or industrial wastes are used as co-substrate. Most of the biodegradable carbon in DM is already digested in the rumen and in the gut. Thus, DM has a lower potential to produce biogas than pig or poultry manure. Also, DM has a lower biodegradability due to the high amount of inorganic compounds and fibers not digested in the cow digestion system and hence $CH_4$ concentration in the biogas is lower (Zhang *et al.,* 2013).

The properties of DM depend on the digestibility, protein and fiber contents of feed, animal age and seasons in which the animals are fed (Hubbard *et al.,* 1998; Amon *et al.,* 2001). One of the most important manure properties for AD systems is volatile solids. In dairy manure AD systems, methane productivity is mainly measured in terms of volatile solids (VS) destroyed, which, as residence time approaches infinity, is called the ultimate $CH_4$ yield (Moller *et al.,* 2004). This is lower than the theoretical $CH_4$ potential (based on chemical oxygen demand (COD) or VS.

## 2.4 Factors that influence the co-digestion with dairy manure

Co-digesting DM with other types of organic wastes enriches the substrate characteristics. The most cited advantages of co-digestion are the increased $CH_4$ yield attributed to additional nutrients (carbon, nitrogen and phosphorous) from the co-substrate and other benefits arising from processing co-substrate (tipping fees, carbon credits etc.). The carbon to nitrogen (C/N) ratio for DM is considered to be 5.8:1 compared to the optimum C/N ratios of 13:1 to 30:1 required for AD (Li *et al.,* 2009b). In order to increase the C/N ratio to 30:1, different types of organic wastes have been co-digested with DM (Li *et al.,* 2009c; Carucci *et al.,* 2005; Lehtomäki *et al.,* 2007). In addition to the C/N ratio, balance is sought between the co-substrate in terms of macro- and micro- nutrients, formation of inhibitors, alkalinity and formation of toxic compounds (Chen *et al.,* 2008; Seppala *et al.,* 2013; Kayhanian, 1995). Substrates that are rich in lipids and/or carbohydrates with high volatile solids content are good candidates for co-digestion with DM (Li *et al.,* 2002; Labatut *et al.,* 2011).

Lipids are characterized as fats, liquid (oils) and solid (greases). They are commonly present in food wastes and in some industrial wastewaters, such as those produced by slaughterhouses, dairies or fat refineries (Li *et al.,* 2002). Lipids are attractive for biogas production due to the high number of C and H atoms in their molecules, which implies high theoretical $CH_4$ potential. However, they can also present several problems such as inhibition of methanogenic bacteria and absorption into biomass that can cause sludge flotation and loss of potential digestible material due to washout from the digester (Neves *et al.,* 2009a).

Carbohydrates are the main components of organic wastes from agriculture-related factories, food waste and collected organic fractions of municipal solid waste (OFMSW) from households and markets. The anaerobic degradation of such wastes is strongly dependent on the ratio between the acidification process rate and the methanogenic process rate. In particular, if the acidification process is faster than the methanogenic process, volatile fatty acids (VFAs) tend to accumulate in the reactor causing progressive drops in pH that stress and inhibit the activity of methanogenic bacteria (Siegert and Banks, 2005). Sometimes cellulose wastes are also used for co-digestion process, these cellulose wastes are produced by paper and cardboard factories or from textile factories. Cellulose wastes have a high C/N ratio ranging from 173/1 to higher than 1,000/1 (Zhang *et al.,* 2008).

In a co-digestion process, waste rich in proteins can provide the buffering capacity and a wide range of nutrients, while waste with a high carbon content can balance the C/N ratio for all substrate characterized by a low C/N ratio, decreasing the risk of ammonia inhibition (Hashimoto, 1983). The optimal C/N ratio seems to be the most interesting factor when different substrates are co-digested; therefore, the C/N ratio has been widely studied. A study on co-digestion of manure with sugar beet tops and grass demonstrated a higher $CH_4$ potential with co-digestion of manure and grass, due to the higher carbon content of grass (46%) compared to that of sugar beet tops (40%) (Lehtomäki *et al.,* 2007). The C/N ratio of 5.8/1 was improved to 20.0/1 when kitchen waste (KW) was co-digested with cattle manure (CM). It was noticed that the $CH_4$ production increased due to improved nutrient balance (C/N ratio) and the synergetic effect between KW and CM (Li *et al.,* 2009a). Synergism of the DM co-digestion has been identified as an increase in the $CH_4$ yield as compared to the individual's substrate weighted in total (Labatut *et al.,* 2011). In contrast, antagonistic behavior leads to diminished specific $CH_4$ yield, e.g. some food wastes and slaughterhouse wastes can cause excessive foaming, scum formation and ammonia inhibition (Alvarez and Lidén, 2008; Murto *et al.,* 2004). Optimizing feed composition and C/N ratio for enhancement in $CH_4$ production during co-digestion of DM and chicken manure (50:50) showed that a C/N ratio of 25:1 and 30:1 had better digestion with stable pH and low concentrations of total ammonium nitrogen and free ammonia ($NH_3$) (Wang *et al.,* 2012c). Co-digestion of DM and corn stalks indicated that at an optimal C/N ratio of 28 to 30 obtained higher fermentabilities (Wang *et al.,* 2012b). Therefore, the optimum C/N ratio for co-digestion of DM with other wastes is commonly believed in the range of 20-30.

The quantity of co-substrate in a co-digestion system is limited by the antagonistic behavior especially scum formation and inhibition (due to ammonia, accumulation of VFA, pH changes etc.). Proper mixing and an optimization of organic loading can reduce scum formation (Murto *et al.,* 2004; Lindorfer *et al.,* 2008). A recent co-digestion study of canola meal and DM indicated that high organic loading resulted in increased VFA accumulation and thus reduced biogas production; however, reduced organic loading and high oil content triggered high biogas production due to less accumulation of VFA and increased volatile matter, respectively (Atandi and Rahman, 2012).

Control of ammonia inhibition is difficult in co-digestion. Ammonia inhibition caused by either ammonium ions ($NH_4^+$) or $NH_3$ is detrimental to the methanogens, reducing their activity as concentration increases beyond 4,000 mg $NH_3$-$N^{-1}$ (Chen *et al.,* 2008). Co-digestion introduces organic matter that sometimes has higher nitrogen content, which poses a threat of ammonia inhibition.

Furthermore, elevated temperatures aggravate ammonia inhibition and VFA. Ahring *et al.* (2001) conducted a study to investigate the influence of temperature increase from 55˚C to 65˚C on the performance of two continuous stirred tank digesters (CSTRs) treating cattle manure at 15 days HRT. The stable biogas of 0.2 $m^3$ $kg^{-1}$ VS $day^{-1}$ was obtained for 10 days after the start-up at 55˚C with a $CH_4$ content of 65–71%. However, they observed a fast drop in the biogas production and the $CH_4$ content (less than 45%) with an increase in temperature in the test reactor to 65˚C. The study concluded that a temperature shift from 55˚C to 65˚C led to a lower $CH_4$ yield and an increased amount of volatile fatty acid (VFA) in the effluent. In a similar study, the influence of temperature (50˚C and 60˚C) on the performance of CSTRs digesting the cow manure was investigated by El-Mashad *et al.* (2004) at HRT levels of 10 and 20 days. The result showed that the hydrolysis stage is the most seriously affected process stage in the AD of CM in the temperature range of 50–60˚C, and the $CH_4$ production rate at 60˚C was found to be lower than that at 50˚C, at all the HRT levels employed. In addition, the authors reported that the concentration of free ammonia affected the performance methanogen bacteria.

The presences of other ions, e.g. $Na^+$, $Mg^{2+}$ and $Ca^{2+}$, can play a role in suppression, even though those ions themselves are inhibitors. Process inhibition is indicated by a decrease in biogas production rate and $CH_4$ content reduction as well as a shift in pH that is accompanied by the accumulation of VFA (Alvarez and Lidén, 2008). The addition of other organic wastes in co-digestion may drop the manure–organic waste mixture pH. The amount of carbon dioxide and VFA produced during the AD process may affect the pH. There are many options to adjust the pH to the optimum range (6.5–8.0); options studied include, 1N HCL (Liu *et al.,* 2009), 0.1 mol/L phosphate buffer (Wan *et al.,* 2012), NaOH (Lin *et al.,* 2012) and 10N KOH (Wang *et al.,* 2012a) is widely used. Otherwise, a suitable co-digestion ratio should be predetermined so that pH is well maintained during the AD process.

## 2.5 Review on substrates (feedstock) co-digested with dairy manure

A diverse number of biological wastes are co-digested with DM. Large numbers of co-digestion studies are conducted with food wastes, energy crops and crop residues compared to other types of waste (Table 2.1). Quite a few selected results are presented in Table 2.1 to show the possible candidates for co-digestion and associated substrate characteristics and operational conditions. Other livestock wastes, like poultry and swine manure, can also be used as either the main substrate or as a co-substrate. It should be noted that the quantity of liquid biofuels, namely bioethanol and biodiesel, has increased quite rapidly in the last decade generating increased amounts of co-products and wastes that can be used in co-digestion (Siles *et al.,* 2009).

**Table 2.1.** Summary of co-substrates digested with dairy manure.

| Co-digested Substrates (Dairy manure was used as base substrate and the following listed substrates used as co-substrates) | Reactor type/ Process type | Temperature (˚C) | Size of reactors (L) | Ratios | Optimum C/N ratio | Characteristics of substrate | Methane yield/ OLR | Pretreatment | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Acidified dairy cow manure (ADCM) | Batch | 50 | 0.5 | ADCM:DM (%) 10:90, 20:80, 30:70 | - | Very high sulphate content | 138 (L kg$^{-1}$ VS) | 96% $H_2SO_4$ | (Sutaryo *et al*., 2012) |
| Agricultural residue (*clover, grass and wheat straw*) | Batch | 10, 20, 35±1 | 1 | Agriculture residue + manure at three given temperature ranges | 27:1 | - | 182 (mL $CH_4$ g$^{-1}$) | - | (Alkaya, *et al*., 2010) |
| Agro waste and energy crops | CSTR | 55 reduced to 47 | 380 | - | - | High carbon content | - | - | (Cavinato, *et al*., 2010) |
| Banana stalks | - | 35±1 | - | - | - | - | 23.9 (L) | - | (Meng *et al*., 2013) |
| Biowaste (*household source-sorted biowaste*) | Batch | 35 and 55 | - | - | - | - | 420-460 (mL $CH_4$ g$^{-1}$ VS) | Spiked with salmonella bacteria | (Paavola & Rintala, 2008) |
| By-products from sugar production (*sugar beet leaves (SBL), sugar beet top (SBT), sugar beet pulp (SBP)*) and desugared molasses | Batch | 37 and 55 | 4.5 | SBP:desugared molasses:DM:water (%)<br>15:35:0:50,<br>0:0:100:0,<br>8:19:3:70,<br>0:0:100:0,<br>5:0:95:0,<br>15:0:85:0,<br>50:0:50:0 | - | - | 500 (mL $CH_4$ g$^{-1}$ VS) | - | (Fang *et al*., 2011a) |

| **Co-digested Substrates (Dairy manure was used as base substrate and the following listed substrates used as co-substrates)** | **Reactor type/ Process type** | **Temperature (˚C)** | **Size of reactors (L)** | **Ratios** | **Optimum C/N ratio** | **Characteristics of substrate** | **Methane yield/ OLR** | **Pretreatment** | **Reference** |
|---|---|---|---|---|---|---|---|---|---|
| Canola meal oil (CO) | Batch | 35±2 | 0.5 | CO:DM<br>10:90, 20:80,<br>40:60,<br>100:0,<br>0:100 | 10 | High levels of lipids and proteins. Crude protein, soluble, cellulose, hemicelluloses, and lignin | 682 (L $CH_4$ kg$^{-1}$ VS) | - | (Atandia & Rahmana, 2012) |
| Cheese whey (CW) | Batch | 35 | 128 | DM:CW<br>80:20<br>65:35<br>50:50<br>35:65 | - | Protein and lactose rich with high organic matter content | 382 (L kg$^{-1}$ VS) | - | (Comino *et al*., 2012) |
|  | Batch | 35±0.5 | 0.1 | CW:DM<br>1:1 | - |  | 320 (mL $CH_4$ g$^{-1}$ VS) | - | (Bertin *et al*., 2013) |
| Cheese whey and poultry waste | - | - | - | - | - | - | - | - | (Patel and Madamwar, 1994) |
| Chicken feathers | - | 25 | 42 | - | - | >90% keratin, mainly as b-keratin. | 241 (L) | Dried for 8 weeks and 4 mm sieved | (Xia *et al*., 2012) |
| Chicken manure and wheat straw | Batch | 35 | 1 | 1:0, 0:1, 1:1 (DM:chicken manure) | 25:1, 27.2:1 and 30:1 | - | 234 (mL g$^{-1}$ VS) | Air dried, Cut into 2-3 cm pieces | (Wang *et al*., 2012c) |
| Corn stover | Batch | 35±1 | 2 | 1:1, 1:2, 1:3, 1:4 (cattle manure: | - | High percentage of | 194 (mL $CH_4$ g$^{-1}$ | NaOH treated | (Li *et al*., 2009c) |

| **Co-digested Substrates (Dairy manure was used as base substrate and the following listed substrates used as co-substrates)** | **Reactor type/ Process type** | **Temperature (˚C)** | **Size of reactors (L)** | **Ratios** | **Optimum C/N ratio** | **Characteristics of substrate** | **Methane yield/ OLR** | **Pretreatment** | **Reference** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | corn stover) | | lignocelluloses (cellulose, hemicelluloses and lignin, | VS) | | |
| | Fermenters | 35 | 10 | 4:1 (DM: corn stover) | - | | - | Grinded and 2 mm sieved | (Yue *et al*., 2013) |
| Corn stalks | - | 15, 35 and 55 | 3 | 1:1, 2:1, 3:1 (DM:corn stalks) | 25 to 30 | - | 25 (L kg$^{-1}$ VS) | Air dried, Cut into 2-3 cm pieces and 0.422 mm sieved | (Wang *et al*., 2012b) |
| Complex organic substrates (*cheese whey (CW), plain pasta (PP), meat pasta (MP), used vegetable oil (UVO), dog food:ice cream (DFI), cola beverage (CB), potatoes (P), switchgrass (SG), mouthwash (MW), cola:mouthwash (CMW)*) | CSTR | 35±1 | 0.250 | DM:CW (VS basis) 90:10, 75:25<br>DM:PP - 90:10, 75:25<br>DM:MP - 90:10, 75:25<br>DM:UVO- 75:25<br>DM:DFI - 50:25:25<br>DM:CB - 75:25<br>DM:P - 75:25<br>DM:SW - 75:25<br>DM:MW - 75:25<br>DM:CMW - 75:12.5:12.5 | - | High heterogeneous characteristics | 360 (mL $CH_4$ g$^{-1}$ VS) | - | (Labatut *et al*., 2011) |
| Corn waste, spent tea waste and | Batch | - | - | 1:1 | - | - | - | - | (Munda *et al*., 2012) |

| **Co-digested Substrates (Dairy manure was used as base substrate and the following listed substrates used as co-substrates)** | **Reactor type/ Process type** | **Temperature (˚C)** | **Size of reactors (L)** | **Ratios** | **Optimum C/N ratio** | **Characteristics of substrate** | **Methane yield/ OLR** | **Pretreatment** | **Reference** |
|---|---|---|---|---|---|---|---|---|---|
| kitchen waste | | | | | | | | | |
| Crops (*grass silage, oat straw and sugar beet tops*) | CSTR | 35±1 | - | - | - | - | - | Chopped to a 3 cm | (Wang *et al*., 2009) |
| Crude glycerin | CSTR and Induced bed | 55±1 | 5 | 6% glycerin | - | Carbon source. Glycerin ($C_3H_5OH$), propane-1,2, triol, and impurities including esters, water, soap stock, alcohol, and catalyst, depending on the vegetable oil quality and chemical process used | 0.60 ($m^3$ $CH_4$ $kg^{-1}$ VS) | Sonicated | (Castrillón *et al*., 2013a) |
| | CSTR | 35 increased to 55 | 2 | 4% glycerin -meso<br>6% glycerin – thermo | - | | 348 (L $CH_4$ $kg^{-1}$ COD) | Ultrasonic | (Castrillón *et al*., 2011) |
| | CSTR | 35 to 37 | 3 | 5% and 10% glycerin | - | | - | - | (Robra *et al*., 2010) |
| Duck manure | Batch | 35±1 | 2.5 | (DM:duck manure) 14%:11% | - | - | - | Screened out the straw and grounded | (Wan *et al*., 2012) |
| Desugared molasses | CSTR | 35 and 55 | 4.5 | Desugared molasses:DM:water | - | Less sugar, high ions such as sodium and | 260 (mL-$CH_4$ $g^{-1}$ VS) | - | (Fang *et al*., 2011b) |

| Co-digested Substrates (Dairy manure was used as base substrate and the following listed substrates used as co-substrates) | Reactor type/ Process type | Temperature (˚C) | Size of reactors (L) | Ratios | Optimum C/N ratio | Characteristics of substrate | Methane yield/ OLR | Pretreatment | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 0:100:0, 5:95:0, 15:85:0, 50:50:0 | | potassium and organic loading and protein. | | | |
| Fruit and vegetable wastes (FVW) | CSTR | 35 | 18 | DM:FVW<br>100:0,<br>80:20,<br>70:30,<br>60:40,<br>50:50 | - | Nitrogen and phosphorus | 0.45 ($m^3$ $CH_4$ $kg^{-1}$ VS) | Macerated | (Callaghan, *et al.*, 2002) |
| Fish offal (FO) | CSTR | 35 | 21.2 | DM:FO<br>100:0,<br>96:4,<br>94:6,<br>100:0,<br>96:0 | - | High fat/oil (High VFAs > 6% FO) | 0.3 ($m^3$ $CH_4$ $kg^{-1}$ VS) | Macerated | (Callaghan, *et al.*, 1998) |
| Food waste | Batch | 35±1 | 1 | FW/DM<br>8/4, 8/2.7,<br>8/2 (g $VS^{-1}$ $L^{-1}$) | 15.8 | Significant quantities of lipids (fats and oils) and proteins | 388 (mL $g^{-1}$ VS) | Grounded into smaller particles <3mm | (Zhang *et al.*, 2013) |
| | CSTR | 37 | | FW:DM<br>4:1, 3:2, 2:3 (w/w) | - | - | - | - | (Banks *et al.*, 2011) |
| | - | 37±2 | 2 | Beer; fat, oil, and grease (FOG); slaughterhouse waste; creamer | - | Creamer contains glucose syrup, hydrogenated | 280 (mL $g^{-1}$ VS) | - | (Zhu *et al.*, 2011) |

| **Co-digested Substrates (Dairy manure was used as base substrate and the following listed substrates used as co-substrates)** | **Reactor type/ Process type** | **Temperature (˚C)** | **Size of reactors (L)** | **Ratios** | **Optimum C/N ratio** | **Characteristics of substrate** | **Methane yield/ OLR** | **Pretreatment** | **Reference** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | with different ratios of DM. Ratios of 1:1, 1:1 for Beer:DM and FOG:DM obtained highest $CH_4$ yield. | | vegetable oil and casein. | | | |
| Food waste (FW) | Batch | 35 | 1 | FW:DM<br>32%:68%,<br>48%:52% | - | - | 311 (L kg$^{-1}$ VS) | Unscreened and screened DM | (El-Mashad *et al.*, 2010) |
| | CSTR | 36 | 2 | - | - | - | 0.63 (L $CH_4$ g$_{-1}$ VS) | Grounded to 2.5 mm, 4 mm, 8 mm | (Agyeman and Tao, 2014) |
| | Induced bed reactor (IBR) | 55 | - | DM/FW/glycerin<br>94/2/4<br>87/10/3<br>83/15/2<br>82/15/3<br>90/10/0 | 15.7 | - | 640 (L $CH_4$ kg$^{-1}$ VS) | Sonication pre-treatment | (Castrillón *et al.*, 2013b) |
| | CSTR | 36 and 55 | 5 | DM:FW:sewage sludge<br>7:2:1, 7:1:2 | Varied between 16 and 18 | Complex ploymers for sewage sludge | 603 (L $CH_4$ kg$^{-1}$ VS) | - | (Marañón *et al.*, 2012) |
| | CSTR | 37 | 5 | Oil concentrations rose 9, 12, 15, 18 gCOD L$^{-1}$ | - | - | 0.90 (gCOD-$CH_4$/gVS) | FW crushed to 1-3 mm | (Neves *et al.*, 2009a) |
| | CSTR | 37 | 5 | - | - | Lipids rich waste | 3.09 (L $CH_4$ day$^{-1}$) | Crushed to 1-3 mm particle | (Neves *et al.*, 2009b) |

| **Co-digested Substrates (Dairy manure was used as base substrate and the following listed substrates used as co-substrates)** | **Reactor type/ Process type** | **Temperature (˚C)** | **Size of reactors (L)** | **Ratios** | **Optimum C/N ratio** | **Characteristics of substrate** | **Methane yield/ OLR** | **Pretreatment** | **Reference** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | size | |
| | Batch | 35 and 55 | 10 | DM:FW<br>1:0,<br>7:3 | - | Significant quantities of lipids (fats and oils) and proteins | 0.17 $CH_4$ L/g VS/day | - | (Yamashiro *et al*., 2013) |
| Food waste (FW) | CSTR | 35±2 | 3.5 | FW:DM<br>0:1,<br>1:1,<br>3:1,<br>6:1 | - | High organic content of VS | 3.97 $L\ L^{-1}$ $day^{-1}$ | Shredded into 5-10mm pieces | (Li *et al*., 2010) |
| Garbage and screened swine manure | Upflow anaerobic filter reactor (UAFR) | 53 | 4 | Garbage:swine manure:DM<br>1:16:27<br>1:19:12 | - | - | 270 (mL $g^{-1}$ VTS) | - | (Liu *et al*., 2009) |
| Grass silage (GS) | CSTR | 35±1 | 5 | GS:DM %<br>0:100, 10:90, 20:80, 30:70, 40:60 | - | - | 0.27 ($m^3$ $CH_4$ $kg^{-1}$ VS) | Chopped to > 3 cm | (Wang *et al*., 2010) |
| Guinea pig manure | Full scale digesters | - | - | - | - | - | - | - | (Garfí *et al*., 2011) |
| Kitchen waste (KW) | Batch | 35 | - | KW:DM<br>0:1, 1:1, 2:1, 3:1, | - | Organic matter 37-55% | 233 (mL $g^{-1}$) | - | (Li *et al*., 2009a) |

| **Co-digested Substrates (Dairy manure was used as base substrate and the following listed substrates used as co-substrates)** | **Reactor type/ Process type** | **Temperature (˚C)** | **Size of reactors (L)** | **Ratios** | **Optimum C/N ratio** | **Characteristics of substrate** | **Methane yield/ OLR** | **Pretreatment** | **Reference** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 1:0 | | | | | |
| Kitchen residue | Batch | 35 | - | 1:1 | - | - | - | - | (Li *et al*., 2008) |
| Olive mill waste (OMW) | CSTR | 37 and 55 | 75 | 3:1 | - | Fats and recalcitrant phenolic compounds | 179 (L $CH_4$ kg$^{-1}$ VS) | - | (Goberna *et al*., 2010) |
| | CSTR | 35 | 0.750 | OMW:DM<br>2:8, 8:2 | - | - | 0.91 (L $CH^4$ L$^{-1}$ d$^{-1}$) | - | (Dareioti *et al*., 2010) |
| Maize | CSTR | 35±1 | 5 | Maize (%)-30, 40, 60, 67. | - | - | 259 Nl $CH_4$ kg$^{-1}$ VS | Chopped to particle size of 3 cm | (Seppala *et al*., 2013) |
| Maize Silage (MS) | - | 35±2 | - | DM:MS:chicken manure<br>1:1:1 | - | - | - | - | (Yangin-Gomec & Ozturk, 2013) |
| | - | - | - | DM:MS<br>3:1 | - | - | - | - | (Ayhan *et al*., 2013) |
| | Full scale biogas plant | - | - | - | - | - | - | - | (Linke *et al*., 2013) |
| | - | - | 5 | MS:DM (g)<br>59.5:850.5,<br>119:791 | - | Crude protein | - | - | (Lomborg *et al*., 2009) |
| Milk (waste milk) | Batch | 35 | 20 | 1:1 | - | Cefazolin, and a | - | - | (Callaghan *et* |

| **Co-digested Substrates (Dairy manure was used as base substrate and the following listed substrates used as co-substrates)** | **Reactor type/ Process type** | **Temperature (˚C)** | **Size of reactors (L)** | **Ratios** | **Optimum C/N ratio** | **Characteristics of substrate** | **Methane yield/ OLR** | **Pretreatment** | **Reference** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | β-lactam antibiotic. Butyric acid. | | | *al*., 1997) |
| | Batch | 35±0.5 | 0.5 | Milk (%)-1, 3, 5, 7, 9, 14, 19 | 10.7 | | - | - | (Wu *et al*., 2011) |
| Municipal solid waste (MSW) | Batch | 55 | 4.5 | 1:1 | - | Higher concentrations of protein, heavy metals and xenobiotic compounds | 0.40 L $g^{-1}$ VS | - | (Hartmann & Ahring, 2005) |
| | Up-flow anaerobic filters (UAF) | - | 222 | MSW:DM (%) 81:9 | 20 | | 0.19 ($m^3$ $CH_4$ $kg^{-1}$ VS) | - | (Macias-Corral *et al*., 2008) |
| Mulched switchgrass (MuS) | Batch | 35 | 6 | MuS (%) 20 | - | 12–19% lignin, 31–37% hemicellulose and 29–45% cellulose. | 45.7 (L $kg^{-1}$) | Finely chooped | (Frigon *et al*., 2012) |
| Palm oil mill effluent (POME) | Batch | 28 and 34 | 1.5 | POME:DM (%) 60:40, 70:30, 80:20 | - | - | 1875 mL | - | (Sidik *et al*., 2013) |
| Poultry wastes | - | 35 | 3.6 | - | - | Organic/nitrogen rich waste | - | - | (Zhang *et al*., 2011b) |
| Rice straw | - | 35 | - | 1:1 | - | - | 440 (L $kg^{-1}$) | - | (Dong *et al*., 2013) |
| Rice chaff, rice straw, and rice husk | Batch | 25-35 | 900 | - | - | - | - | - | (Vivekanandan & Kamaraj, 2011) |
| Sugar beets (top-T; whole-W; root-R) | Batch | 55 | 0.8 | DM:T:W:R<br>500:0:0:0<br>300:200:0:0 | - | - | - | Blended to pass through 3 mm sieve | (Umetsu *et al*., 2006) |

| **Co-digested Substrates (Dairy manure was used as base substrate and the following listed substrates used as co-substrates)** | **Reactor type/ Process type** | **Temperature (˚C)** | **Size of reactors (L)** | **Ratios** | **Optimum C/N ratio** | **Characteristics of substrate** | **Methane yield/ OLR** | **Pretreatment** | **Reference** |
|---|---|---|---|---|---|---|---|---|---|
| | | | | 400:0:100:0<br>450:0:0:50 | | | | | |
| Llama manure (LM), Sheep manure (SM) | Batch | 18-25 | 2 | LM:DM:SM:Water (%) – 17.2:0:0:0:82.8, 8.6:0:6.3:85.1, 5.7:13.4:4.2:76.6 | - | - | 0.14 ($m^3$ $CH_4$ $kg^{-1}$ VS) | - | (Alvarez & Liden, 2009) |
| Table olive debittering and washing effluent (DWE), pig manure (PM) | Batch and continuous | 35 and 55 | 50 | DM:PM:DWE (%) 50:25:25, 40:30:30, 35:35:30, 30:30:40, 25:35:40 | 16.6 | Polyphenols | - | - | (Zarkadas & Pilidis, 2011) |
| Tomato waste (TW) | - | 35±1 | 15 | Greenhouse TW (%) 85:15, 70:30, 55:45, 40:60, 25:75 and 10:90 | - | Agricultural organic waste | 0.665 (L $L^{-1}$ $d^{-1}$) | Dried TW | (Sözer & Yaldiz, 2012) |
| | - | 34±0.5 | 2000 | DM:TW 90:10, 80:20, 60:40, 40:60, 20:80 | 15 | - | 0.22 ($m^3$ $CH_4$ $kg^{-1}$ VS) | Blended | (Saev *et al.*, 2009) |
| Turkey processing wastewater (TPW) | - | 37 | 15 | DM:TPW (%) 100:0, 67:33, 50:50, 33:67, 0:100. | - | Nutrients | - | - | (Ogejo & Li, 2010) |
| Vegetable processing wastes | Batch | 35±2 | 0.5 | - | - | - | 329 (mL $CH_4$ g | Grounded to 1 mm particle | (Molinuevo-Salces *et al.*, |

| Co-digested Substrates (Dairy manure was used as base substrate and the following listed substrates used as co-substrates) | Reactor type/ Process type | Temperature (˚C) | Size of reactors (L) | Ratios | Optimum C/N ratio | Characteristics of substrate | Methane yield/ OLR | Pretreatment | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | VS) | size | 2010) |
| Waste water sludge (WWS) | Batch | 35 | 2.5 | DM:WWS 1:0, 4:1, 3:2, 2:3, 1:4, 0:1 | - | - | 36.91 (L $kg^{-1}$) | - | (Li *et al*., 2011) |
| Water hyacinth (WH) | Batch | 26 | - | Waste paper:DM:WH 4:5:5, 8:5:5, 12:5:5, 20:5:5 | - | - | 0.34 (L $g^{-1}$) | - | (Yusuf & Ify, 2011) |
| Wheat straw (WS) | CSTR | 37, 44, and 52 | 5 | DM:WS 75:25, 26:74, 78:22, 100:0 | 32 | High content of lignocellulosic | 0.18-0.21 (L $kg^{-1}$ VS $day^{=1}$) | Stream exploded | (Risberg *et al*., 2013)] |
| Whey mix (WM) | Batch | 35 | 128 | DM:WM (L) 32:32 | - | Easy degradable carbohydrates | 211.4 (L $CH_4$ $kg^{-1}$ VS) | - | (Comino *et al*., 2009) |
| Whole stillage (WS) | CSTR | 37 | 5 | WS:DM 85:15 | 21 | High levels of proteins | 0.31 (N L $CH_4$ $g^{-1}$ VS) | - | (Westerholm *et al*., 2012) |
| Wine distillery wastewater (WDW) | - | - | - | WDW:DM:inoculum 16:64:20 | - | Phenolic compounds: catechol, tannins and p-Coumaric acid | 172 (mL $g^{-1}$ VS) | - | (Akassou *et al*., 2010) |

cm=centimeters; mm=millimeters; w/w=wet weight basis; VTS=volatile total solids; DM=dairy manure.

Ratios underlined in Table 2.1 are the optimum mixing ratios under which the biogas and $CH_4$ production were highest for that specific study.

### 2.5.1 Food Waste

Food wastes are promising co-substrate due to their availability from increased food processing and the ban on landfilling of organic wastes in some countries (Li *et al*., 2009c; Murto *et al*., 2004). Wastes from food processing are high in organic matter and are therefore ideal for AD. However, AD of food waste alone may be hindered by the presence of various inhibitors. Co-digesting food waste with DM increases biogas production and $CH_4$ yield (Zhang *et al*., 2013; Banks *et al*., 2011). Furthermore, it improves the nutrient balance, adjusts buffering capacity by mixing the substrate and promotes activities of the microbial population. Co-digestion of manure and food wastes has an effect of reducing the accumulation of VFA and other AD intermediates, consequently resulting in higher $CH_4$ content from the beginning as compared to the digestion of food wastes alone (Murto *et al*., 2004; El-Mashad *et al*., 2010).

Fruit and vegetable wastes tend to have low total solids and high volatile solids, and are easily degraded in an AD process. However, the rapid hydrolysis of these feedstocks may lead to acidification of a digester and the consequent inhibition of methanogenesis (Ward *et al*., 2008).

Several co-digestion studies on food waste with DM showed positive results. For example, during mesophilic anaerobic co-digestion of cattle manure and fruit and vegetable wastes (FVW) in a CSTR at 35˚C, Callaghan *et al*. (2002) found that increasing the percentage of FVW from 20% to 50% increased the $CH_4$ yield from 230 to 450 L/kgVS added. Co-digestion of food waste with DM enhanced gas production by 0.8–5.5 times as compared to the digestion with DM alone (Li *et al*., 2010). The suitability of food as a co-digestion substrate is subject to seasonal and composition variation, as well as high heterogeneity associated with the nutrient content and the particle sizes (Neves *et al*., 2009a; Agyeman & Tao, 2014). Nevertheless, food that is rich in lipids and easily biodegradable carbohydrates, such as confectionary wastes, used oil, pasta, ice cream, whey, etc., has been identified as a prime co-substrate (Labatut *et al*., 2011). However, co-digestion of manure with one or more food wastes needs to be investigated because composition of food wastes varies widely and biodegradation of organic matter may not be the same. Also, micronutrient concentrations in food wastes may influence metabolic activities of microorganisms and the resulting biogas production (Zhang *et al*., 2011a). Other challenges with food wastes are that, like food composition, the supply of food wastes might not be constant to meet the waste need for co-digestion.

### 2.5.2 Energy crops and agricultural residues

Use of energy crops for co-digestion is very challenging due to the lignocellulosic composition of the material (Li *et al*., 2009c; Yue *et al*., 2013). The most common type of energy crops include *cereals* (e.g. barley, wheat, oats, maize and rye) s*tarch and sugar crops* (e.g. potato, sugar beet, Jerusalem artichoke and sugarcane), *cellulose crops* (e.g. straw, wood, short rotation coppice (SRC), and s*olid energy crops* (e.g. cardoon, sorghum, kenaf, prickly pear, whole crop maize, reed canary grass, miscanthus and SRC willow, poplar and eucalyptus) (Sims *et al*., 2006). Most energy crops have a high carbon content that balances the low C/N ratio in DM, effectively decreasing the risk of ammonia inhibition (Lehtomäki *et al*., 2007), but lignocellulosic materials are difficult to degrade (Li *et al*., 2009c; Yue *et al*., 2013). Co-digestion of DM with 40% sugar beet tops improved $CH_4$ production by 150% (Umetsu *et al*., 2006), while the co-digestion of switch grass with DM did not show any increase in the biogas yield (Ahn *et al*., 2010). Similarly, the co-digestion of DM with rice husks did not improve the overall biogas production. In some cases, it may be profitable to pre-treat energy crops to ease the hydrolysis step and consequently reduce the retention times (Lehtomäki *et al*., 2007; Ward *et al*., 2008).

#### 2.5.2.1 Pretreatment improves biogas yields

Pretreatment can be defined as treating the waste matter before anaerobically treating the waste to achieve quick and easy biodegradability of waste matter. There are various pre-treatment techniques such as size reduction, steam explosion, lime pretreatment, ammonification and chemical treatment (acid and alkaline treatment). Each pretreatment has its own effect(s) on the cellulose, hemicellulose and lignin—the three main components of lignocellulosic biomass (Hendriks & Zeeman, 2009). Pretreatment has proven to be a simple and effective method to improve biodegradability of lignocellulose materials (Li *et al.,* 2009c)

Angelidaki & Ahring (2000) studied the effects of pretreatment on fiber degradation of manure using several treatment methods such as mechanical maceration, chemical treatment (NaOH, $NH_4OH$), hemicellulolytic or cellulolytic enzymes treatment and biological treatment (hemicellulose degrading bacterium B4). They found that mechanical maceration resulted in an average increase of the biogas potential of approximately 17%. Chemical treatment of the fibers with bases such as NaOH, $NH_4OH$ or a combination of bases resulted in an increased of $CH_4$ potential. But treatment of the fibers with hemicellulolytic or cellulolytic enzymes showed that there was no significant increase of the $CH_4$ potential. Biological treatment of manure fibers with the hemicellulose degrading bacterium B4 resulted in a significant increase of the biogas potential of manure. Pretreatment of substrate prior to AD process to accelerate the hydrolysis of substrate has shown improved biogas productions (Hendriks & Zeeman, 2009; Vavilin *et al*., 2008). Of several pretreatment methods, acid and alkaline pre-treatment is widely used due to cost, effectiveness and ease of controlling pH following AD of lignocellulosic material.

Methane yield is affected by particle sizes, lignin quantity and pre-treatment used. Siddique *et al*. (2014) stated that the oxidation of $H_2O_2$ pretreatment of petrochemical wastewater co-digested with beef and dairy cattle manure converted the recalcitrant materials into biodegradable ones and achieved the best performance at mesophilic conditions in terms of reactor stability and wastewater stabilization. Li *et al*. (2009c) investigated the performance and synergistic effect of co-digestion of cattle manure (CM) with NaOH-pretreated corn stover (CS) to determine the optimal CM/CS ratio and found that co-digestion of CM with NaOH-treated corn stover could be one of the options for efficient biogas production and waste treatment. The study on NaOH pretreated kitchen waste and sulfuric acid pretreated cattle manure showed that the total lignin, cellulose, and hemicelluloses were reduced by 13.1, 9.4, and 28% on dry basis and the $CH_4$ yield and VS reduction for acid-pretreated CM were 116 and 74% higher than raw CM (Li *et al*., 2009b). However, by-products such as potassium ions resulting from caustic pre-treatment and resins generated in breaking the lignin are likely to add inhibition (Chen *et al*., 2008). Studies have shown that pre-treatment such as size reduction of residues permits faster and better hydrolysis (Agyeman & Tao, 2014; Angelidaki & Ahring, 2000). In addition, energy crops that are lignocellulosic have low digestibility, require prolonged HRT (Ward *et al*., 2008), and they are also slow in adapting to the microbial population in the reactor (Lindorfer *et al*., 2008).

When using the energy crops and other high strength organic wastes for co-digestion, size reduction might be very important because microbial hydrolysis of lignocellulose is a slow and difficult process. Co-digestion studies showed that pretreating the co-digested substrate by reducing the particle size (by chopping, grounding or blending) or chemical treatment such as NaOH, etc, benefits co-digestion process (Table 2.1). Research has shown that $CH_4$ yield is inversely proportional to particle size (Agyeman & Tao, 2014). Angelidaki & Ahring (2000) described that the best results showed an approximately 20% increase of the biogas potential with fibers smaller than 0.35 mm, whereas the increase was approximately 16% with fibers of size 2 mm. There was no significant difference in biogas potential from fibers in the 5-20 mm range. Large particle size provides a small surface area, whereas small particle size provides a large surface area for the microorganism, thus greater microbial degradation of organic waste and increased biogas production. Therefore, by reducing particle size, methane production may be increased, and thus also the energy output.

### 2.5.3 Biofuel industry waste

Increase of biodiesel production has led to increased production of crude glycerin (Siles *et al*., 2009), which cannot be digested alone because it contains higher amounts of carbon and lower nitrogen (Thompson & He, 2006). To overcome the nitrogen deficiency, Robra *et al*. (2010) digested cattle slurry with crude glycerin in CSTR reactors at mesophilic range, and found that the optimal proportion of glycerin that should be mixed with cattle slurry ranged between 5% and 10% (w/w) to obtained optimum biogas production. Castrillón *et al*. (2011) described that under mesophilic conditions, the addition of 4% glycerin to screened manure increased biogas production by up to 400%. Application of sonication (20 kHz, 0.1 kW, and 4 min) to a mixture of manure + 4% glycerin increased production of biogas by up to 800% compared to untreated manure. This study also showed that best results were obtained under thermophilic conditions using sonicated mixtures of ground cattle manure with 6% added glycerin. Similarly, study by Castrillón *et al*. (2011) showed that 6% crude glycerin with cattle manure achieved the best results.

## 2.6 Development of mathematical models for co-digestion

The complicated and unpredictable nature of potential co-substrate creates difficulty in predicting and anticipating the whole impact of co-digestion (Angelidaki and Ellegaard, 2003), including the possibility of inhibitory behavior (Chen *et al*., 2008). The optimum mixing ratio, composition of substrate, physical characteristics (e.g. particle size) and any pre-treatment of the possible co-substrate may affect the biogas production (Umetsu *et al*., 2006). Some co-substrates, irrespective of temperature, are known to cause inhibition and/or toxicity to the digestion process (Alvarez and Lidén, 2008). Intermittent addition of small quantities of tallow oil has the potential to interrupt a stable digestion process (Robra *et al*., 2010) due to the accumulation of ammonia and the presence of long chain fatty acids (LCFA) from blood and tallow oil, respectively. Theoretical $CH_4$ yield based on the COD has a discrepancy when compared to the actual $CH_4$ yield (Labatut *et al*., 2011). Methane yield using prediction model(s) are always higher than the observed. Therefore, knowing the individual substrate composition is not enough to determine $CH_4$ yields. In theory, based on the stoichiometry (bioenergetics), carbon content, COD or volatile solids, the $CH_4$ yield can be approximated. This value is normally higher than the actual value because the theoretical approach doesn't account for biodegradability. Substrate biodegradability is defined as the ease of biological break down, which is dependent on both the physical and chemical properties (Labatut *et al*., 2011).

Mathematical models can be used to account for biodegradability in co-digestion. To know the correct combination of different substrates, many experiments are needed (i.e. Bio-chemical $CH_4$ potential - BMP tests). Accurate modeling can help to define a correct ratio between different organic substrate to be digested. However, for this purpose, typical mono substrate models are not suitable as they are not capable to simulate the biodegradation behaviors of different substrates in terms of kinetics, particle size, nutrient balance, etc. The first co-digestion model was proposed by Bozinis *et al*. (1996). In this model the main component groups (i.e. lipids, carbohydrates and proteins) are simulated and it is a steady state mathematical model. A mathematical model for co-digesting piggery waste, olive-mill and dairy waste based on batch kinetic experiments was developed by Gavala *et al*. (1996). This model considers a four-step process (hydrolysis, acidogenesis, acetogenesis, and methanogenesis). The model cannot predict the $CH_4$ concentration, and does not consider the inhibitory effect by high ammonia concentration, volatile fat acids (VFAs), long chain fat acids (LCFAs) and hydrogen. Kiely *et al*. (1997) developed and validated a two-stage mathematical model of acidogenesis and methanogenesis, including ammonia inhibition and pH prediction.

The 2002 International Water Association (IWA) Task Group for Mathematical Modelling of AD Processes developed a comprehensive mathematical model known as ADM1-Anaerobic Digestion Model no. 1 (Batstone *et al.*, 2002), which was based on the knowledge of modelling and simulation of AD systems developed over the previous years. However, this model neglects some processes involved in the AD such as sulphate reduction, acetate oxidation, homo-acetogenesis, solids precipitation and inhibition due to sulphide, nitrate, LCFAs, weak acid and base (Fujita *et al.*, 1980).

## 2.7 Significance of dairy manure co-digestion studies

Most of the studies have been done in a laboratory as either batch or continuous stirred tank reactors (CSTR) of volumes less than 5 L operating in the mesophilic temperature range (35–40˚C) (Table 2.1). Co-digestion in the thermophilic range (55–65˚C) with an optimum temperature of 55–60˚C, although more expensive to operate, has been shown to be an excellent option in terms of better performance and achieving high sanitation compared to the mesophilic operations (Atandi and Rahman, 2012). The overall reporting of the biogas production and $CH_4$ yield are inconsistent. Some are based on the COD while others are based on VS or dry matter content, and others are based on either per unit time or volume. This inevitably brings about discrepancies in comparing various co-substrates. In contrast, there is an agreement on the need to optimize composition, organic loading, hydraulic retention times and proper monitoring of the processes. In a conventional anaerobic liquid digestion (or wet digestion), <10% total solids (TS) is used but the use of food wastes and other agricultural wastes may increase TS content. Dairy manure with <10% TS are less acidic and more likely to produce high volumes of biogas (Itodo and Awulu, 1999). When solid content of manure is between 25% and 40%, the AD process is described as dry digestion, whereas when the solids content is below 15% it is referred to as wet digestion. Instead of wet AD, dry AD might be beneficial due to the relatively stable process and lower energy input.

## 2.8 Conclusions

1) To a large extent, waste from agro industry (food waste and energy crops) has been co-digested with dairy manure, but waste from biofuels industry and alga waste has not been explored.
2) Co-digestion improves the nutrient balance, thus improving the biogas yield. The important process parameters affecting the co-digestion process are optimum mixing ratio, C/N ratio, temperature, OLR, and HRT. Sometimes particle size reduction might be very important because microbial hydrolysis of lignocellulose is a slow and difficult process. Smaller particle size provides large surface areas for the microorganism, thus greater microbial degradation of organic waste, which increases biogas production. Therefore, by reducing particle size, methane production and energy output may be increased.
3) Most of the co-substrate digested with dairy manure have had successful correlation of biogas production and methane yield using empirical data based on laboratory studies. Nevertheless, there is need for generalized models that can simulate co-digestion and a systematic approach is required in defining the direction for the exploitation of co-

digestion and selection of co-substrate.

## 2.9 References

Agyeman, F. O., & Tao, W. (2014). Anaerobic co-digestion of food waste and dairy manure: Effects of food waste particle size and organic loading rate. *Journal of Environmental Management, 133*, 268-274.

Ahn, H. K., Smith, M. C., Kondrad, S. L., and White, J. W. (2010). Evaluation of biogas production potential by dry anaerobic digestion of switchgrass–animal manure mixtures, *Appl. Biochem. Biotech. 160*, 965–975.

Ahring, B. K., Ibrahim, A. A., Mladenovska, Z. (2001). Effect of temperature increase from 55 to 65 °C on performance and microbial population dynamics of an anaerobic reactor treating cattle manure. *Water Res. 35*, 2446–2452.

Akassou, M., Kaanane, A., Crolla, A., Kinsley, C. (2010). Statistical modelling of the impact of some polyphenols on the efficiency of anaerobic digestion and the co-digestion of the wine distillery wastewater with dairy cattle manure and cheese whey. IWA Publishing, London, UK, *Water Science and Technology, 62*, 3, 475-483.

Alkaya, E., Erguder, T. H., & Demirer, G. N. (2010). Effect of operational parameters on anaerobic co-digestion of dairy cattle manure and agricultural residues: A case study for the Kahramanmaraş region in Turkey. *Engineering in Life Sciences, 10(6)*, 552-559.

Alvarez, R., & Liden, G. (2009). Low temperature anaerobic digestion of mixtures of llama, cow and sheep manure for improved methane production. *Biomass and Bioenergy, 33, 3*, 527-533.

Alvarez, R., and Lidén, G. (2008). Semi-continuous co-digestion of solid slaughterhouse waste, manure, and fruit and vegetable waste, *Renew. Energ. 33*, 726–734.

Amon, T., Hackl, E., Jeremic, D., Amon, B., Boxberger, J. (2001). Biogas production from animal wastes, energy plants and organic wastes. In: van Velsen, A. F. M. & Verstraete, W. H. (eds), Proc. 9th World Congress on Anaerobic Digestion: 381-386.

Angelidaki, I., & Ahring, B. K. (2000). Methods for increasing the biogas potential from the recalcitrant organic matter contained in manure. *Water Science and Technology: a Journal of the International Association on Water Pollution Research, 41*, 3, 189-94.

Angelidaki, I., and Ellegaard, L. (2003). Co-digestion of manure and organic wastes in centralized biogas plants, Appl. *Biochem. Biotech. 109*, 95–105.

Atandi E. M., and Rahman, S. (2012). Suitability of canola meal for anaerobic co-digestion with dairy manure, *Biol. Eng. T. 5(2)* (2012), pp. 71–86.

Atandia, E., & Rahmana, S. (2012). The impact of organic loading and canola meal oil content on dairy manure co-digestion for biogas production. *American Journal of Biomass and Bioenergy, 1*, 1.

Ayhan, A., Liu QingYu, Alibas, K., Unal, H. (2013). Biogas production from maize silage and dairy cattle manure. Medwell Online, Faisalabad, Pakistan, *Journal of Animal and Veterinary Advances, 12, 5*, 553-556.

Banks, C. J., Salter, A. M., Heaven, S., Riley, K. (2011). Energetic and environmental benefits of co-digestion of food waste and cattle slurry: a preliminary assessment. Elsevier Ltd, Oxford, UK, Resources, *Conservation and Recycling, 56, 1*, 71-79.

Batstone, D. J., Keller, J., Angelidaki, I., Kalyuzhnyi, S. V., Pavlostathis, S. V., Rozzi, A., Sanders, W. T. M., Siegrist, H., Vavilin, V. A. (2002). Anaerobic digestion model no. 1. Rep. No. 13. IWA Publishing, London.

Beddoes, J, C., Bracmort, K. S., Burns, R. T., Lazarus, W. F., Herbert, N., Boyd, W., Hansen, C, L., Raj Raman, D., Kintzer, B. (2007). An Analysis of Energy Production Costs from Anaerobic Digestion Systems on U.S. Livestock Production Facilities. Technical Note No. 1. Natural Resources Conservation Service, USDA.

Beddoes, J.C., Bracmort, K.S., Burn, R.B., Lazarus, W.F. (2007). An analysis of energy production costs from anaerobic digestion systems on US livestock production facilities. Technical Note No. 1. USDA, Natural Resources Conservation Service.

Bekkering, J., Broekhuis, A. A. and Van Gemert, W. J. T. (2010). Optimisation of a green gas supply chain: a review, *Bioresource Technol. 101*, 450–456.

Bertin, L., Grilli, S., Spagni, A., & Fava, F. (2013). Innovative two-stage anaerobic process for effective codigestion of cheese whey and cattle manure. *Bioresource Technology, 128*, 779-783.

Bozinis, N. A., Alexiou, I. E., Pistikopoulos, E. N. (1996) A mathematical model for the optimal design and operation of an anaerobic co-digestion plant. *Water Sci Technol 34*:383–391.

Brown, D., & Li, Y. (2013). Solid state anaerobic co-digestion of yard waste and food waste for biogas production. *Bioresource Technology, 127*, 275-280.

Callaghan, F. J., Luecke, K., John, W. D. A., Thayanithy, K., & Forster, C. F. (1997). Co-Digestion of Cattle Slurry and Waste Milk under Shock Loading Conditions. *Journal of Chemical Technology & Biotechnology, 68, 4*, 405-410.

Callaghan, F. J., Wase, D. A. J., Thayanithy, K., & Forster, C. F. (2002). Continuous co-digestion of cattle slurry with fruit and vegetable wastes and chicken manure. *Biomass and Bioenergy, 22, 1*, 71-77.

Callaghan, F. J., Wase, D. A. J., Thayanithy, K., & Forster, C. F. (1998). An Examination of the Continuous Anaerobic Co-Digestion of Cattle Slurry and Fish Offal. *Process Safety and Environmental Protection, 76, 3*, 224-228.

Cantrell, K. B., Ducey, T., Ro, K. S., and Hunt, P. G. (2008). Livestock waste-to-bioenergy generation opportunities, *Bioresource Technol. 99*, 7941–7953.

Carucci, G., Carrasco, F., Trifoni, K., Majone, M., and Beccari, M. (2005). Anaerobic digestion of food industry wastes: effect of co-digestion on methane yield, *J. Environ. Eng. 131*, 1037–1045.

Castrillón, L., Fernández-Nava, Y., Ormaechea, P., & Marañón, E. (2011). Optimization of biogas production from cattle manure by pre-treatment with ultrasound and co-digestion with crude glycerin. *Bioresource Technology, 102, 17*, 7845-7849.

Castrillón, L., Fernández-Nava, Y., Ormaechea, P., Marañón, E. (2013a). Methane production from cattle manure supplemented with crude glycerin from the biodiesel industry in CSTR and IBR. *Bioresource Technology, 127*, 312-317.

Castrillón, L., Marañón, E., Fernández-Nava, Y., Ormaechea, P., & Quiroga, G. (2013b). Thermophilic co-digestion of cattle manure and food waste supplemented with crude glycerin in induced bed reactor (IBR). *Bioresource Technology, 136*, 1, 73-77.

Cavinato, C., Fatone, F., Bolzonella, D., & Pavan, P. (2010). Thermophilic anaerobic co-digestion of cattle manure with agro-wastes and energy crops: comparison of pilot and full scale experiences. *Bioresource Technology, 101, 2*, 545-50.

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

Comino, E., Riggio, V. A., & Rosso, M. (2012). Biogas production by anaerobic co-digestion of cattle slurry and cheese whey. *Bioresource Technology, 114*, 46-53.

Comino, E., Rosso, M., Riggio, V. (2009). Development of a pilot scale anaerobic digester for biogas production from cow manure and whey mix. *Bioresource Technology 21*, 5072–5078.

Dareioti, M. A., Dokianakis, S. N., Stamatelatou, K., Zafiri, C., Kornaros, M., Clarke, P. K., Alibardi, L. (2010). Exploitation of olive mill wastewater and liquid cow manure for biogas production. Elsevier Ltd, Oxford, UK, *Waste Management, 30, 10*, 1841-1848.

Department of Energy. Energy Information Administration. (2007). Average Wholesale Electric Price by NERC region, 2001–2005. Form EIA–861, Annual Electric Power Industry Report. Washington, DC. Retrieved from http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesalet2.xls on Aug 5th, 2013.

Dong, L., JingQing, Y., YongMing, S., Feng, Z., ZhenHong, Y. (2013). Continuous anaerobic co-digestion of rice straw and cow manure for biogas production. Chinese Society of Agricultural Machinery, Beijing, China, Nongye Jixie Xuebao. *Transactions of the Chinese Society for Agricultural Machinery, 44, 1*, 101-105.

El-Mashad, H. M., & Zhang, R. (2010). Biogas production from co-digestion of dairy manure and food waste. *Bioresource Technology, 101, 11*, 4021-4028.

El-Mashad, H. M., Zeeman, G., van, L. W. K., Bot, G. P., & Lettinga, G. (2004). Effect of temperature and temperature fluctuation on thermophilic anaerobic digestion of cattle manure. *Bioresource Technology, 95, 2*, 191-201

Fang, C., Boe, K., & Angelidaki, I. (2011a). Anaerobic co-digestion of by-products from sugar production with cow manure. *Water Research, 45, 11*, 3473-3480.

Fang, C., Boe, K., & Angelidaki, I. (2011b). Anaerobic co-digestion of desugared molasses with cow manure; focusing on sodium and potassium inhibition. *Bioresource Technology, 102, 2*, 1005-1011.

Frigon, J. C., Roy, C., & Guiot, S. R. (2012). Anaerobic co-digestion of dairy manure with mulched switchgrass for improvement of the methane yield. *Bioprocess and Biosystems Engineering, 35, 3*, 341-9.

Fujita, M., Scharer, J. M., Moo-Young, M. (1980). Effect of corn stover addition on the anaerobic digestion of swine manure. *Agric Wastes 2*:177–184.

Garfí, M., Ferrer-Martí, L., Perez, I., Flotats, X., & Ferrer, I. (2011). Codigestion of cow and guinea pig manure in low-cost tubular digesters at high altitude. *Ecological Engineering, 37, 12*, 2066-2070.

Gavala, H. N., Skiadas, I. V., Bozinis, N. A., Lyberatos, G. (1996). Anaerobic co-digestion of agricultural industries' wastewaters. *Water Sci Technol 34*:67–75.

Goberna, M., Schoen, M. A., Sperl, D., Wett, B., Insam, H. (2010). Mesophilic and thermophilic co-fermentation of cattle excreta and olive mill wastes in pilot anaerobic digesters. Elsevier Ltd, Oxford, UK, *Biomass and Bioenergy, 34, 3*, 340-346.

Gumisiriza, R., Mshandete, A. M., Rubindamayugi, M. S. T., Kivaisi, A. K., & Kansiime, F. (2009). Enhancement of anaerobic digestion of Nile perch fish processing wastewater. *African Journal of Biotechnology, 8, 2*, 328-333.

Hartmann, H., & Ahring, B. K. (2005). Anaerobic digestion of the organic fraction of municipal solid waste: Influence of co-digestion with manure. *Water Research, 39, 8*, 1543-1552.

Hashimoto, A. G. (1983). Conversion of straw-manure mixtures to methane at mesophilic and thermophilic temperatures. *Biotechnology and Bioengineering, 25, 1*, 185-200.

Hendriks, A. T., & Zeeman, G. (2009). Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresource Technology, 100, 1*, 10-8.

Hubbard R. K., and Lowrance, R. R. (1998). Dairy cattle manure management, in Agricultural Utilization of Municipal, Animal and IndustrialWastes,USDAAgricultural Research Service, Washington, DC, 91–102.

Itodo, I. N., and Awulu, J. O. (1999). Effects of total solids concentrations of poultry, cattle, and piggery waste slurries on biogas yield, T. ASABE, 42, 1853–1856.

Kashyap, D.R., Dadhich, K.S., Sharma, S.K. (2003). Biomethanation under psychrophilic conditions: a review. *Bioresource Technol. 87*, 147–153.

Kayhanian, M., Rich, D. (1995). Pilot-scale high solids thermophilic anaerobic digestion of municipal solid waste with an emphasis on nutrient requirements. *Biomass Bioenergy 8*, 433–444.

Kiely, G., Tayfur, G., Dolan, C., Tanji, K. (1997). Physical and mathematical modelling of anaerobic digestion of organic wastes. *Water Res 31*:534–540.

Labatut, R. A. (2012). Anaerobic Biodegradability of Complex Substrates. A Dissertation, Cornell University.

Labatut, R. A., and Gooch, C. A. (2012). Monitoring of Anaerobic Digestion Process to Optimize Performance and Prevent System Failure. Retrieved from http://www.manuremanagement.cornell.edu/Pages/General_Docs/Events/21.Rodrigo.Labatut.pdf on April 3rd, 2014.

Labatut, R. A., Angenent, L. T., & Scott, N. R. (2011). Biochemical methane potential and biodegradability of complex organic substrates. *Bioresource Technology, 102, 3*, 2255-64.

Lazarus, W. F. (2008). Farm-based anaerobic digesters as an energy odour control technology: background policy issues, in USDA Agricultural Economic Report 843. Retrieved from http://www.usda.gov/oce/reports/energy/AnerobicDigesters0308.pdf on July 18th, 2013.

Lehtomäki, A., Huttunen, S., & Rintala, J. A. (2007). Laboratory investigations on co-digestion of energy crops and crop residues with cow manure for methane production: Effect of crop to manure ratio. *Resources, Conservation and Recycling, 51, 3*, 591-609.

Li, J., Jha, A. K., He, J., Ban, Q., Chang, S., & Wang, P. (2011). Assessment of the effects of dry anaerobic codigestion of cow dung with wastewater sludge on biogas yield and biodegradability. *International Journal of Physical Sciences, 6, 15*, 3679-3688.

Li, R. P., Liu Y. P., Li X. J. (2008). Biogasification performance of anaerobic co-digestion of kitchen residues and cattle manure. Renewable Energy Resources Press, Yingkou, China, Kezaisheng Nengyuan / Renewable Energy Resources, 26, 2, 64-68.

Li, R., Chen, S., & Li, X. (2010). Biogas production from anaerobic co-digestion of food waste with dairy manure in a two-phase digestion system. *Applied Biochemistry and Biotechnology, 160, 2*, 643-54.

Li, R., Chen, S., and Li, X. (2009a). Anaerobic Co-digestion of Kitchen Waste and Cattle Manure for Methane Production. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 31, 20, 1848-1856.

Li, R., Chen, S., Li, X., Saifullah, L. J., He, Y., & Zhu, B. (2009b). Anaerobic Codigestion of Kitchen Waste with Cattle Manure for Biogas Production. *Energy & Fuels : an American Chemical Society Journal, 23, 2*, 2225-28.

Li, X., Li, L., Zheng, M., Fu, G., Lar, J.S. (2009c). Anaerobic codigestion of cattle manure with corn stover pretreated byhydroxide for efficient biogas production. *Energy Fuel 23*, 4635–4639.

Li, Y. Y., Sasaki, H., Yamashita, K., Seki, K., & Kamigochi, I. (2002). High-rate methane fermentation of lipid-rich food wastes by a high-solids co-digestion process. *Water Science and Technology : a Journal of the International Association on Water Pollution Research, 45, 12*, 143-50.

Lin, Y., Yin, J., Wang, J., & Tian, W. (2012). Performance and microbial community in hybrid anaerobic baffled reactor-constructed wetland for nitrobenzene wastewater. *Bioresource Technology, 118*, 128-135.

Lindorfer, H., Corcoba, A., Vasilieva, V., Braun, R., Kirchmayr, R. (2008). Doubling the organic loading rate in the co-digestion of energy crops and manure – a full scale case study. *Bioresource Technology. 99*, 1148–1156.

Linke, B., Muha, I., Wittum, G., & Plogsties, V. (2013). Mesophilic anaerobic co-digestion of cow manure and biogas crops in full scale German biogas plants: A model for calculating the effect of hydraulic retention time and VS crop proportion in the mixture on methane yield from digester and from digestate storage at different temperatures. *Bioresource Technology, 130*, 689-695.

Liu, K., Tang, Y. Q., Matsui, T., Morimura, S., Wu, X. L., & Kida, K. (2009). Thermophilic anaerobic co-digestion of garbage, screened swine and dairy cattle manure. *Journal of Bioscience and Bioengineering, 107, 1*, 54-60.

Lomborg, C. J., Holm-Nielsen, J. B., Oleskowicz-Popiel, P., & Esbensen, K. H. (2009). Near infrared and acoustic chemometrics monitoring of volatile fatty acids and dry matter during co-digestion of manure and maize silage. *Bioresource Technology, 100, 5*, 1711-9.

Macias-Corral, M., Samani, Z., Hanson, A., Smith, G., Funk, P., Yu, H., & Longworth, J. (2008). Anaerobic digestion of municipal solid waste and agricultural waste and the effect of co-digestion with dairy cow manure. *Bioresource Technology, 99, 17*, 8288-93.

Marañón, E., Castrillon, L., Quiroga, G., Fernandez-Nava, Y., Gomez, L., & Garcia, M. M. (2012). Co-digestion of cattle manure with food waste and sludge to increase biogas production. *Waste Management, 32, 10*, 1821-1825.

Meng, T., XiaoLing, L., ShiZhong, L., JianShuang, L., YunFei, Z. (2013). Biogas production characteristics of solid-state anaerobic co-digestion of banana stalks and manure. Chinese Society of Agricultural Engineering, Beijing, China, *Transactions of the Chinese Society of Agricultural Engineering, 29, 7*, 177-184.

Molinuevo-Salces, B., Garcia-Gonzalez, M. C., Gonzalez-Fernandez, C., Cuetos, M. J., Moran, A., & Gomez, X. (2010). Anaerobic co-digestion of livestock wastes with vegetable processing wastes: A statistical analysis. *Bioresource Technology, 101, 24*, 9479-9485.

Moller, H. B., Sommer, S. G., and Ahring, B. (2004). Methane productivity of manure, straw and solid fractions of manure, *Biomass Bioenerg. 26*, 485–495.

Munda, U. S., Pholane, L., Kar, D. D., Meikap, B. C. (2012). Production of bioenergy from composite waste materials made of corn waste, spent tea waste, and kitchen waste co-mixed with cow dung. Taylor & Francis, Philadelphia, USA, *International Journal of Green Energy, 9, 4*, 361-375.

Murto, M., Björnsson, L., and Mattiasson, B. (2004). Impact of food industrial waste on anaerobic co-digestion of sewage sludge and pig manure, *J. Environ. Manage. 70*,101–107.

Neves, L., Oliveira, R., & Alves, M. M. (2009a). Co-digestion of cow manure, food waste and intermittent input of fat. *Bioresource Technology, 100, 6*, 1957-62.

Neves, L., Oliveira, R., & Alves, M. M. (2009b). Fate of LCFA in the co-digestion of cow manure, food waste and discontinuous addition of oil. *Water Research, 43, 20*, 5142-5150.

Novak, J. T., and Carlson, D. A. (1970). The Kinetics of Anaerobic Long-chain Fatty-acid Degradation. *J. Water Pollut. Control Fed., 42*, 1932.

Ogejo, J. A., & Li, L. (2010). Enhancing biomethane production from flush dairy manure with turkey processing wastewater. *Applied Energy, 87, 10*, 3171-3177.

Paavola, T., & Rintala, J. (2008). Effects of storage on characteristics and hygienic quality of digestates from four co-digestion concepts of manure and biowaste. *Bioresource Technology, 99, 15*, 7041-50.

Patel, C. and Madamwar, D. (1994). Effect of metals on biomethanation of mixture of cheese whey, poultry waste and cattle dung. Fresenius Environmental Bulletin, 3, 10, 604-609.

Risberg, K., Sun L. i., Levén, L., Horn, S. J., Schnürer, A. (2013). Biogas production from wheat straw and manure - impact of pretreatment and process operating parameters. Elsevier Ltd, Oxford, UK, *Bioresource Technology, 149*, 232-237.

Robra, S., Serpa, . C. R., de, O. A. M., Neto, J. A. A., & Santos, J. V. (2010). Generation of biogas using crude glycerin from biodiesel production as a supplement to cattle slurry. *Biomass and Bioenergy, 34, 9*, 1330-1335.

Saev, M., Koumanova, B., & Simeonov, I. V. (2009). Anaerobic co-digestion of wasted tomatoes and cattle dung for biogas production. *J. Univ. Chem. Tech. Mtlgy, 44*, 55-60.

Schievano, A., Pognani, M., D'Imporzano, G., and Adani, F. (2008). Predicting anaerobic biogasification potential of ingestates and digestates of a full-scale biogas plant using chemical and biological parameters, *Bioresource Technol. 99*, 8112–8117.

Seppala, M., Pyykkonen, V., Vaisanen, A., & Rintala, J. (2013). Biomethane production from maize and liquid cow manure - Effect of share of maize, post-methanation potential and digestate characteristics. *Fuel, 107*, 209-216.

Sialve, B., Bernet, N., and Bernard, O. (2009). Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable, *Biotech. Adv. 27*, 409–416.

Siddique, M. N. I., Sakinah, A. M. M., & Zularisam, A. W. (2014). Mesophilic and thermophilic biomethane production by co-digesting pretreated petrochemical wastewater with beef and dairy cattle manure. *Journal of Industrial and Engineering Chemistry, 20, 1*, 331-337.

Sidik, U. H., Razali, F., Rafidah, S. W. A., Maigari, F. (2013). Biogas production through co-digestion of palm oil mill effluent with cow manure. Usmanu Danfodiyo University, Sokoto, Nigeria, *Nigerian Journal of Basic and Applied Sciences, 21, 1*, 79-84.

Siegert, I., Banks, C. (2005). The effect of volatile fatty acid additions on the anaerobic digestion of cellulose and glucose in batch reactors. Process Biochem 40:3412–3418

Siles, L. J. A., Martin, S. M. A., Chica, P. A. F., & Martin, M. A. (2009). Anaerobic digestion of glycerol derived from biodiesel manufacturing. *Bioresource Technology, 100, 23*, 5609-5615.

Sims, R., Hastings, A., Schlamadinger, B., Taylor, G., & Smith, P. (2006). Energy crops: current status and future prospects. *Global Change Biology, 12, 11*, 2054-2076.

Sosnowski, P., Wieczorek, S., Ledakowicz. (2003). Anaerobic co-digestion of sewage sludge and organic fraction of municipal solid wastes. *Advances in Environmental Research, 7, 3*, 609-616.

Sözer, S., Yaldiz, O. (2012). Methane production from tomatoes wastes via co-fermentation. CIGR-EurAgEng, Valencia, Spain, Energy, biomass and biological residues. International Conference of Agricultural Engineering - CIGR-AgEng 2012: Agriculture and Engineering for a Healthier Life, Valencia, Spain, P-0686.

Sutaryo, S., Ward, A. J., & Møller, H. B. (2012). Thermophilic anaerobic co-digestion of separated solids from acidified dairy cow manure. *Bioresource Technology, 114*, 195-200.

Tafdrup, S. (1995). Viable energy production and waste recycling from anaerobic digestion of manure and other biomass materials, *Biomass Bioenerg. 9*, 303–314.

Thompson, J. C., & He, B. B. (2006). Characterization of Crude Glycerol from Biodiesel Production from Multiple Feedstocks. *Applied Engineering in Agriculture, 22, 2*, 261-266.

Umetsu, K., Yamazaki, S., Kishimoto, T., Takahashi, J., Shibata, Y., Zhang, C., Misaki, T., Komiyama, M. (2006). Anaerobic co-digestion of dairy manure and sugar beets. International Congress Series, 1293, 307-310.

USDA, Changes in the Size and Location of U.S. Dairy Farms (2007). Retrieved from http://www.ers.usda.gov/ersDownloadHandler.ashx?file=/media/430528/err47b_1_.pdf on Aug 7th, 2013.

USEPA (U.S. Environmental Protection Agency). (2012). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010 (publication No. EPA 430-R-12-001). Washington, DC: Author. Retrieved from http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2012-Main-Text.pdf on July 18th, 2013.

USEPA (U.S. Environmental Protection Agency). (2013). Common manure handling systems. Ag 101. Retrieved from http://www.epa.gov/oecaagct/ag101/dairymanure.html on April 22nd, 2013.

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.

Vivekanandan, S., Kamaraj, G. (2011). Effect of co-digestion of cow dung with rice chaff, rice straw and rice husk in biogas production using anaerobic digestion. International Research Journals, Sapele, Nigeria, *International Research Journal of Biotechnology, 2, 5*, 114-118.

Wan, S., Xi, B., Xia, X., Li, M., Lv, D., Wang, L., & Song, C. (2012). Using fluorescence excitation-emission matrix spectroscopy to monitor the conversion of organic matter during anaerobic co-digestion of cattle dung and duck manure. *Bioresource Technology, 123*, 439-44.

Wang, F., Hidaka, T., Tsuno, H., & Tsubota, J. (2012a). Co-digestion of polylactide and kitchen garbage in hyperthermophilic and thermophilic continuous anaerobic process. *Bioresource Technology, 112*, 67-74.

Wang, H., Lehtomäki, A., Tolvanen, K., Puhakka, J., & Rintala, J. (2009). Impact of crop species on bacterial community structure during anaerobic co-digestion of crops and cow manure. *Bioresource Technology, 100, 7*, 2311-5.

Wang, H., Tolvanen, K., Lehtomäki, A., Puhakka, J., & Rintala, J. (2010). Microbial community structure in anaerobic co-digestion of grass silage and cow manure in a laboratory continuously stirred tank reactor. *Biodegradation, 21, 1*, 135-46.

Wang, X. J., Yang, G. H., Feng, Y. Z., & Ren, G. X. (2012b). Potential for Biogas Production from Anaerobic Co-Digestion of Dairy and Chicken Manure with Corn Stalks. *Advanced Materials Research Zug*, 2484-2492.

Wang, X., Yang, G., Feng, Y., Ren, G., & Han, X. (2012c). Optimizing feeding composition and carbon-nitrogen ratios for improved methane yield during anaerobic co-digestion of dairy, chicken manure and wheat straw. *Bioresource Technology, 120*, 78-83.

Ward, A. J., Hobbs, P. J., Holliman, P. J., & Jones, D. L. (2008). Optimisation of the anaerobic digestion of agricultural resources. *Bioresource Technology, 99, 17*, 7928-40.

Westerholm, M., Hansson, M., Schnürer, A. (2012). Improved biogas production from whole stillage by co-digestion with cattle manure. Elsevier Ltd, Oxford, UK, *Bioresource Technology, 114*, 314-319.

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. Biosyst. Eng. 89*, 457–471.

Wu, X., Dong, C., Yao, W., & Zhu, J. (2011). Anaerobic digestion of dairy manure influenced by the waste milk from milking operations. *Journal of Dairy Science, 94, 8*, 3778-86.

Xia, Y., Massé, D. I., McAllister, T. A., Kong, Y., Seviour, R., & Beaulieu, C. (2012). Identity and diversity of archaeal communities during anaerobic co-digestion of chicken feathers and other animal wastes. *Bioresource Technology, 110*, 111-9.

Yamashiro, T., Lateef, S. A., Ying, C., Beneragama, N., Masahiro, I., Nishida, T., Umetsu, K., Ihara, I. (2013). Anaerobic co-digestion of dairy cow manure and high concentrated food processing waste. *Journal of Material Cycles and Waste Management, 15, 4*, 539-547.

Yangin-Gomec, C., & Ozturk, I. (2013). Effect of maize silage addition on biomethane recovery from mesophilic co-digestion of chicken and cattle manure to suppress ammonia inhibition. Elsevier Ltd, Oxford, UK, *Energy Conversion and Management, 71*, 92-100.

Yiridoe, E. K., Gordon, R and Brown, B. B. (2009). Non-market co-benefits and economic feasibility of on-farm biogas energy production, *Energ. Policy 37*, 1170–1179.

Yue, Z., Chen, R., Yang, F., MacLellan, J., Marsh, T., Liu, Y., & Liao, W. (2013). Effects of dairy manure and corn stover co-digestion on anaerobic microbes and corresponding digestion performance. *Bioresource Technology, 128, 2*, 65-71.

Yusuf, M. O. L., Ify, N. L. (2011). The effect of waste paper on the kinetics of biogas yield from the co-digestion of cow dung and water hyacinth. Elsevier Ltd, Oxford, UK, *Biomass and Bioenergy, 35, 3*, 1345-1351.

Zarkadas, I. S., & Pilidis, G. A. (2011). Anaerobic co-digestion of table olive debittering & washing effluent, cattle manure and pig manure in batch and high volume laboratory anaerobic digesters: effect of temperature. *Bioresource Technology, 102, 8*, 4995-5003.

Zhang, C., Xiao, G., Peng, L., Su, H., & Tan, T. (2013). The anaerobic co-digestion of food waste and cattle manure. *Bioresource Technology, 129*, 170-176.

Zhang, L., Lee, Y. W., and Jahng, D. (2011a). Anaerobic co-digestion of food waste and piggery wastewater: focusing on the role of trace elements, *Bioresource Technol. 102*, 5048–5059.

Zhang, P., Zeng, G., Zhang, G., Li, Y., Zhang, B., Fan, M. (2008). Anaerobic co-digestion of biosolids and organic fraction of municipal solid waste by sequencing batch process. *Fuel Process Technol 89*:485–489.

Zhang, R., El-Mashad, H. M., Hartman, K., Wang, F., Liu, G., Choate, C., and Gamble, P. (2007). Characterization of food waste as feedstock for anaerobic digestion, *Bioresource Technol. 98*, 929–935.

Zhang, Y., Zamudio, C. E. M., Zhu, Z., Linville, J. L., Chen, S., & He, Q. (2011b). Robustness of archaeal populations in anaerobic co-digestion of dairy and poultry wastes. *Bioresource Technology, 102, 2*, 779-785.

Zhu, D., Wan, C., Li, Y. (2011). Anaerobic co-digestion of food wastes and dairy manure for enhanced methane production. American Society of Agricultural and Biological Engineers, St Joseph, USA, *Biological Engineering Transactions, 4, 4*, 195-206.

# CHAPTER 3 - ANAEROBIC CO-DIGESTION OF DAIRY MANURE WITH POTATO WASTE

**Sai Krishna Reddy Yadanaparthi [a,d], Lide Chen [b,d,*], Benton Glaze [c,d]**

[a] Environmental Science Program, University of Idaho, Moscow, ID, USA
[b] Department of Biological and Agricultural Engineering, University of Idaho, Moscow, ID, USA
[c] Department of Animal and Veterinary Science, University of Idaho, Moscow, ID, USA
[d] Twin Falls Research and Extension Center, University of Idaho, Twin Falls, ID, USA

## 3.1 Abstract

In this study, anaerobic co-digestion of dairy manure (DM) and potato waste (PW) was evaluated to determine the best mixing ratio in terms of biogas and methane ($CH_4$) productions. Batch lab-scale anaerobic co-digestion of DM with PW was conducted at three different temperature ranges (thermophilic (55-57˚C), mesophilic (35-37˚C), and ambient (20-25˚C) temperatures). The tests were conducted at five DM:PW mixing ratios (100:0, 90:10, 80:20, 60:40, and 40:60) on a volatile solids (VS) basis. During the 30 days of batch digestion, the highest cumulative biogas and $CH_4$ production (CBP) of 182 liters (L) and 93 L was achieved for the thermophilic co-digestion at the mixing ratio of 80:20; 76 L and 43 L for the mesophilic co-digestion at the mixing ratio of 90:10; and 33 L and 8 L for the digestion of DM alone (the mixing ratio of 100:0) at ambient temperature, respectively. Based on test results the optimum mixing ratio depends on temperature. The concentrations of VFA and $NH_3$-N and pH were not concerns for either co-digestion of DM and PW or digestion of DM alone in terms of process stability. Thermophilic temperature proved to be the best temperatures in terms of biogas and $CH_4$ productions.

Keywords: anaerobic digestion; dairy manure; potato waste; biogas; methane.

## 3.2 Introduction

Dairy production is one of the single largest agricultural activities in the state of Idaho, USA. All cattle and calves in the state of Idaho as of January 1, 2014 totaled 2,190,000 head (USDA, 2014). Dairy manure (DM) is a common organic waste from the dairy industry with an estimated annual production of 22 tons of DM/cow/year (USEPA, 2013b). Major air pollution problems are associated with DM as carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$) and ammonia ($NH_3$) gases are released into the atmosphere. The main greenhouse gas is $CH_4$, which is 20 times more efficient as $CO_2$ at trapping heat in the atmosphere (National Greenhouse Gas Inventories Programme, 1996). The $CH_4$ emissions increased by 64.0 percent from 31.7 teragrams of $CO_2$ equivalents (Tg $CO_2$ Eq.) in 1990 to 52.0 Tg $CO_2$ Eq. in 2010 due to the growth in animal production (mainly from dairy and swine manure) (USEPA, 2012). Appropriate treatment of DM is necessary to minimize pollution.

In addition to the dairy industry, Idaho is the largest potato producing state in the USA (USDA, 2011). According to National Agricultural Statistics of the United States Department of Agriculture (USDA, 2011), approximately 42.9 billion pounds of potatoes were produced in USA where Idaho alone produced 12.8 billion pounds. Among Idaho’s total potato production, 800 million pounds, which was approximately 6% of Idaho's total potato production, were considered as waste due to shrinkage and losses (USDA, 2011). Waste produced from potato processing is a disposal problem for the processor. Some potatoes are unusable for fresh market or dehydration because they do not meet quality standards of size or grade. These potatoes are considered as potato waste (PW). There are a number of ways that can be used to dispose of PW, which include landfills, application to cropland, and composting (Nelson, 2010). The volume of PW is too large to be disposed of economically through the above methods. The accumulation or disposal of PW leads to serious consequences such as sprouting and re-growth of potatoes, nematodes, infestations, pathogen exposure to surrounding crops, source of late blight inoculums, leaf roll virus, and other diseases (Olsen *et al.,* 2001). Additionally, decomposing of PW leads to nutrient leaching to ground and surface waters (Olsen *et al.,* 2001). Finding a treatment method to properly dispose of PW is a challenging task.

Anaerobic digestion (AD) has been regarded as a promising technology to treat organic waste (USEPA, 2013a). The microorganisms in the AD process transform organic constituents and nitrogen-containing compounds into biogases in the absence of oxygen. The main components of biogas are $CH_4$ and $CO_2$. Methane can be recovered and diverted to generate heat and electricity. Research has shown that AD of DM brings many benefits including pathogen destruction, odor reduction, reduced lagoon loading, and biogas generation (Rico *et al.,* 2011). Digestion of DM alone proves less efficient than co-digesting DM with other organic waste, which provides additional nutrients (carbon to nitrogen ratio - C/N ratio) and acts as a buffering agent (Macias-Corral *et al.,* 2008; Umetsu *et al.,* 2006). Co-digestion is a process in which additional organic materials are added for higher digestion efficiency. Co-digestion of two or more waste sources enhances biogas and $CH_4$ production. Several studies have been performed to determine the efficiency of the co-digestion process (Li *et al.,* 2009a, 2009b). However, co-digestion is efficient only at certain mixing ratios under suitable pH and temperature conditions.

The stability of the AD process can be determined by pH value. The pH influences the bacterial activity of the AD process since each type of bacteria (acidogenesis, acetogenesis and methanogenesis) survives and reproduces within a specific and narrow pH range. Methanogenesis is more susceptible to change in pH than acidogenesis or acetogenesis. Methanogenic bacteria survive best at an optimal pH of 7.0-7.2. If a pH value decreases below 6.1 or increases above 8.5, due to accumulation of volatile fatty acids (VFAs) or due to increase in concentrations of ammonia nitrogen ($NH_3$-N), the rate of $CH_4$ production declines (Lay *et al.,* 1997). The existence of each type of bacteria at different stages of the AD process requires the pH value to vary from acidic (5.2) to neutral (7.5) throughout the AD process.

Temperature is one of the main factors influencing the process of AD. According to the literature, changes in temperature result in destruction of solids, biogas production, and $CH_4$ content. Several studies have reported on AD of waste materials at the ambient temperatures (AT) (WU *et al.,* 2006; Hills and Roberts, 1981), mesophilic temperatures (MT), and thermophilic temperatures (TT) (Kim *et al.,* 2006; Choorit & Wisarnwan, 2007). Most of the pilot scale or conventional AD processes were carried out at the MT (Sakar *et al.,* 2009). At the TT, faster reaction rate occurred with a higher destruction of pathogens and a higher biogas production (Kim *et al.,* 2006), and the reduction in volatile solids (VS) content will be greater at the TT than at the MT (Choorit & Wisarnwan, 2007).

For the co-digestion studies, mixing ratio is one of the important parameters to determine the efficiency of the digestion process. A study on anaerobic co-digestion of DM and food waste (FW) indicated that co-digesting 60% FW with 40% DM enhanced biogas production with a HRT of 20 days (El-Mashad and Zhang, 2010). When a batch anaerobic co-digestion test of DM and sugar beets (SB) was performed, it was determined that a mix of 60% DM and 40% SB produced 1.49 times more $CH_4$ than digestion of DM alone (Umetsu *et al.,* 2006). Previous studies showed differences in appropriate mixing ratios for co-digestion of different waste products. There is a limited amount of information on anaerobic co-digestion of DM and PW.

In this study, DM was co-digested with PW in a batch digestion system to determine the best mixing ratio at three temperature ranges (thermophilic (55-57˚C)), mesophilic (35-37˚C), and ambient (20-25˚C)). The main objective of this study was to investigate the effect of temperature and mixing ratios on anaerobic co-digestion of DM and PW in terms of biogas and $CH_4$ production.

## 3.3 Materials and Methods

### 3.3.1 Materials

#### 3.3.1.1 Anaerobic batch digester setup

The AD tests were carried out using digesters constructed with PVC pipes having dimensions of 39.5 cm x 27.8 cm (height x diameter) as shown in Figs. 3.1A-B. The total volume of each digester was 24 L with a working volume of 16 liters. One end of the PVC pipe was completely sealed with a cap (bottom portion of anaerobic digester) and the other end was covered with a flat plastic transferable cap attached with wing type screws to make it an openable top (top portion of anaerobic digester) as shown in Fig. 3.1A. Temperature and pH probes (submersible Automatic Temperature Compensation (ATC) probe - Model # 3983701-010BTV12, Cole-Parmer, Chicago, IL), connected to a display monitor (Model # pH 550 pH/orp, Eutech instruments, Nijkerk, Netherlands) were inserted into the digester through a hole that was properly sealed to make the system gas tight.

A 1.27 centimeters (cms) internal diameter pipe was installed at the middle portion of the openable cap to collect gas samples (septa provided at the open end for gas sampling). The middle portion of the 1.27 cms pipe was joined with "T" shaped fitting to collect the gases emitted through the AD process using a wet tip gas meter (Wet-tip gas meter Co., Nashville, Tennessee, USA). The wet-tip gas meter was used to monitor biogas generated in each digester. A high heat resistant (> 100 ˚C) 0.635 cms internal diameter flexible pipe was used as a heating coil to circulate hot water and to keep the substrate at the desired temperature. The heating coil was connected to the water heater as shown in Fig. 3.1A. The water heater (Model # M11OU6SS-INAL, Bradford White Corporation, Pennsylvania, USA) was used to supply hot water through the heating coil to maintain the inside temperature at pre-set levels. Two grundfos pumps (Model # UP15-100F and UPS15-58FC, Grundfos Pumps Corporation, Kansas, USA) were used to circulate hot water and to mix the waste within each digester. The hot water circulating pump, which was controlled by a timer, operated for 30 minutes every two hours. The waste mixing pump, which was also controlled by a timer, ran for 30 minutes every two hours.

### 3.3.1.2 Collection and preparation of waste

Dairy manure was collected from a commercial dairy located in Jerome, Idaho, USA. The collected manure was transported to the Waste Management Laboratory at the University of Idaho Twin Falls Research and Extension Center, located in Twin Falls, Idaho. The manure was screened with a 3 millimeter (mm) sieve to remove fibers and other large particles. Total solids (TS) and volatile solids (VS) were determined for the sieved manure. Fresh manure was collected for each experiment and was screened and analyzed for TS, VS, chemical oxygen demand (COD), volatile fatty acids (VFA), ammonia nitrogen ($NH_3$-N), total Kjeldhal nitrogen (TKN), C/N ratio, and pH. The biological characteristics of DM (TS, VS, COD, VFA, $NH_3$-N, TKN, C/N ratio and pH values) are represented in Table 3.1.

**Table 3.1** - Biological Characteristics of Dairy Manure and Potato Waste.

| Parameters[1] | Dairy Manure | Potato Waste |
|---|---|---|
| TS (g/L) | 15±1 | 388 |
| VS (g/L) | 10±1 | 376 |
| COD (mg/L) | 25,840±2000 | 36,176 |
| $NH_3$-N (mg/L) | 316±100 | 477 |
| VFA’s (mg/L) | 3081±100 | 5,676 |
| TKN (mg/L) | 560±150 | 1,378 |
| pH | 7.0 to 8.3 | 5.1 at 16 ºC |
| C/N Ratio | 6 | 16 |

[1] TS: total solids; VS: volatile solids; COD: chemical oxygen demand; $NH_3$-N: ammonia nitrogen; VFAs: volatile fatty acids; TKN: total kjeldahl nitrogen; C/N ratio: carbon to nitrogen ratio; ºC: degrees Celsius.

Potato waste (PW) was collected from the University of Idaho Kimberly Research and Extension Center, located in Kimberly, Idaho. The PW was shredded into tiny pieces (< 3mm) with a food grinder. The shredded potato waste was mixed with tap water and then stored in a refrigerator at -2˚C for future use. The stored PW was used for all the experiments. The biological characteristics of PW are given in Table 3.1.

As compared to DM, PW contained higher percentages of TS, VS, chemical oxygen demand (COD), volatile fatty acids (VFA), ammonia nitrogen ($NH_3$-N), total Kjeldhal nitrogen (TKN), C/N ratio, but lower pH.

### 3.3.2 Methods

#### 3.3.2.1 Experiment design

To investigate the effect of the co-digestion performance of DM and PW, a complete randomized design with three levels of temperature (55-57, 35-37, and 25-28˚C) by five mixing ratios of DM to PW (100:0, 90:10, 80:20, 60:40, and 40:60) with a fixed HRT of 30 days were carried out. The HRT of 30 days was selected based on the experimental trials conducted prior to these experiments (data not included in this paper) and those found in the literature (Liu *et al.,* 2009). The total VS for all the ratios were kept constant at 165 g VS/batch test. Two replicate tests were performed for each combination of temperature and DM to PW ratio. The concentrations of $NH_3$-N, VFA and TKN were measured on a weekly basis. Total organic carbon (TOC) was measured at the beginning of each experiment. Daily pH and gas readings were recorded.

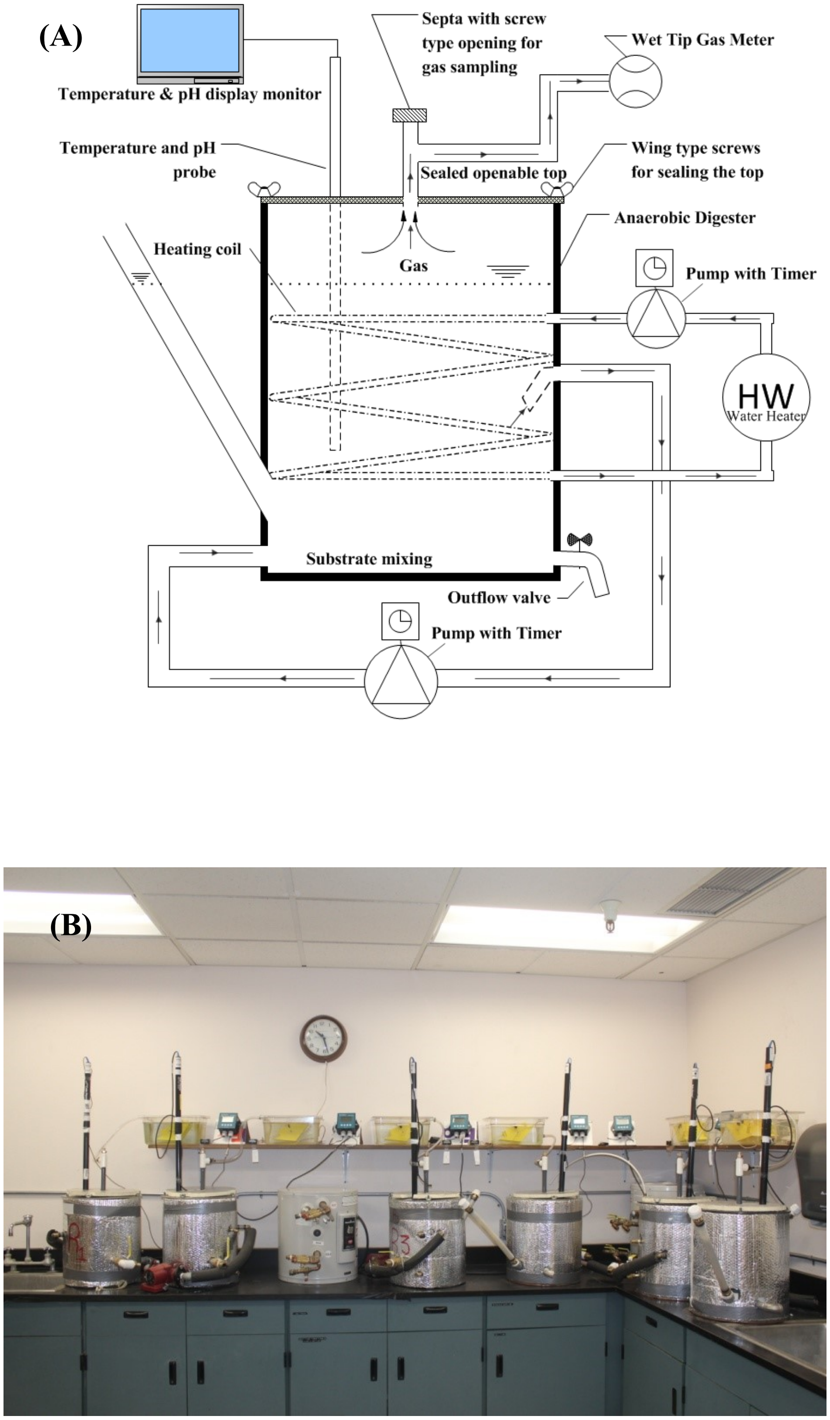


**Fig. 3.1** - Schematic of anaerobic digester and a picture of the anaerobic digesters in a laboratory setup (A) schematic of anaerobic digester, (B) picture of six anaerobic digesters used for anaerobic digestion test.

A total of six digesters were constructed to perform the laboratory experiments. Two water heaters were used for the AD tests, with each being connected to the three digesters.

### 3.3.2.2 Analytical methods

A spectrophotometer (DR/5000 Hach Company, Loveland, CO) was used for analyzing COD, TKN, VFA, $NH_3$-N and TOC. Procedures for analyzing COD, TKN, VFA, $NH_3$-N and TOC were based on the spectrophotometer manual (November 05 Edition 2, Catalog # DOC082.98.00670). Method 8000 (Reactor digestion method), Method 10242 (s-TKNTM method), Method 8196 (Esterification method, Acetic acid equivalent), Method 10031 (Salicylate method), and Method 10129 (Direct method) were used for COD, TKN, VFA, $NH_3$-N, and TOC analysis, respectively. Chemicals used for these analyses were purchased from the Hach Company according to the prescribed manual methods. The TS and VS were determined according to the APHA standard methods (APHA, 2012).

Biogas composition ($CH_4$ and $CO_2$) was measured with a gas chromatography (GC) (Model: 7890A, Agilent Technologies, Santa Clara, CA) equipped with a flame ionization detector (FID) and a thermal conductivity detector (TCD). A computer with Agilent ChemStation software was connected to the GC and used to view and export results. A gas-pro capillary column (60 m × 0.32 mm i.d.) was used for separation of a mixture of compounds. The column temperature was set at 35˚C and held for 4 min for an injection, then programmed at 30˚C min−1 to 150˚C and held for 0.25 min. The split injection (0.25 mL) was conducted with a split ratio of 10:1. High-purity helium was used as the carrier gas with a flow rate of 3.0 mL $min^{-1}$. Biogas samples were manually collected using 5 mL gas-tight syringes (Model# PN 5190-1540, Agilent technologies, Santa Clara, CA) from the digesters. The collected biogas samples were immediately injected into the GC through the GC's gas sampling valve.

### 3.3.3 Statistical analysis

The data were statistically analyzed using a two-way ANOVA to test the main effects of temperature and mixing ratio and their interaction for cumulative biogas production in a completely random design. The data were analyzed considering three temperatures (thermophilic, mesophilic and ambient) each at five mixing ratios (Dairy Manure: Potato Waste – 100:0, 90:10, 80:20, 60:40 and 40:60) for 30 days. The Tukey's Post Hoc test was applied to determine the significantly different treatment means. The statements of statistical significance were based on $P<0.05$ using SAS software version 9.3 (SAS, Cary, North Carolina, USA).

## 3.4 Results and discussion

The initial and final pH, cumulative biogas production, $CH_4$ yields and reduction of VS for the digestion of DM and PW at the five mixing ratios in three different temperature ranges (thermophilic, mesophilic, and ambient) are presented in Table 3.2.

### 3.4.1 Biogas and methane production and pH at thermophilic digestion.

At TTs, biogas production began on day 1 of digestion for all the mixing ratios (DM:PW) as shown in Figs. 3.2A-E. Among the five mixing ratios, the mixing ratio of 80:20 achieved the highest biogas production of 182 L followed by 105 L, 84 L, 73 L and 70 L for the mixing ratios of 90:10, 60:40, 40:60 and 100:0, respectively. Even though the VS loading rates for all the mixing ratios were the same (165 g VS in total for each mixing ratio), a higher biogas production for the mixing ratio of 80:20 can be attributed to synergistic effect that has taken place between DM and PW. Synergistic effects can be simplified into different forms such as increased alkalinity, balanced nutrients or improved biodegradability. Our test results showed that digestion of DM alone at TTs generated less biogas and $CH_4$ compared with the four co-digested mixing ratios. Typically, the C/N ratio of DM is around 6, which is considered low for the AD process (Wang *et al.,* 2012; Li *et al.,* 2009b; Li *et al.,* 2009c). Adding PW (C/N ratio of 16), into DM can improve the overall digestion process. Achieving the highest biogas production at the mixing ratio of 80:20 can be attributed to balanced nutrients (C/N ratio) between DM and PW.

The co-digestion at the mixing ratio of 80:20 produced the highest $CH_4$ yield of 0.563 L g-1 VS, which was 158% higher than that of digestion DM alone. The highest cumulative $CH_4$ yield of 93 L was achieved for the mixing ratio of 80:20 followed by 62L, 53L, 44L and 36L for the mixing ratios 90:10, 60:40, 40:60, and 100:0. All five mixing ratios used at TTs achieved over 70% $CH_4$ content in the biogas.

**Table 3.2**. Summary of the test results at different temperatures.

| Temperature | Ratios (DM:PW) | Initial pH | Final pH | Cumulative biogas (L) | Cumulative methane yield (L) | Methane yield (L g-1 VS) | VS reduction (%) |
|---|---|---|---|---|---|---|---|
| TT | 100:0 | 7.0 | 7.3 | 70 | 36 | 0.218 | 75.4 |
|  | 90:10 | 7.4 | 7.2 | 105 | 62 | 0.375 | 80.5 |
|  | 80:20 | 7.2 | 7.3 | 182 | 93 | 0.563 | 79.6 |
|  | 60:40 | 7.2 | 6.9 | 84 | 53 | 0.321 | 80.2 |
|  | 40:60 | 7.3 | 7.0 | 73 | 44 | 0.266 | 76.4 |
| MT | 100:0 | 7.6 | 7.0 | 68 | 34 | 0.206 | 70.3 |
|  | 90:10 | 8.2 | 7.1 | 76 | 43 | 0.260 | 68.8 |
|  | 80:20 | 8.1 | 7.2 | 65 | 36 | 0.218 | 71.1 |
|  | 60:40 | 7.3 | 7.1 | 49 | 25 | 0.151 | 71.6 |
|  | 40:60 | 7.1 | 6.8 | 45 | 22 | 0.133 | 73.8 |
| AT | 100:0 | 7.3 | 7.1 | 33 | 8 | 0.048 | 53.5 |
|  | 90:10 | 7.8 | 6.8 | 27 | 5 | 0.036 | 26.2 |
|  | 80:20 | 7.7 | 6.7 | 23 | 6 | 0.036 | 25 |
|  | 60:40 | 8.2 | 7.1 | 19 | 5 | 0.030 | 15 |
|  | 40:60 | 8.0 | 6.8 | 16 | 3 | 0.018 | 13 |

DM: dairy manure; PW: potato waste; TT: thermophilic temperature; MT: mesophilic temperature; AT: ambient temperature; L: liters; g: grams; VS: volatile solids; %: percentage.

As shown in Figs. 3.2A-E, there was a sudden reduction in pH for all five mixing ratios. The reduction in pH indicated the startup of hydrolysis and accumulation of acids. The stability of the digestion process depends on the pH of the substrate (Solera *et al.,* 2002).

Many studies describe a significant change in the AD process due to a change in pH (Macias-Corral *et al.,* 2008; Umetsu *et al.,* 2006; Marañón *et al.,* 2012). Previous research has shown that, for acidogenic bacteria, the optimum pH is 5.2 to 6.5 (Solera *et al.,* 2002; Li *et al.,* 2009a), whereas for methanogenic bacteria the optimum pH is in between 6.8 to 7.3 (Lay *et al.,* 1997). In this study, after feeding the substrate, the digester pH decreased due to increased VFA production. However, as VFAs were metabolized, the pH became stable over the digestion period. The lowest/highest pH recorded for the mixing ratio (DM:PW) of 100:0, 90:10, 80:20, 60:40, and 40:60 was 6.6/7.4, 6.2/7.3, 6.0/7.3, 6.2/7.0, and 5.9/7.1, respectively. For both the mixing ratios of 90:10 and 80:20, pH reached the lowest value on day 2 (pH of 6.2 for 90:10 and 6.0 for 80:20) and then increased till a stable value of 7.3 for the mixing ratio of 90:10 on day 14 and for the mixing ratio of 80:20 on day 20. For the rest of three mixing ratios, pH reached the lowest value on day 3. It then increased until the stable value of 7.4 for the mixing ratio of 100:0 on day 23, 7.0 for the mixing ratio of 60:40 on day 7 and 7.1 for the mixing ratio of 40:60 on day 16. Even though the pH during the digestion of DM alone (100:0) never fell below 6.6, the production of biogas was the lowest, which corresponds to lowest monitored VFA concentration (Fig. 3.6A).

### 3.4.2 Biogas and methane production and pH at mesophilic digestion.

The pH and biogas production obtained for the five mixing ratios (DM:PW) digested at MTs are shown in Figs. 3.3A-E. At MTs, biogas production started immediately on day 1 of digestion in all the digesters. Among the five mixing ratios, the mixing ratio of 90:10

achieved the highest biogas production of 76 L followed by 68 L, 65 L, 49 L and 45 L for the mixing ratios of 100:0, 80:20, 60:40, and 40:60, respectively.

Among the five mixing ratios (100:0, 90:10, 80:20, 60:40, and 40:60), three (80:20, 60:40, and 40:60) showed less biogas production than digestion of DM alone (100:0). The reason for the decrease in biogas production for the mixing ratios of 80:20, 60:40, and 40:60 might be due to the failure in breakdown of hard biodegradable components of PW. According to Elefsiniotis *et al.,* (2005), starch rich waste or wastewaters reduced the efficiency of AD process by lowering the pH. This study showed a decrease in pH when the amount of PW was increased (Figs. 3.3B-E). Another reason for the decrease in biogas production for the mixing ratios of 80:20, 60:40, and 40:60 might be due to the MTs tested. As the temperature was decreased from thermophilic to mesophilic the percentage reduction of VS was decreased (Table 3.2). When the VS portion of PW was increased at MTs, biogas production showed a decreasing trend. This indicates that the organic portion of PW was harder to degrade at MD than at TD. At MD, the mixing ratio 90:10 gave the highest $CH_4$ yield of 0.260 L g-1 VS, which was 26% higher than that of the mixing ratio of 100:0.

The highest cumulative $CH_4$ yield of 43 L was achieved for the mixing ratio of 90:10 followed by 36L, 34L, 25L and 22L for the mixing ratios of 80:20, 100:0, 60:40, and 40:60, respectively. Among the five mixing ratios used at the MTs, four mixing ratios (100:0, 90:10, 80:20 and 60:40) achieved 70% $CH_4$ content in the composition of biogas except the mixing ratio of 40:60.

As discussed previously, the pH for the mixing ratios of 100:0 and 90:10 was greater than 6.5 throughout the digestion period. However, for the mixing ratios of 80:20, 60:40, and 40:60, pH decreased below 6.5. For the mixing ratios of 80:20, 60:40, and 40:60, the lowest pH of 6.4, 6.3 and 5.7 was achieved on day 7. Then, the pH attained a neutral pH of 7.0 for the mixing ratio of 80:20 on day 13 and for the mixing ratio of 60:40 on day 18. But, for the mixing ratio of 40:60, the pH never reached a neutral pH of 7.0. This study showed that increasing the mixing ratio of PW resulted in lower pH. The desirable pH range of 6.5 to 7.3 tended to be better for mesophilic co-digestion of DM and PW.

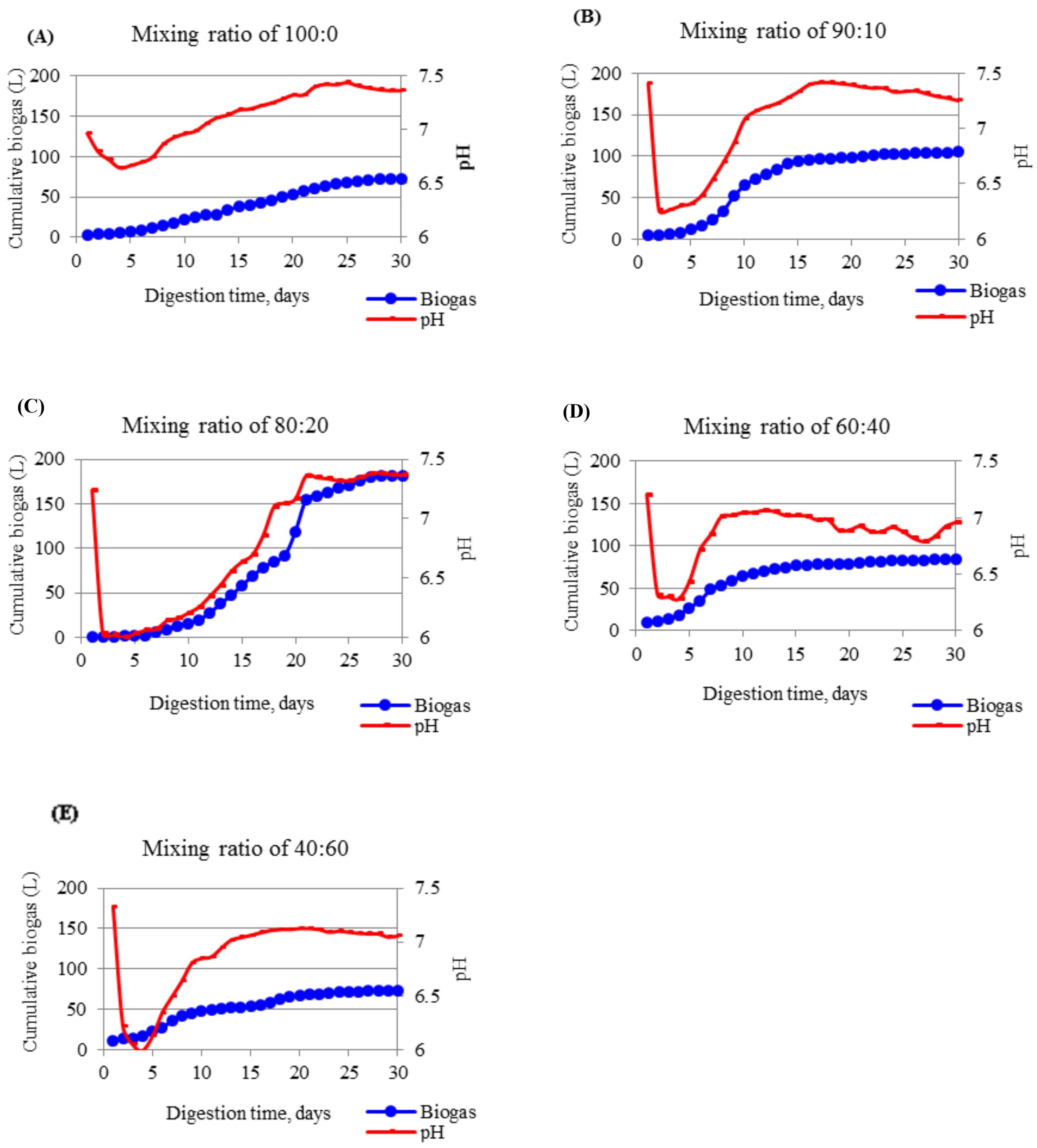


**Fig. 3.2.** Biogas and pH results at thermophilic temperatures (A) Mixing ratio of 100:0, (B) Mixing ratio of 90:10, (C) Mixing ratio of 80:20, (D) Mixing ratio of 60:40, and (E) Mixing ratio of 40:60.

### 3.4.3 Biogas and methane production and pH at ambient digestion.

The pH and biogas production obtained for the five mixing ratios used at ATs are given in Figs. 3.4A-E. At ATs, biogas production started immediately on the day 1 of digestion but the biogas production was very low compared to thermophilic and mesophilic digestion. Among the five mixing ratios, the mixing ratio of 100:0 achieved the highest biogas production of 33 L followed by 27 L, 23 L, 19 L and 16 L for the mixing ratios of 90:10, 80:20, 60:40 and 40:60, respectively. The biogas production was higher for the digestion of DM alone than co-digestion of DM and PW at ATs. The results showed that co-digesting PW with DM at ATs did not increase biogas production.

The reason for the decrease in biogas production at ATs might be due to the decrease in temperatures: 1) at reduced temperatures, the degradation of organic matter is tremendously reduced and requires a retention time (RT) approximately twice as long as does MD; 2) methanogenesis is particularly more sensitive to change in temperature than other organisms present in digesters, which affects the activity of the microbial community (Dhaked *et al.,* 2010); 3) as the mixing ratio of PW was increased, the organic matter was not being easily biodegradable. Mixing 20% PW with 80% DM achieved the highest biogas production at TT and mixing 10% PW with 90% DM yielded highest biogas at MT. At an ambient temperature, none of the co-digested mixing ratios achieved higher biogas production than digestion of DM alone.

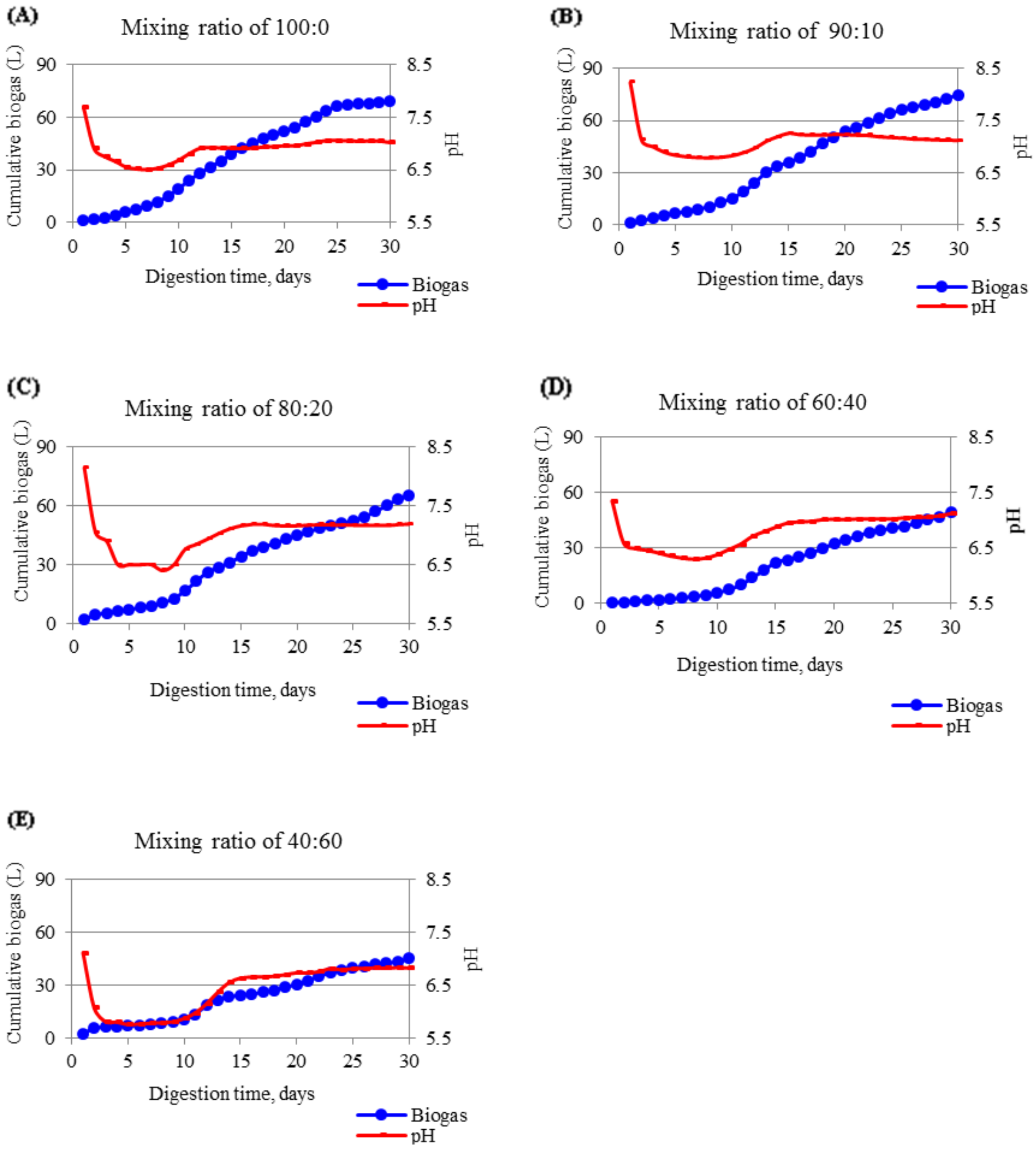


**Fig. 3.3.** Biogas and pH results at mesophilic temperatures (A) Mixing ratio of 100:0, (B) Mixing ratio of 90:10, (C) Mixing ratio of 80:20, (D) Mixing ratio of 60:40, and (E) Mixing ratio of 40:60.

At an ambient temperature, the mixing ratio of 100:0 achieved the highest $CH_4$ yield of 0.048 L g-1 VS. The highest cumulative $CH_4$ yield of 8 L was achieved for the mixing ratio of 100:0 followed by 6L, 5L, 5L and 3L for mixing ratios of 80:20, 90:10, 60:40, and 40:60, respectively. The $CH_4$ content of the yielded biogas never achieved 70% for any mixing ratio at ATs. The yielded $CH_4$ content of the produced biogas for all five mixing ratios at ATs is given in Table 3.3.

Sudden decrease of pH was not observed for any mixing ratio at ATs. From day 1, there was a slow decrease in the pH value for all mixing ratios tested at ATs. For the mixing ratio of 100:0, pH decreased from 7.3 to 6.6 (day 21). On day 22, pH showed a very slow increasing trend indicating that VFAs were being converted to biogas. For mixing ratios of 90:10, 80:20, 60:40, and 40:60, pH decreased from 7.8 to 6.4 (until day 18), 7.7 to 6.4 (until day 13), 8.2 to 6.7 (until day 11), 8.0 to 6.3 (until day 12) and showed an increasing trend thereafter.

### 3.4.4 Statistical analysis results

Statistical results showed that there were significant temperature, mixing ratio, and interaction effects (all tests $p < 0.0001$) for biogas production. The interaction means and associated significant differences are given in Table 3.4. These data showed that the mixing ratio of 80:20 at TT, 90:10 at MT and 100:0 at AT yielded higher biogas productions.

## 3.5 Process stability

The stability of a digestion process depends on a number of factors such as temperature, pH, VFA, $NH_3$-N and supplement of nutrients required for digestion process. The main factors used to determine the stability of the digestion process were $NH_3$-N and

VFA concentrations. This study showed a stable operation without any failure of $NH_3$-N or VFA concentrations for all mixing ratios used at thermophilic, mesophilic and ambient temperatures.

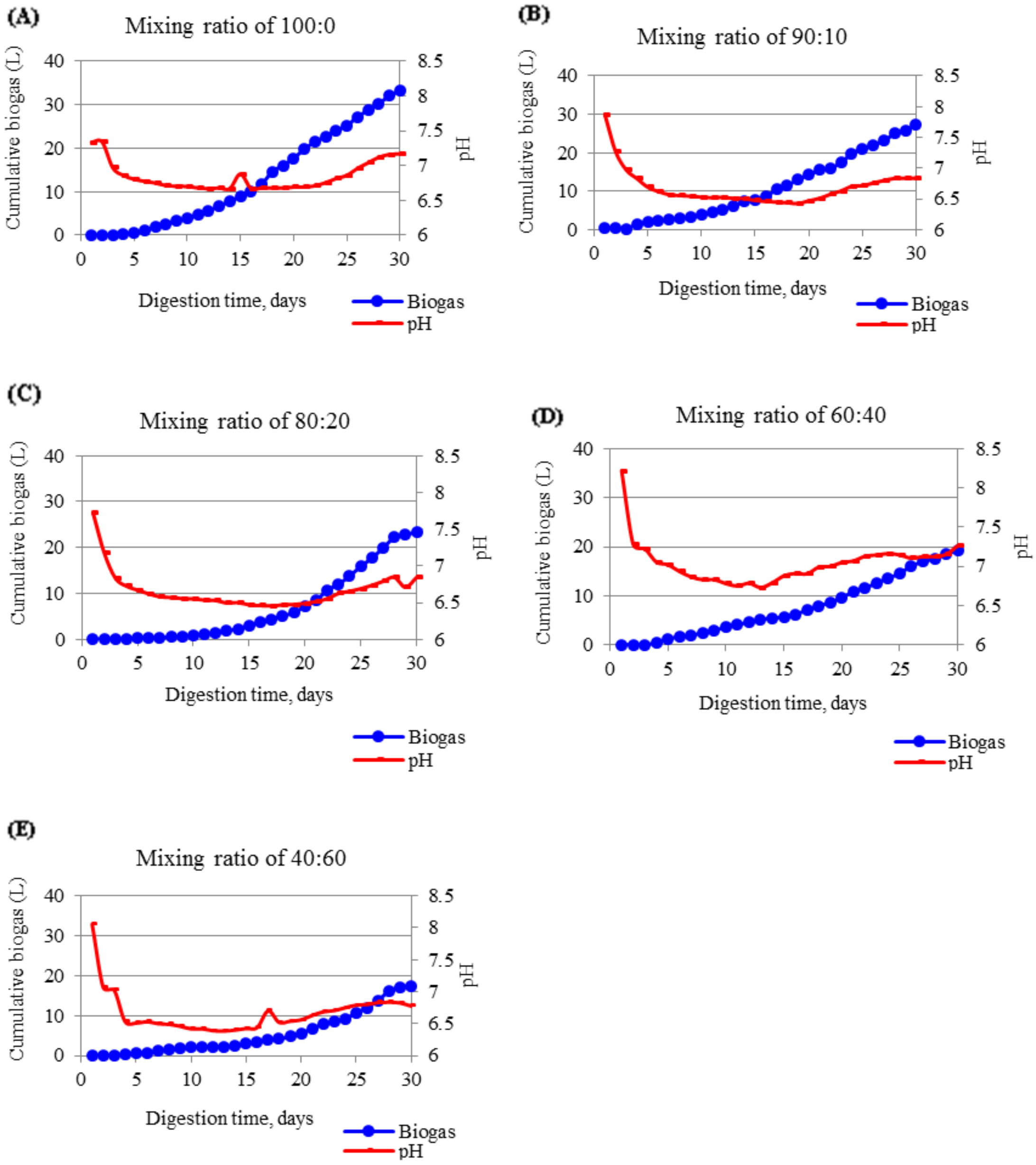


**Fig. 3.4.** Biogas and pH results at ambient temperatures (A) Mixing ratio of 100:0, (B) Mixing ratio of 90:10, (C) Mixing ratio of 80:20, (D) Mixing ratio of 60:40, and (E) Mixing ratio of 40:60.

**Table 3.3**. Methane content in the biogas for all five ratios at ambient temperatures.

| Mixing ratio (DM:PW)[1] | Highest methane content achieved | Digestion day at which methane content reached 60% |
|---|---|---|
| 100:0 | 68.5% on 24th day | 18th day |
| 90:10 | 67% on 30th day | 27th day |
| 80:20 | 51.5 % on 30th day | Never achieved |
| 60:40 | 51.5% on 30th day | Never achieved |
| 40:60 | 38% on 29th day | Never achieved |

[1] DM: dairy manure; PW: potato waste; %: percentage.

### 3.5.1 Concentration of ammonia nitrogen ($NH_3$-N)

The concentrations of $NH_3$-N for the five mixing ratios at TTs, MTs, and ATs are shown in Figs. 3.5A-C. Ammonia is produced from the degradation of nitrogenous matter of waste material that mainly consists of proteins or urea (McCarty, 1964). Ammonia can primarily be in two forms including ammonium ion ($NH_4^+$) or free ammonia ($NH_3$). For all mixing ratios used in this study, the concentrations of $NH_3$-N were less than 1,000 mg/L at thermophilic, mesophilic and pyschrophilic co-digestions of DM and PW throughout the digestion process. Studies show that the presence of high concentration (>1000 mg/L) of free ammonia leads to inhibition of microbial activities during the AD process (Sung and Liu, 2003). McCarty (1964) describe that 50-200 mg/L of $NH_3$ was beneficial to the AD process; 200-1,000 mg/L of $NH_3$ showed no adverse effects; 1,500-3,000 mg/L of $NH_3$ inhibited AD at higher pH values (7.4-7.6); and above 3,000 mg/L of $NH_3$ had toxic effects for the AD process. This indicates that the concentration of $NH_3$-N during the co-digestion of DM and PW was not a major concern for system stability.

**Table 3.4**. Biogas interaction means for the two-way ANOVA of temperatures and mixing ratios.

| Statistical results | | |
|---|---|---|
| **Temperature (°C)** | **Ratio (DM:PW)** | **Biogas (L)** |
| **Thermophilic-** (55-57) | 100:0 | $70^{e}$ |
| 55-57 | 90:10 | $105^{b}$ |
| 55-57 | 80:20 | $182^{a}$ |
| 55-57 | 60:40 | $84^{c}$ |
| 55-57 | 40:60 | $73^{d}$ |
| **Mesophilic-** (35-37) | 100:0 | $68^{b}$ |
| 35-37 | 90:10 | $76^{a}$ |
| 35-37 | 80:20 | $65^{c}$ |
| 35-37 | 60:40 | $49^{d}$ |
| 35-37 | 40:60 | $45^{e}$ |
| **Ambient-** (20-28) | 100:0 | $33^{a}$ |
| 20-28 | 90:10 | $27^{b}$ |
| 20-28 | 80:20 | $23^{c}$ |
| 20-28 | 60:40 | $19^{d}$ |
| 20-28 | 40:60 | $16^{e}$ |

$^{a\text{-}e}$ Biogas values within each temperature range not sharing a same superscript are significantly different ($P<0.05$).

### 3.5.2 Concentration of volatile fatty acids (VFAs)

The presence of VFA is also important to the stability of the AD process. Many investigators have reported the toxic effects of high VFA concentrations (Angelidaki *et al.,* 2005). It is well known that VFAs are important intermediary compounds in the metabolic pathway of $CH_4$ fermentation, and if present in high enough concentrations, causes microbial stress, which can lead to failure of the digester. In the present study, the concentrations of VFAs were determined on weekly basis. The VFA concentration and the $CH_4$ content (%) in biogas are shown in Figs. 3.6A-E (thermophilic), Figs. 3.7A-E (mesophilic) and Figs. 3.8A-E (ambient), respectively.

At TD, for the mixing ratios of 90:10 and 80:20, there was a sudden increase in VFA concentrations during week one of digestion, with the VFA concentration decreasing toward the end of the digestion. The $CH_4$ content was lower when the concentration of VFAs was higher for the mixing ratios of 90:10 and 80:20. The highest concentration of VFAs for the mixing ratios of 90:10 and 80:20 was 7.1 g/L and 6.1 g/L, respectively. Both the values were higher than 3.0 g/L (Dogan *et al.,* 2005), which was commonly considered to be the upper limit for stable AD operation. The AD system still maintained normal operation at such high VFA concentrations. However, at this stage, the composition of biogas obtained was low in $CH_4$ content. When the concentrations of VFAs started decreasing, the $CH_4$ content in the composition of biogas increased for both the mixing ratios (90:10 and 80:20). For the mixing ratios of 60:40 and 40:60, the VFA concentrations showed a decreasing trend from the beginning of digestion and it was noted that $CH_4$ content steeply increased. For the mixing ratio of 100:0 the VFA concentrations showed a very slow decreasing trend throughout the digestion process.

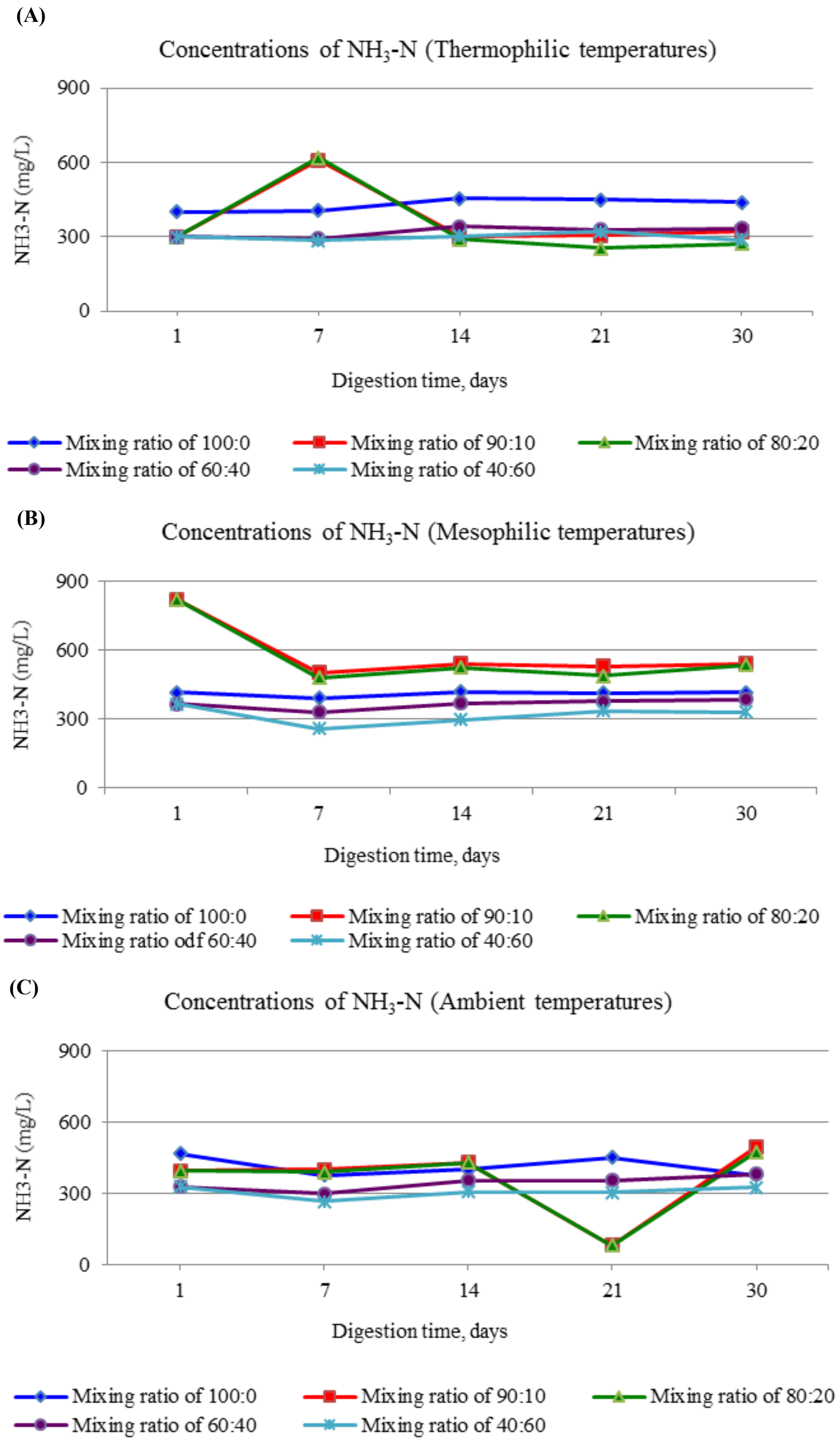


**Fig. 3.5**. Weekly $NH_3$-N concentrations (A) Thermophilic temperatures, (B) Mesophilic temperatures, and (C) Ambient temperatures.

The average $CH_4$ contents of the biogas produced for the mixing ratios of 100:0, 90:10, 80:20, 60:40 and 40:60 were 51%, 59%, 51%, 63% and 60%, respectively. Even though the $CH_4$ content was lower for the mixing ratio of 80:20, this mixing ratio achieved higher biogas production compared to other four mixing ratios (90:10, 60:40, 40:60, and 100:0). This might be explained in two ways. First, the quicker degradation of organic matter for the mixing ratio of 80:20 increased the concentration of VFAs. The organic matter of DM with organic matter of PW for the mixing ratio of 80:20 might have achieved sufficient nutrient (C/N ratio) balance. Second, as the percentage of PW was increased from 20% to 40% and then to 60%, $CH_4$ content in the biogas was increased but the total biogas production was reduced showing that the organic matter of PW was not completely degraded for the mixing ratios of 60:40 and 40:60. This shows that PW is a valuable substrate for co-digestion but the PW percentage should be limited.

At MD, the mixing ratios of 90:10 and 80:20 showed a trend for decreased VFA concentrations throughout the digestion process. For both mixing ratios, there was a steep increase of $CH_4$ content from the beginning of digestion (Figs. 3.7B-C). For the mixing ratios of 60:40 and 40:60, the concentrations of VFAs increased (Figs. 3.7D-E) and with the increase in VFA concentrations the $CH_4$ content in the biogas did not show much increase. Thereafter, with the decrease in VFA concentration, the $CH_4$ content in the biogas increased. For the mixing ratio of 100:0, the concentration of VFAs was stable until week two of digestion and thereafter showed a slight decrease in VFA concentration (Fig. 3.7A). The average $CH_4$ content of the biogas produced for the mixing ratios of 100:0, 90:10, 80:20, 60:40 and 40:60 at MD were 50%, 56%, 56%, 51% and 48%, respectively.

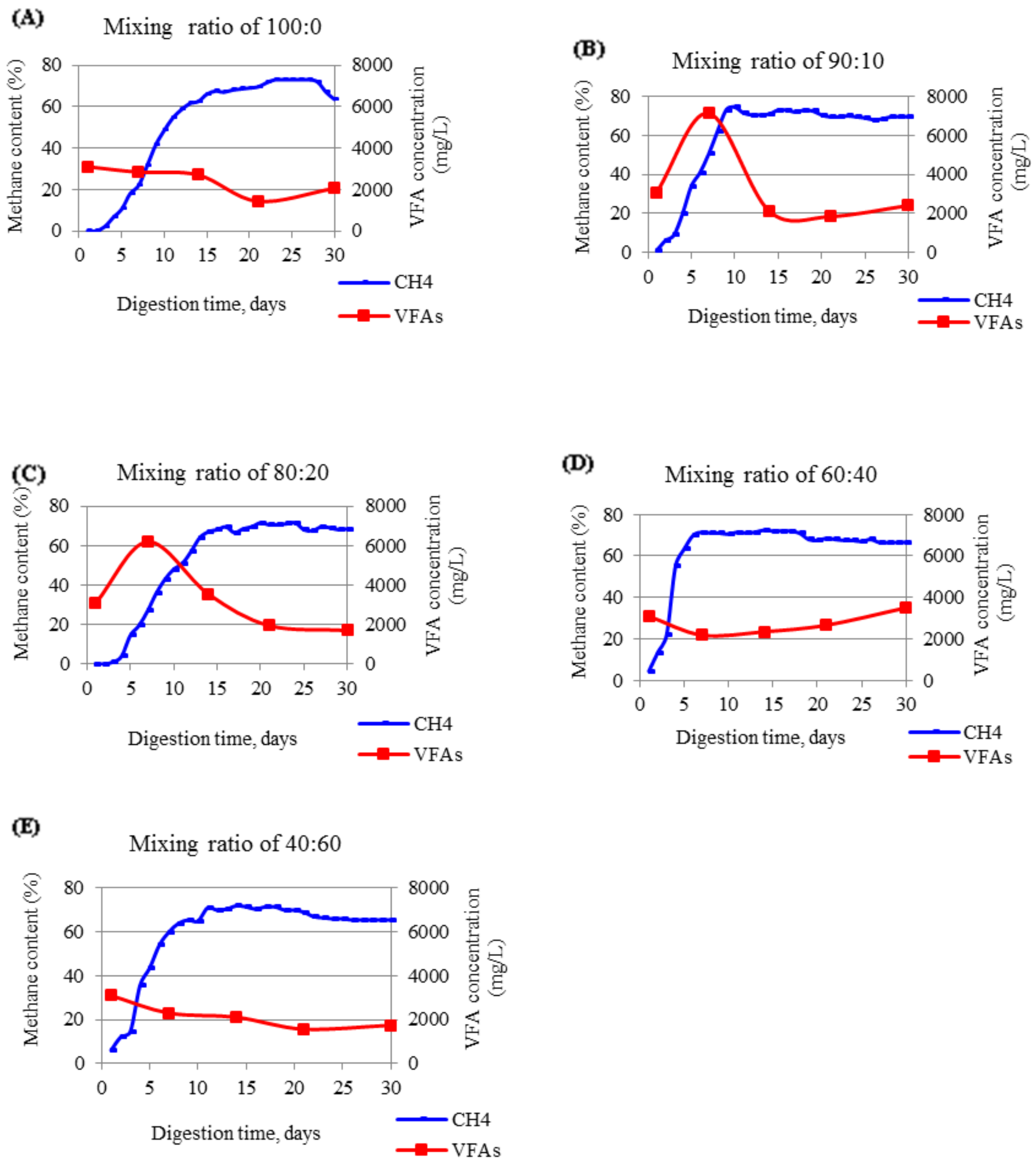


**Fig. 3.6**. Concentration of volatile fatty acids and methane content. Thermophilic temperatures - (A) Mixing ratio of 100:0, (B) Mixing ratio of 90:10, (C) Mixing ratio of 80:20, (D) Mixing ratio of 60:40, and (E) Mixing ratio of 40:60.

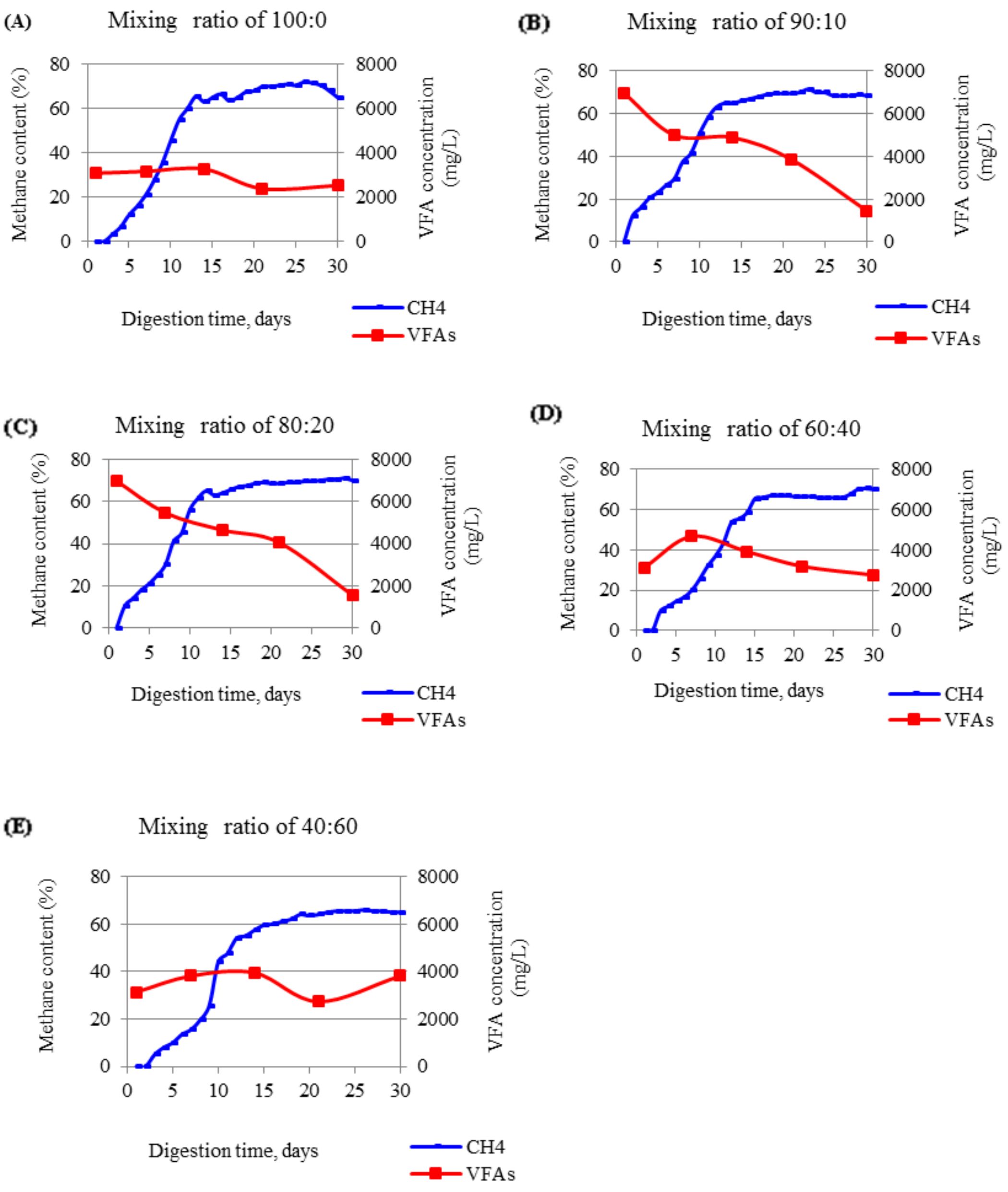


**Fig. 3.7**. Concentration of volatile fatty acids and methane content. Mesophilic temperatures - (A) Mixing ratio of 100:0, (B) Mixing ratio of 90:10, (C) Mixing ratio of 80:20, (D) Mixing ratio of 60:40 and (E) Mixing ratio of 40:60.

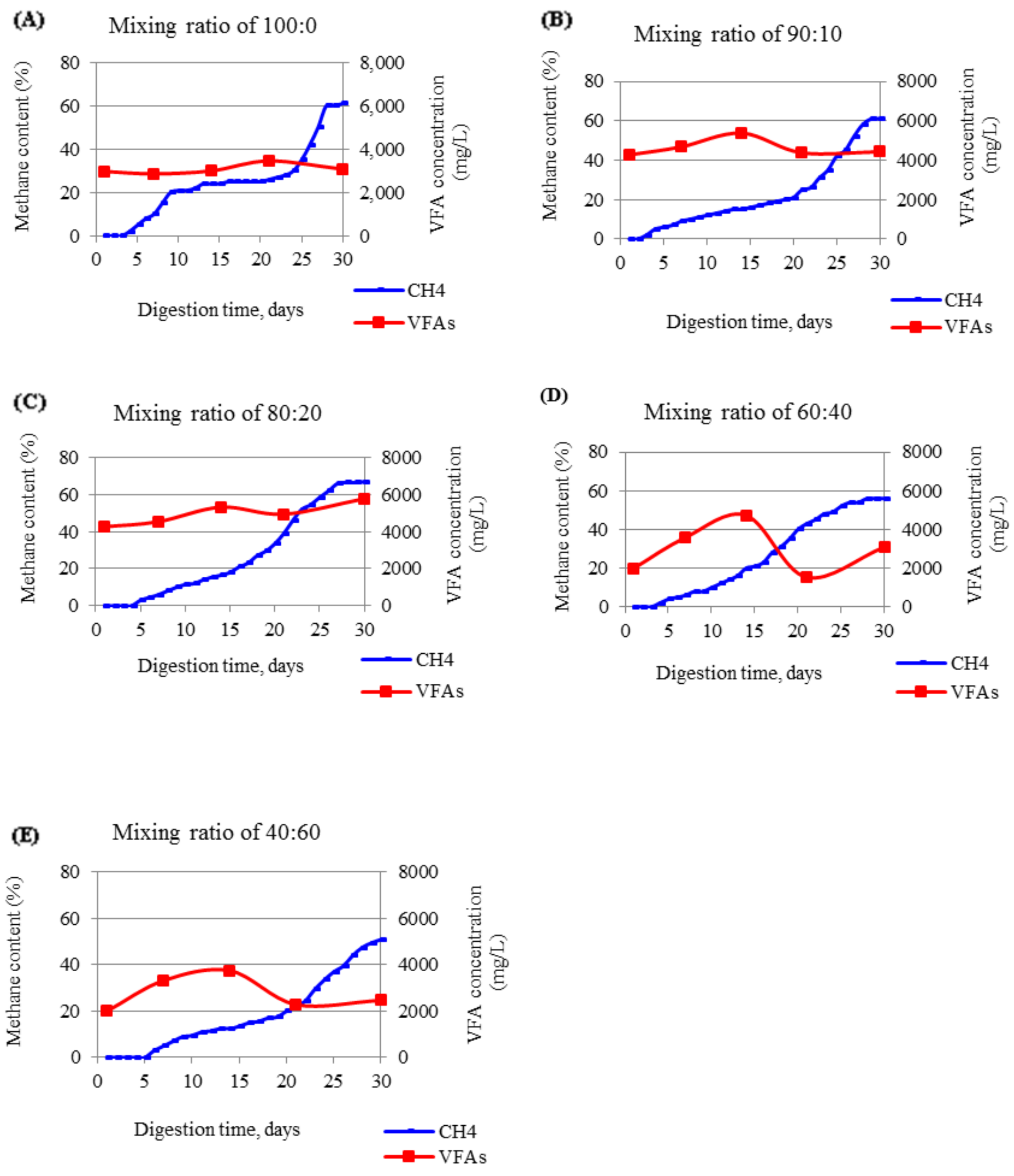


**Fig. 3.8**. Concentration of volatile fatty acids and methane content. Ambient temperatures - (A) Mixing ratio of 100:0, (B) Mixing ratio of 90:10, (C) Mixing ratio of 80:20 (D) Mixing ratio of 60:40 and (E) Mixing ratio of 40:60.

At PD, the concentration of VFAs increased for the mixing ratios of 90:10, 80:20, 60:40 and 40:60 from the week 1 of digestion through week 2 of digestion, which was followed by a decrease in VFA concentrations by the end of week 3 of digestion. The VFA concentrations decreased by 19%, 7%, 68%, and 39% for the mixing ratios of 90:10, 80:20, 60:40, and 40:60 by the end of week 3 compared to the VFA concentrations at the end of week 2 of digestion. Similar results were reported by Singh *et al.* (1999) where at 30˚C the concentration of VFAs decreased as a function of time and reduced to ¼ of initial value. For the mixing ratio of 100:0, the VFA concentrations were stable from day 1 of digestion until the end of week 2 of digestion. Volatile fatty acids concentrations increased by 15% from the end of week 2 of digestion until the end of week 3. The average $CH_4$ content of the biogas produced for the mixing ratios of 100:0, 90:10, 80:20, 60:40 and 40:60 at PD were 25%, 20%, 25%, 27% and 20%, respectively.

## 3.6 Conclusions

Mixing PW with DM enhanced biogas and $CH_4$ production. Temperature played a key role in the enhancement of biogas and $CH_4$ production. The biogas and $CH_4$ production was enhanced by 157% and 158% for the mixing ratio of 80:20 (DM:PW) at TT and 12% and 26% for the mixing ratio of 90:10 (DM:PW) at MT compared to the digestion of DM alone. At AT, digestion of DM alone (100:0) achieved the highest biogas and $CH_4$ production of 33 L and 8 L, respectively. Higher operating temperatures allow high percentage of PW in the mixture to be anaerobically digested. The concentrations of VFA, $NH_3$-N and pH were not a problem either for co-digestion of DM and PW or digestion of DM alone in terms of process stability. Thermophilic temperatures proved to be the optimum temperatures in terms of biogas and methane production for co-digestion of DM and PW.

## 3.7 Acknowledgements

This research was supported by the United States Department of Agriculture (USDA) through an Agriculture and Food Research Initiative (AFRI) grant under the USDA-National Institute of Food and Agriculture (NIFA) and the University of Idaho through a seed grant.

### 3.8 References

Angelidaki, I., Boe, K. and Ellegaard, L. (2005) Effect of operating conditions and reactor configuration on efficiency of full-scale biogas plants. *Water Science and Technology, 52*, 189-194.

APHA (American Public Health Association), (2012). American Water Works Association (AWWA) & Water Environment Federation (WEF). Standard methods for the examination of water & wastewater, 22nd ed.

Choorit, W., & Wisarnwan, P. (2007). Effect of temperature on the anaerobic digestion of palm oil mill effluent. *Electronic Journal of Biotechnology, 10*, 3.

Dhaked, R. K., Singh, P., & Singh, L. (2010). Biomethanation under psychrophilic conditions. *Waste Management, 30, 12*, 2490-2496.

Dogan, T., Ince, O., Oz, N., & Ince, B. (2005). Inhibition of Volatile Fatty Acid Production in Granular Sludge from a UASB Reactor. *Journal of Environmental Science and Health*, Part A: Toxic/hazardous Substances & Environmental Engineering, *40, 3*, 633-644.

Elefsiniotis, P., Wareham, D. G., & Smith, M. O. (2005). Effect of a Starch-Rich Industrial Wastewater on the Acid-Phase Anaerobic Digestion Process. *Water Environment Research, 77, 4*, 366-371.

El-Mashad, H. M., and Zhang, R. (2010). Biogas production from co-digestion of dairy manure and food waste. *Bioresource Technology, 101, 11*, 4021-4028.

Hills, D., Roberts, D.W. (1981). Anaerobic digestion of dairy manure and field crop residues. *Agricultural Wastes, 3, 3*, 179-189.

Kim, J. K., Oh, B. R., Chun, Y. N., & Kim, S. W. (2006). Effects of temperature and hydraulic retention time on anaerobic digestion of food waste. *Journal of Bioscience and Bioengineering, 102, 4*, 328-332.

Lay, J.-J., Li, Y.-Y., & Noike, T. (1997). Influences of pH and Moisture Content on the Methane Production in High-Solids Sludge Digestion. *Water Research, 31, 6*, 1518-1524.

Li, R., Chen, S., Li, X., Saifullah, L. J., He, Y., & Zhu, B. (2009a). Anaerobic Codigestion of Kitchen Waste with Cattle Manure for Biogas Production. *Energy & Fuels : an American Chemical Society Journal, 23, 2*, 2225.

Li, R., Li, X., & Chen, S. (2009b). Anaerobic co-digestion of kitchen waste and cattle manure for methane production. Energy Sources, Part A: Recovery, *Utilization and Environmental Effects, 31, 20*, 1848-1856.

Li, X., Li, L., Zheng, M., Fu, G., & Lar, J. S. (2009c). Anaerobic Co-Digestion of Cattle Manure with Corn Stover Pretreated by Sodium Hydroxide for Efficient Biogas Production. *Energy and Fuels, 23,* 5, 4635-4639.

Liu, G., Zhang, R., El-Mashad, H. M., & Dong, R. (2009). Effect of feed to inoculum ratios on biogas yields of food and green wastes. *Bioresource Technology, 100, 21*, 5103-5108.

Macias-Corral, M., Samani, Z., Hanson, A., Smith, G., Funk, P., Yu, H., & Longworth, J. (2008). Anaerobic digestion of municipal solid waste and agricultural waste and the effect of co-digestion with dairy cow manure. *Bioresource Technology, 99, 17*, 8288-8293.

Marañón, E., Castrillón, L., Quiroga, G., Fernández-Nava, Y., Gómez, L., & García, M. M. (2012). Co-digestion of cattle manure with food waste and sludge to increase biogas production. *Waste Management, 32, 10*, 1821-1825.

McCarty, P. L. (1964). Anaerobic Waste Treatment Fundamentals, Part One, Chemistry and Microbiology. Public Works, 107-112.

National Greenhouse Gas Inventories Programme (IPPC-1996). Intergovernmental panel on climate change. Retrieved from http://www.ipcc.ch/graphics/speeches/sbsta-19-statement-revision-1996.pdf on April 22nd, 2012.

Nelson, M. L. (2010). Utilization and application of wet potato processing coproducts for finishing cattle. *Journal of Animal Science, 88, 13*, 133-42.

Olsen, N., Nolte, P., Harding, G. and Ohlensehlen, B. (2001). Cull and waste potato management. University of Idaho, College of Agriculture, Cooperative Extention System CIS Bulletin # 814.

Rico, C., Rico, J. L., Tejero, I., Munoz, N., & Gomez, B. (2011). Anaerobic digestion of the liquid fraction of dairy manure in pilot plant for biogas production: Residual methane yield of digestate. *Waste Management, 31*, 2167-2173.

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

Singh, L., Alam, S. I., & Ramana, K. V. (1999). Effect of Fluctuating Temperature Regime on Psychrophilic Anaerobic Digestion of Nightsoil. Defence Science Journal, 49, 2, 135.

Solera, R., Romero, L. I., & Sales, D. (2002). The Evolution of Biomass in a Two-phase Anaerobic Treatment Process During Start-up. *Chemical and Biochemical Engineering Quarterly, 16*, 25-30.

Sung, S., and Liu, T. (2003). Ammonia inhibition on thermophilic anaerobic digestion. *Chemosphere, 53, 1*, 43-52.

Umetsu, K., Yamazaki, S., Kishimoto, T., Takahashi, J., Shibata, Y., Zhang, C., Misaki, T., Komiyama, M. (2006). Anaerobic co-digestion of dairy manure and sugar beets. International Congress Series, 1293, 307-310.

USDA (U.S. Department of Agriculture), Cattle. (2014). National Agricultural Statistics Service (NASS). Retrieved from http://usda.mannlib.cornell.edu/usda/current/Catt/Catt-01-31-2014.pdf on April 4th, 2014.

USDA (U.S. Department of Agriculture), Potatoes summary. (2011). National Agricultural Statistics Service (NASS). Retrieved from http://usda01.library.cornell.edu/usda/current/Pota/Pota-09-20-2012.pdf on June 6th, 2012.

USEPA (U.S. Environmental Protection Agency). (2012). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010 (publication No. EPA 430-R-12-001). Washington, DC: Author. Retrieved from http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2012-Main-Text.pdf on July 18th, 2013.

USEPA (U.S. Environmental Protection Agency). (2013a). Anaerobic digestion (Waste – resource Conservation – Food Waste). Reterived from http://www.epa.gov/foodrecovery/fd-anaerobic.htm on July 6th, 2012.

USEPA (U.S. Environmental Protection Agency). (2013b). Common manure handling systems. Ag 101. Retrieved from http://www.epa.gov/oecaagct/ag101/dairymanure.html on April 22nd, 2012.

Wang, X., Yang, G., Feng, Y., Ren, G., & Han, X. (2012). Optimizing feeding composition and carbon-nitrogen ratios for improved methane yield during anaerobic co-digestion of dairy, chicken manure and wheat straw. *Bioresource Technology, 120*, 78-83.

WU, M., Sun, K., Zhang, Y. (2006). Influence of temperature fluctuation on thermophilic anaerobic digestion of municipal organic solid waste. Journal of Zhejiang University Science B. ISSN 1673-1581 (Print); ISSN 1862-1783 (Online).

# CHAPTER 4 - EVALUATION OF ANAEROBIC DIGESTION SYSTEM BASED ON THE RESULTS OBTAINED FROM LABORATORY TEST – AN ECONOMIC ANALYSIS.

## 4.1 Abstract

Economic analysis of dairy manure (DM) based anaerobic digesters prior to installation helps owners to understand the structure of the payback period and the year of positive cash flow. This paper evaluates the economic feasibility of an anaerobic digester on a dairy farm using the results obtained from laboratory AD tests on "Anaerobic co-digestion of dairy manure and potato waste" (Chapter 3). A spreadsheet-based assessment tool designed by Enahoro and Gloy (2008) was used for the economic analysis. It is similar to the tool called FarmWare 3.1 developed by United States Environmental Protection Agency's (U.S. EPA) AgStar program.

The spreadsheet-based assessment tool was designed to check for positive cash flow within a certain time period. It was designed to determine total capital cost (based on the number of cows supplying manure to the digester), electricity generation potential and probability of profit within a ten year time period of anaerobic digestion (AD) system. Digesters treating manure generated by a range of 1,000 to 10,000 cows were chosen for the analysis. Capital costs of $1,400/cow, $1,000/cow and $600/cow used in this analysis were based on average costs of on-farm complete-mix digesters, and high and low costs for on-farm plug flow digesters, respectively given by AgSTAR, 2012 and Beddoes *et al.,* 2007. The analysis was divided into two parts: part I and part II. In part I, all the given parameters such

as land, building, manure piping, generator, boiler, digester tank, etc., listed in the Enahoro and Gloy tool have been considered for analysis. But in part II, the cost of electricity generation equipment (generator), which accounts for 36 percent of total capital cost (Beddoes *et al.,* 2007) has been subtracted before the analysis. In part I, the analysis shows that digesters treating manure for a range of 1,000 to 10,000 cows will not generate positive cash flow until the capital cost is reduced from $1,400 to $600/cow. In part II, positive cash flow was generated for all three capital cost levels (i.e. for $1,400/cow, $1,000/cow and $600/cow). However, the positive cash flow was generated only for certain ratios at each capital cost, i.e. only for the ratios which produce a higher volatile solids conversion rate.

## 4.2 Introduction

Anaerobic digestion (AD) systems provide an opportunity for dairy farms to produce renewable energy from livestock wastes. Anaerobic digestion systems are typically quite capital intensive and require a thorough economic analysis to assess economic feasibility. Rising energy prices continue to improve the economic potential of these systems. In addition, various incentive programs have emerged to further encourage the development of AD systems. A spreadsheet-based tool developed by Enahoro and Gloy (2008) can assist potential digester owners in making better decisions in terms of investment (Krich *et al.,* 2005). Biogas generated by on-farm digesters can offset the costs of purchasing natural gas and propane which cost $1.13 per therm and $1.82 per therm (Beddoes *et al.,* 2007), respectively. The significant increase in both natural gas and propane costs over the past 7 years has made the use of on-farm-produced biogas economically attractive as a replacement for natural gas and liquid propane.

Before implementing the task of design and construction of AD system on a particular dairy farm, total capital cost, the availability of financial incentives, gas production assumptions, and income received by selling the electricity to a grid, operation, repair and maintenance costs should be estimated. It is very important that cost analysis be performed prior to investment based on the total number of cows since capital cost varies with cow numbers. The capital cost also varies based on the digester type. In United States, most of the on-dairy digesters are covered lagoon, plug-flow, and completely mixed types. On average, the covered lagoon digester costs \$93/cow (ranged from \$85/cow to \$101/cow), the plug flow digester costs \$775/cow (ranged from \$502/cow to \$1,512/cow), and the completely mixed digester costs \$1,275/cow (ranged from \$1,086/cow to \$1,917/cow) (Beddoes *et al.,* 2007).

In this study the economic analysis was started at a capital cost of \$1,400/cow and then the capital cost was lowered to \$1,300, \$1,200, \$1,100/cow, etc. until positive cash flow was obtained for at-least one ratio among three temperature ranges (thermophilic, mesophilic and ambient). The analysis was performed for 1,000 to 10,000 - cow dairy farms. The cost analysis was divided into two parts, part I and part II. In part I, the cost analysis was performed by choosing all the parameters provided in the spreadsheet-based assessment tool and by incorporating values of "volatile solids converted to biogas" and "cubic feet of biogas produced per pound of volatile solid converted" obtained from laboratory study (Chapter 3). The cost obtained in part I was considered as the total capital cost required for constructing an anaerobic digester, including electricity generating equipment. In part II, the cost for electricity-generating equipment was subtracted and the analysis was performed based on an assumption that the biogas generated can be on-farm utilized. A cost analysis for energy production through anaerobic digesters (Beddoes *et al.,* 2007) showed that electricity generation equipment for anaerobic digesters cost 36% of the overall project price.

The primary goal of this study was to determine the highest total system cost where positive cash flow can be obtained with in a ten year time period in both cases (with and without electricity equipment). The analysis was performed based on both the laboratory test results and the parameters provided in the spreadsheet-based assessment tool. The secondary goal was to discuss benefits of on-farm anaerobic digesters with and without electricity generation equipment.

## 4.3 Materials and methods

The analysis was carried out based on the spreadsheet-based assessment tool (Enahoro and Gloy, 2008), which was designed to conduct an economic assessment prior to invest on AD systems. This spreadsheet-based assessment tool is available at http://www.agfinance.aem. cornell.edu/ad-systems.html in the section of “Spreadsheet Analysis Tools for Anaerobic Digestion”. This tool is similar to a United States Environmental Protection Agency’s (U.S. EPA) AgStar program designed tool called FarmWare 3.1 (currently under development – Noted on EPAs website, http://www.epa.gov/agstar/tools/project-dev/farmware.html). The FarmWare 3.1 tool requires that the user input information regarding the dairy farm and biogas system. Then, the tool estimates the capital costs, the electricity generation potential, and the profitability of the AD system (currently unavailable – under development). The spreadsheet-based tool is similar to

FarmWare 3.1 but with slightly different set of inputs to conduct the analysis. The Enahoro and Gloy spreadsheet-based tool is more flexible since the user can enter a wider variety of parameters that impact the economic viability of the project. It utilizes the values entered by users and estimates the cash flow based on a net present value (NPV) and an internal rate of return (IRR) concepts.

## 4.4 Parameters required for the spreadsheet-based tool

The information required (parameters) for the spreadsheet-based assessment tool are discussed below in detail. It is important to note that unless otherwise specified, most of the parameter values in Tables 4.1, 4.5, 4.7, 4.10 & 4.11 for this analysis were the default values taken from the spreadsheet-based assessment tool designed by Enahoro and Gloy (2008) (permission obtained from the authors for using those values).

The analysis was based on 1,000 to 10,000 cow dairy operations. The basic information required for the analysis is shown in Table 4.1. The tool requires the input of the number of lactating and dry animals. This is important because manure production differs considerably for these two types of animals. Additionally, any capacity and performance incentives through the state of Idaho are required inputs. Finally, it is necessary to input the gross value of any additional grants received for the proposed project.

In general, dairy farms will have a large number of lactating cows than dry cows, so it was assumed that 80% of the dairy cows are lactating cows (SiEllen dairy farm, Jerome, ID). Lactating cows produce about 81 cubic feet of biogas per day (Enahoro and Gloy, 2008). This value is approximately equivalent to 51,000 British thermal units (BTU’s)/lactating cow/day.

At a price of $6/MMBTU, manure from lactating dairy cows would have an energy value of approximately $4 per ton. These values and calculations are pre-assigned in the gas production calculations in the spreadsheet. For this analysis, no incentive programs and no grant dollars were assumed, so these numbers were zero.

**Table 4.1**. Basic Input Parameters for the AD Financial Analysis.

| | **Estimation of cows in a dairy farm** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Parameters** | **1,000** | **2,000** | **3,000** | **4,000** | **5,000** | **6,000** | **7,000** | **8,000** | **9,000** | **10,000** |
| Lactating cows | 800 | 1,600 | 2,400 | 3,200 | 4,000 | 4,800 | 5,600 | 6,400 | 7,200 | 8,000 |
| Dry Cows | 200 | 400 | 600 | 800 | 1,000 | 1,200 | 1,400 | 1,600 | 1,800 | 2,000 |
| Participation in Idaho capacity incentives | No | No | No | No | No | No | No | No | No | No |
| Participation in Idaho performance incentives | No | No | No | No | No | No | No | No | No | No |
| Other grant dollars | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 | $0 |

### 4.4.1 Capital budgets

A capital budget often determines whether a project such as building a new plant or investing in a long-term venture is worth pursuing. Long term investments once made cannot be reversed without a significance loss of invested capital. They influence the whole conduct of the business for the years to come. Investment decisions are based on the profit that will be earned and probably measured through the return on the capital. Capital budgeting is essential for proper capital investment to ensure adequate rate of return on investment. The estimated amount as capital budgets for investing on AD systems based on $1,400/cow, $1,000/cow, and $600/cow on dairy farms having 1,000 to 10,000 cows is given in Tables 4.2, 4.3, and 4.4, respectively. Tables 4.2, 4.3 and 4.4 show the estimated construction cost for a range of herd size from 1,000 to 10,000.

According to Beddoes *et al.* (2007) the average cost for completely mixed digesters was $1,339/cow; however, to account for cost increase since that time and to round off the value, I used a value of $1,400/cow. At this moment, $1,400/cow is a reasonable price for construction of anaerobic digester (Standley & Co., Idaho). The values in Tables 4.2, 4.3 and 4.4 were based on spreadsheet default parameter values scaled to give a total cost of $1,400/cow, $1,000/cow, and $600/cow, respectively. In addition to capital budgets, the values taken for "working capital," "pre-system on-farm power requirement (kWh/Year)," and "power use of ADG-to-E system (kWh/Year)" in the analysis were also given in Table 4.2, 4.3 and 4.4, respectively. The working capital was given as $30,000 for a 1,000 cow dairy farm and for every 1,000 cow increment, $5,000 was added as shown in Table 4.2. The values for pre-system on-farm power requirement and power use of ADG-to-E system was calculated based on the concept of linear increase of power requirement when the capacity of dairy farm increases (i.e. number of cow's increases from 1,000 to 10,000). So, $850,000 was multiplied by consecutive numbers from 1 to 10.

The capital budgets for the economic analysis (values given in Tables 4.2, 4.3 and 4.4) were estimated based on information obtained from Standley & Co., Jerome, Idaho. Standley & Co. supplies equipment for construction and maintenance of anaerobic digesters. Based on the information from AgSTAR (2012), Beddoes *et al.* (2007), and Standley & Co., $1400/cow could be a reasonable price to construct an anaerobic digestion project. However, the price for constructing anaerobic digesters depends on type of digesters chosen. For example, covered lagoons are cheaper than plug-flow or continuously stirred digesters (Beddoes *et al.,* 2007). In this study, the cost analysis was performed by lowering the price from $1400/cow and until the positive cash flow was seen within a ten year time period.

**Table 4.2**. Capital Budgets allocated for the present study based on $1,400 per cow (based on completely mixed digester design).

| | Estimated capital cost for construction of anaerobic digester on a dairy farm having number of cows | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Calculations are based on $1,400/cow** | | | | | | | | | |
| **Number of cows** | **1,000** | **2,000** | **3,000** | **4,000** | **5,000** | **6,000** | **7,000** | **8,000** | **9,000** | **10,000** |
| Land | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Building | 100,000 | 240,000 | 500,000 | 500,000 | 500,000 | 500,000 | 500,000 | 500,000 | 500,000 | 500,000 |
| Site work | 50,000 | 100,000 | 100,000 | 100,000 | 500,000 | 500,000 | 500,000 | 500,000 | 500,000 | 500,000 |
| Power Wiring | 100,000 | 300,000 | 500,000 | 500,000 | 670,000 | 770,000 | 970,000 | 1,200,000 | 1,570,000 | 1,570,000 |
| Manure Piping | 100,000 | 200,000 | 500,000 | 500,000 | 500,000 | 500,000 | 1,500,000 | 1,500,000 | 1,500,000 | 1,500,000 |
| Generator | 200,000 | 590,000 | 700,000 | 1,000,000 | 1,700,000 | 2,100,000 | 2,100,000 | 3,270,000 | 4,100,000 | 4,100,000 |
| Boiler | 100,000 | 100,000 | 500,000 | 500,000 | 500,000 | 500,000 | 500,000 | 500,000 | 500,000 | 500,000 |
| Digester Tank | 300,000 | 820,000 | 840,000 | 1,600,000 | 1,700,000 | 2,300,000 | 2,300,000 | 2,300,000 | 2,500,000 | 3,800,000 |
| Pumps | 100,000 | 100,000 | 130,000 | 470,000 | 500,000 | 600,000 | 800,000 | 800,000 | 800,000 | 800,000 |
| Controls | 80,000 | 80,000 | 100,000 | 100,000 | 300,000 | 300,000 | 300,000 | 300,000 | 300,000 | 300,000 |
| **Total Materials cost** | **1,130,000** | **2,530,000** | **3,870,000** | **5,270,000** | **6,870,000** | **8,070,000** | **9,470,000** | **10,870,000** | **12,270,000** | **13,570,000** |
| Project Development | 60,000 | 60,000 | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 | 100,000 | 200,000 |
| Engineering | 60,000 | 60,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 | 80,000 |
| Construction/Mgt | 130,000 | 130,000 | 130,000 | 130,000 | 130,000 | 130,000 | 130,000 | 130,000 | 130,000 | 130,000 |
| Consulting | 20,000 | 20,000 | 20,000 | 20,000 | 20,000 | 20,000 | 20,000 | 20,000 | 20,000 | 20,000 |
| **Total other cost** | **270,000** | **270,000** | **330,000** | **330,000** | **330,000** | **330,000** | **330,000** | **330,000** | **330,000** | **430,000** |
| **Total Capital costs** | **1,400,000** | **2,800,000** | **4,200,000** | **5,600,000** | **7,200,000** | **8,400,000** | **9,800,000** | **11,200,000** | **12,600,000** | **14,000,000** |
| | | | | | | | | | | |
| Working capital | 30,000 | 35,000 | 40,000 | 45,000 | 50,000 | 55,000 | 60,000 | 65,000 | 70,000 | 75,000 |
| | | | | | | | | | | |
| Pre-system on-farm power requirement (kWh/Year) | 850,000 | 1,700,000 | 2,550,000 | 3,400,000 | 4,250,000 | 5,100,000 | 5,950,000 | 6,800,000 | 7,650,000 | 8,500,000 |
| Power use of ADG-to_E system (kWh/Year) | 54,750 | 109,500 | 164,250 | 219,000 | 273,750 | 328,500 | 382,250 | 438,000 | 492,750 | 547,500 |

**Table 4.3**. Capital Budgets allocated for the present study based on $1,000 per cow (based on high cost plug flow reactor design).

| | Estimated capital cost for construction of anaerobic digester on a dairy farm having number of cows | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Calculations are based on $1,000/cow** | | | | | | | | | |
| **Number of cows** | **1,000** | **2,000** | **3,000** | **4,000** | **5,000** | **6,000** | **7,000** | **8,000** | **9,000** | **10,000** |
| Land | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Building | 100,000 | 200,000 | 300,000 | 400,000 | 500,000 | 500,000 | 600,000 | 700,000 | 700,000 | 800,000 |
| Site work | 50,000 | 100,000 | 200,000 | 200,000 | 300,000 | 400,000 | 500,000 | 600,000 | 700,000 | 800,000 |
| Power Wiring | 50,000 | 100,000 | 200,000 | 300,000 | 400,000 | 500,000 | 600,000 | 700,000 | 800,000 | 900,000 |
| Manure Piping | 100,000 | 200,000 | 300,000 | 400,000 | 500,000 | 500,000 | 600,000 | 700,000 | 800,000 | 900,000 |
| Generator | 100,000 | 200,000 | 300,000 | 500,000 | 600,000 | 880,000 | 1,000,000 | 1,000,000 | 1,200,000 | 1,400,000 |
| Boiler | 50,000 | 100,000 | 200,000 | 300,000 | 400,000 | 500,000 | 590,000 | 650,000 | 750,000 | 850,000 |
| Digester Tank | 100,000 | 260,000 | 360,000 | 560,000 | 660,000 | 760,000 | 860,000 | 960,000 | 1,060,000 | 1,260,000 |
| Pumps | 100,000 | 200,000 | 300,000 | 400,000 | 500,000 | 600,000 | 700,000 | 800,000 | 800,000 | 800,000 |
| Controls | 80,000 | 100,000 | 200,000 | 200,000 | 300,000 | 300,000 | 400,000 | 500,000 | 700,000 | 800,000 |
| **Total Materials cost** | **730,000** | **1,460,000** | **2,360,000** | **3,260,000** | **4,160,000** | **4,940,000** | **5,850,000** | **6,610,000** | **7,510,000** | **8,510,000** |
| Project Development | 60,000 | 120,000 | 220,000 | 240,000 | 260,000 | 300,000 | 300,000 | 400,000 | 500,000 | 500,000 |
| Engineering | 60,000 | 120,000 | 1200,000 | 120,000 | 180,000 | 300,000 | 330,000 | 320,000 | 320,000 | 320,000 |
| Construction/Mgt | 130,000 | 260,000 | 260,000 | 340,000 | 360,000 | 400,000 | 450,000 | 600,000 | 600,000 | 600,000 |
| Consulting | 20,000 | 40,000 | 40,000 | 40,000 | 40,000 | 60,000 | 70,000 | 70,000 | 70,000 | 70,000 |
| **Total other cost** | **270,000** | **540,000** | **640,000** | **740,000** | **840,000** | **1,060,000** | **1,150,000** | **1,390,000** | **1,490,000** | **1,490,000** |
| **Total Capital costs** | **1,000,000** | **2,000,000** | **3,000,000** | **4,000,000** | **5,000,000** | **6,000,000** | **7,000,000** | **8,000,000** | **9,000,000** | **10,000,000** |
| | | | | | | | | | | |
| Working capital | 30,000 | 35,000 | 40,000 | 45,000 | 50,000 | 55,000 | 60,000 | 65,000 | 70,000 | 75,000 |
| | | | | | | | | | | |
| Pre-system on-farm power requirement (kWh/Year) | 850,000 | 1,700,000 | 2,550,000 | 3,400,000 | 4,250,000 | 5,100,000 | 5,950,000 | 6,800,000 | 7,650,000 | 8,500,000 |
| Power use of ADG-to_E system (kWh/Year) | 54,750 | 109,500 | 164,250 | 219,000 | 273,750 | 328,500 | 382,250 | 438,000 | 492,750 | 547,500 |

**Table 4.4**. Capital Budgets allocated for the present study based on $600 per cow (based on low cost plug flow reactor design).

| | Estimated capital cost for construction of anaerobic digester on a dairy farm having number of cows | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Calculations are based on $600/cow** | | | | | | | | | |
| **Number of cows** | **1,000** | **2,000** | **3,000** | **4,000** | **5,000** | **6,000** | **7,000** | **8,000** | **9,000** | **10,000** |
| Land | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Building | 50,000 | 90,000 | 130,000 | 170,000 | 210,000 | 260,000 | 300,000 | 340,000 | 380,000 | 420,000 |
| Site work | 30,000 | 60,000 | 90,000 | 120,000 | 150,000 | 180,000 | 210,000 | 240,000 | 270,000 | 300,000 |
| Power Wiring | 40,000 | 70,000 | 100,000 | 130,000 | 160,000 | 190,000 | 230,000 | 240,000 | 270,000 | 300,000 |
| Manure Piping | 50,000 | 110,000 | 170,000 | 230,000 | 290,000 | 400,000 | 460,000 | 520,000 | 580,000 | 640,000 |
| Generator | 80,000 | 210,000 | 340,000 | 470,000 | 500,000 | 600,000 | 700,000 | 800,000 | 990,000 | 1,350,000 |
| Boiler | 50,000 | 70,000 | 90,000 | 110,000 | 130,000 | 150,000 | 170,000 | 190,000 | 210,000 | 230,000 |
| Digester Tank | 80,000 | 210,000 | 340,000 | 470,000 | 600,000 | 700,000 | 850,000 | 1,030,000 | 1,100,000 | 1,000,000 |
| Pumps | 40,000 | 90,000 | 140,000 | 190,000 | 240,000 | 290,000 | 340,000 | 390,000 | 440,000 | 490,000 |
| Controls | 30,000 | 60,000 | 90,000 | 120,000 | 150,000 | 180,000 | 210,000 | 240,000 | 270,000 | 300,000 |
| **Total Materials cost** | **450,000** | **970,000** | **1,490,000** | **2,010,000** | **2,430,000** | **2,950,000** | **3,470,000** | **3,990,000** | **4,510,000** | **5,030,000** |
| Project Development | 30,000 | 70,000 | 110,000 | 150,000 | 190,000 | 230,000 | 270,000 | 310,000 | 350,000 | 500,000 |
| Engineering | 30,000 | 40,000 | 50,000 | 60,000 | 170,000 | 180,000 | 190,000 | 200,000 | 210,000 | 320,000 |
| Construction/Mgt | 80,000 | 100,000 | 120,000 | 140,000 | 160,000 | 180,000 | 200,000 | 220,000 | 240,000 | 600,000 |
| Consulting | 10,000 | 20,000 | 30,000 | 40,000 | 50,000 | 60,000 | 70,000 | 80,000 | 80,000 | 70,000 |
| **Total other cost** | **150,000** | **230,000** | **310,000** | **390,000** | **570,000** | **650,000** | **730,000** | **810,000** | **890,000** | **970,000** |
| **Total Capital costs** | **600,000** | **1,200,000** | **1,800,000** | **2,400,000** | **3,000,000** | **3,600,000** | **4,200,000** | **4,800,000** | **5,400,000** | **6,000,000** |
| | | | | | | | | | | |
| Working capital | 30,000 | 35,000 | 40,000 | 45,000 | 50,000 | 55,000 | 60,000 | 65,000 | 70,000 | 75,000 |
| | | | | | | | | | | |
| Pre-system on-farm power requirement (kWh/Year) | 850,000 | 1,700,000 | 2,550,000 | 3,400,000 | 4,250,000 | 5,100,000 | 5,950,000 | 6,800,000 | 7,650,000 | 8,500,000 |
| Power use of ADG-to_E system (kWh/Year) | 54,750 | 109,500 | 164,250 | 219,000 | 273,750 | 328,500 | 382,250 | 438,000 | 492,750 | 547,500 |

### 4.4.2 Days of Inventory

Days of inventory is a measure of performance calculated by average inventory cost divided by average daily cost of sales. This number returns a figure equivalent to the number of days an item is held as inventory before it is used. The lower the day's inventory, the more efficient the anaerobic digester performs. The days of inventory for supplies and accounts payable and receivable are given in Table 4.5.

**Table 4.5**. Days in Inventory for Various Balance Sheet Items.

| Item | Days in inventory |
|---|---|
| Fuels, etc. | 20 |
| Accounts receivable | 20 |
| Accounts payable | 25 |

The days in inventory information is used for creation of the inventory numbers on the pro-forma balance sheets.

### 4.4.3 Data on volatile solids, biogas and methane production from the laboratory test

The laboratory experiment was conducted at three different temperatures: Thermophilic (TT-55˚C), Mesophilic (MT-35˚C), and Ambient (25˚C). At each temperature, five ratios of dairy manure (DM) to potato waste (PW) were chosen. The chosen five ratios of DM:PW were 100:0, 90:10, 80:20, 60:40 and 40:60. The results obtained for each ratio are shown in Table 4.6.

**Table 4.6**. Summary of the results obtained from batch digestion at different temperatures.

| **Temperature** | **Ratios (DM:PW)** | **Cumulative methane yield (Liters) (Y)** | **VS reduction (%) (X)** | **(X/100)*165 g (Z)** | **Methane yield (L $g^{-1}$ VS) (Y/Z)** | **Methane yield conversion – (L $g^{-1}$ VS to cf/lb VS) (16.018*(Y/Z))** |
|---|---|---|---|---|---|---|
| TT | 100:0 | 36 | 75.4 | 124 | 0.290 | 4.6 |
| | 90:10 | 62 | 80.5 | 133 | 0.466 | 7.5 |
| | 80:20 | 93 | 79.6 | 131 | 0.710 | 11.4 |
| | 60:40 | 53 | 80.2 | 133 | 0.399 | 6.4 |
| | 40:60 | 44 | 76.4 | 126 | 0.349 | 5.6 |
| MT | 100:0 | 34 | 70.3 | 116 | 0.293 | 4.7 |
| | 90:10 | 43 | 68.8 | 114 | 0.377 | 6.0 |
| | 80:20 | 36 | 71.1 | 117 | 0.308 | 4.9 |
| | 60:40 | 25 | 71.6 | 118 | 0.212 | 3.3 |
| | 40:60 | 22 | 73.8 | 122 | 0.180 | 2.8 |
| AT | 100:0 | 8 | 53.5 | 88 | 0.090 | 1.4 |
| | 90:10 | 5 | 26.2 | 43 | 0.116 | 1.9 |
| | 80:20 | 6 | 25 | 41 | 0.146 | 2.3 |
| | 60:40 | 5 | 15 | 25 | 0.2 | 3.2 |
| | 40:60 | 3 | 13 | 21 | 0.143 | 2.3 |

Cf: cubic foot; lb: pounds; cf/lb: cubic feet of biogas produced per pound of volatile solid converted; DM: dairy manure; PW: potato waste; L: liters; %: percentage; g: grams; VS: volatile solids;
Note - 1 liter per grams = 16.018 (cubic feet) per pounds

All the given values (Table 4.6) were obtained from laboratory test on anaerobic co-digestion of dairy manure and potato waste (Chapter 3). From Table 4.6, the values of VS reduction (%) (Column 4, Table 4.6) and conversion (L g-1 VS) (column 7, Table 4.6) were used for this economic analysis.

### 4.4.4 Energy and biogas production assumptions

In this section of the tool, the information required to calculate the energy generation potential of the system was entered. The parameters listed in this section with the given values are shown in Table 4.7.

**Table 4.7**. Energy and biogas production values required for spreadsheet-based assessment tool.

| **Parameters for economic analysis** | **Values** |
|---|---|
| ***Manure:*** | |
| Solid conversion to biogas [VS reduction in Table 4.6] (%) | e.g. 75.4 for TT, 100:0 (DM:PW) condition |
| Cubic feet of biogas produced per pound of volatile solid converted [Conversion – L $g^-1$ VS to cf/lb VS in Table 4.6] | e.g. 4.6 for TT, 100:0 (DM:PW) condition |
| BTU’s per cubic foot of biogas | 625 |
| ***Other Waste Streams:*** | |
| Tipping fees per ton of waste (net of disposal costs) | 0 |
| Tons of other waste per day | 0 |
| Volatile solid content (%) | 0 |
| Solid conversion to biogas (%) | 0 |
| Cubic feet of biogas produced per pound of volatile solid converted | 0 |

| **Parameters for economic analysis** | **Values** |
|---|---|
| BTU's per cubic foot of biogas | 0 |
| ***Electricity Conversion and Use Assumptions:*** | |
| Thermal conversion efficiency of electricity generation equipment (%) | 25% |
| Daily on-line percent for electricity generation equipment (%) | 90% |
| Pre-system on-farm power requirement (kWh/year) | 850,000 (This value changes with change in cow numbers) |
| Power use of AD system (kWh/year) | 54,750 (This value changes with change in cow numbers) |
| Purchase price of electricity from grid ($'s/kWh) | 0.0509 |
| Sale price to grid ($'s/kWh) | 0.0850 |
| Carbon credit price ($'s/ MT $CO_2$) | 0 |
| Type of existing manure storage Anaerobic lagoon | 0 |

In Table 4.7, except for two manure parameters ("solid conversion to biogas" value and "cubic feet of biogas produced per pound of volatile solid converted" value) in "Manure" section and two parameters in "Electricity Conversion and Use Assumptions" section ("purchase price of electricity from grid" and "sale price to grid"), all the other given values in Table 4.7 are default values taken from the spreadsheet-based assessment tool designed by Enahoro and Gloy (2008) (permission obtained from authors). The values for the purchase price of electricity from the grid and sale price to the grid in Table 4.7 were determined based on Idaho's electricity rates. At present, according to Idaho's Schedule 9 Secondary/Large General Service (Idaho Power, 2014), demand charge per kilowatt is given in Table 4.8.

In the Electricity Conversion and Use Assumptions section (Table 4.7), "thermal conversion efficiency of the engine generator equipment" represents the thermal conversion efficiency of the electrical generation equipment. This information was used to convert the BTU of biogas generated into kWh. The standard conversion factor of 1 kWh per 3,412 BTU was combined with the efficiency factor to estimate the total number of kWhs generated by the system. Another important parameter that needs to be considered is the amount of energy (electricity) that the farm used before installing the anaerobic digester on the dairy farm.

**Table 4.8**. Service Charge per month, Basic Charge per kW.

| | Summer | Non-Summer |
|---|---|---|
| Demand Charge per kW (over 20 kW) | $6.00 | $4.40 |
| Block 1 – First 2000 kWh | 9.6994¢ | 8.6579¢ |
| Block 2 – Over 2000 kWh | 4.0963¢ | 3.6483¢ |

Source: Idaho power, Idaho Business Rates

This value determines the amount of energy purchased that can be offset by the AD system. This value was taken as the total kWh used per year. It is important to consider the amount of energy that the AD system consumed and the value that was given in the spreadsheet as the total kWh used by the AD system per year. This value was not credited toward system savings or sales. The purchase price for electricity for the farm was entered in dollars per kWh. These values were taken assuming the price that the farm had been paying for electricity purchased from the grid prior to installation of the AD system. These values did not include "standby" or "demand" charges that will still be charged to the farm after the digester is installed and operated on-farm. The next input was the electricity sale price in dollars per kWh.

Finally, the price for any carbon credits sold as a result of installation AD system on a dairy farm and the type of manure storage system currently used were entered. The carbon credits generated by the system and the price of the carbon credits were required to estimate the revenues of the AD system. The value was entered as dollars per metric ton of $CO_2$ equivalent.

Calculating the amount of carbon credits depends on the farm current manure storage systems such as an anaerobic lagoon or a liquid/slurry manure storage system. The farms using anaerobic lagoons are eligible for a greater amount of $CO_2$ equivalent offsets than using liquid/slurry manure storage systems. For this study, the amount of carbon credits entered was zero (Table 4.7).

The purchase price of electricity from grid (for a 1,000 cow dairy) was calculated as follows:

**Table 4.9**. Calculations for price of electricity purchased from grid.

| **kWh/month** | **kW demand** | **kWh/hours for time** |
|---|---|---|
| Pre-system on-farm power requirement per month (850,000kWh/year)/(12 months) = **70833.33kWh**/month | On average we assume we have 30 days per month and we have 24 hours per day.<br>30 x 24 = 720 hours/month<br>70833.33kWh/720h =<br>**98.4kW** | *Demand Charge*<br>98.4 x \$6 (value from Table 4.8, summer rate) = **\$590.28** |
| | | *Price for first 2000 kWh*<br>2000 x \$0.096994 (value from Table 4.8, summer rate) = **\$193.99** |
| | | *Price for above 2000 kWh*<br>(70833.33-2000) x \$0.040963 (value from Table 4.8, summer rate) = **\$2,819.62** |
| | | *Total*<br>(590.28+193.99+2819.62) = **3,603.89** |
| | | Calculated purchase price of electricity from grid for 1,000 cow dairy farm<br>3,603.89/70833.33 = **0.050878** |

Calculations shown in Table 4.9 were recommended by Wilson Gray, Economist, University of Idaho, Twin Falls Research and Extension Center.

### 4.4.5 Operating Costs

In this section various operating costs were included. The spreadsheet provides the option of entering values for a variety of operating costs as given in Table 4.10.

**Table 4.10**. Operating Expense Estimates for the AD System.

| **Operating Expense** | **Value** |
|---|---|
| Operating, Repairs and Maintenance % of Capital | 5.0% |
| Operating, Repairs, and Maintenance | 5% of the total capital budget |
| Property Taxes | 0 |
| Insurance | 0 |
| Office | 0 |
| Oil and Fuel | 0 |
| Accounting and Legal | 0 |
| Labor | 0 |
| Total Expenses | Calculated |
| Cost per kWh ($'s/kWh) | Calculated |

For this analysis, 5.0% total capital costs per each year was taken as Operating, Repairs and Maintenance cost. There is no personal property tax in Idaho so it is taken as "0".

### 4.4.6 Financial Assumptions

The financial information is required and important to calculate the interest and principle payments for the AD system. For this analysis, the values that are taken in the spreadsheet are given in Table 4.11.

**Table 4.11**. Financial Assumptions for economic analysis of AD systems.

| **Variable** | **Value** |
|---|---|
| Percent Financing on Personal Property | 65% |
| Term on Personal Property (years) | 7 |
| Rate on Personal Property (%) | 6% |
| Percent Financing on Real Property | 65% |
| Land percent financed | 65% |
| Term on Long-Term Financing | 20 |
| Rate on Long-Term financing | 6% |
| Discount Rate | 5% |
| Terminal Value Multiple | 10 |
| Terminal Value Implied by Discount Rate | Calculated |

Input values shown in Table 4.11 were recommended by Wilson Gray, Economist, University of Idaho, Twin Falls Research and Extension Center.

In Table 4.11, the financing percentage of personal property was taken for a period of 7 years. If 65% of the cost of the property will be financed with debt, the user would enter 65%. The term of the loan and the interest rate were then entered. Different values for land and long term property were entered. This information was used by the program to calculate the debt service for the project.

For this analysis, a discount rate of 5% was considered. This value was used to discount the future cash flows generated by the project. The discount rate should reflect the opportunity cost of capital for the firm conducting the analysis. The establishment of a proper discount rate is beyond the scope of this report. In most cases users should enter their weighted average cost of capital. The weighted average cost of capital is simply the required return on debt and equity capital weighted by the proportions of each that are used to finance operations (Enahoro and Gloy, 2008). For example, if an operation uses 70% debt with an average interest rate of 6% and the required rate of return on equity is 10%, the weighted average cost of capital is 9.6% (e.g.: 0.60*0.08 + 0.40*0.12). If the project is financed differently, then some changes should be made for establishing the discount rate. It is important to note that, in all cases, the discount rate should be greater than the interest rate paid on debt.

The basic discounted cash flow analysis used a project time horizon of ten years. A terminal value multiple can be used to place an ending value on the project. The terminal value multiple was based upon the concept of valuing the ongoing business as a multiple of the cash flow that it generates into perpetuity (Martin, EPA Contract No. GS 10F-0036K). The perpetuity value was then discounted by an appropriate number of periods to bring to a net present value. For example, if the multiple of 10 is employed at the tenth year, the free cash flow at the end of the tenth period is multiplied by 10 to determine the terminal value. This value is then discounted by 10 periods to bring it to present value. The selection of a terminal value can have a large impact on the net present value of the project. The most conservative assumption is to use a terminal value multiplied by 0.

### 4.4.7 Financial statements and assessment

By using all the above discussed inputs, the spreadsheet generated an income statement, balance sheet, cash flow statement, net present value, and internal rate of return. The discounted cash flow analysis was conducted by calculating cash flow generated by the project as the earnings before interest, taxes, depreciation, and amortization (EBITDA).

By using all the above discussed parameters and the results obtained from laboratory test, the cost analysis for 1,000 to 10,000 cow dairy farms has been conducted.

## 4.5 Part I – Anaerobic digester connected with electricity generation equipment.

### 4.5.1 Cost analysis for 1,000 to 10,000 cow dairy farms.

By entering all the given values from Tables 4.1 to 4.5 and Tables 4.7, 4.10 and 4.11 into the spreadsheet-based assessment tool, the analysis was conducted. The analysis was performed using the results obtained from laboratory AD experiment on anaerobic co-digestion of DM and PW (Table 4.6). First, the analysis was conducted assuming that a particular dairy farm has 1000 cows (2$^{st}$ column, Table 4.2) where the total cost was taken as \$1400/cow (Table 4.2). All the parameters were used as defined in Tables 4.1 to 4.7 and 4.10 and 4.11 except five parameters from Table 4.7. The five parameters from Table 4.7 were: 1) solid conversion to biogas (%), 2) cubic feet of biogas produced per pound of volatile solid converted, 3) pre-system on-farm power requirement, 4) power use of AD system and 5) purchase price of electricity from grid. These five parameters were changed according to capacity of dairy farm (1,000 to 10,000), AD temperature regime and the DM/PW ratio for which the analysis was performed. For example, if we choose a 1,000 cow dairy farm running a digester at mesophilic temperatures (MT) and the ratio of 90:10, then the solid conversion to biogas (%) value would be 68.8, cubic feet of biogas produced per pound of volatile solids.

The unit conversion value would be 6.0 (values from columns 4 and 7, Table 4.6, respectively). The pre-system on-farm power requirement, the power use of AD system and the purchase price of electricity from grid would be 850,000, 54,750, and 0.0501 (values from Table 4.2, 4.3, and 4.4), respectively. Keeping 1,000 cows as a constant value, the analysis was performed for three temperature ranges (TT, MT, and ambient) and five mixing ratios in each temperature range to check for profitability. The same analysis was performed for 2,000, 3,000, 4,000, 5,000, 6,000, 7,000, 8,000, 9,000 and 10,000 cows. In a similar way, the analysis was performed for $1,000/cow (Table 4.3) and $600/cow (Table 4.4). The results obtained using $1,400/cow, three temperatures ranges, and five mixing ratios are given in Table 4.12. The results obtained using $1,000/cow and $600/cow, three temperatures ranges, and five mixing ratios are given in Tables 4.13 and 4.14, respectively.

**Table 4.12**. Cost analysis on AD systems considering $1,400/cow based on laboratory test results.

| **Temperature** | **Ratios (DM: PW)** | **VS reduction (%)** | **Conversion (L g$^{-}$1 VS to cf/lb VS)** | **Cost analysis for ten year**<br>(Net present value with zero terminal value in Excel sheet)<br>**Calculations are based on $1,400/cow** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **1,000 cows ($)** | **2,000 cows ($)** | **3,000 cows ($)** | **4,000 cows ($)** | **5,000 cows ($)** | **6,000 cows ($)** | **7,000 cows ($)** | **8,000 cows ($)** | **9,000 cows ($)** | **10,000 cows ($)** |
| TT | 100:0 | 75.4 | 4.6 | -1,441,764 | -2,858,528 | -4,275,291 | -5,692,055 | -7,386,036 | -8,525,583 | -9,942,347 | -11,359,110 | -12,775,874 | -14,192,638 |
| | 90:10 | 80.5 | 7.5 | -1,050,104 | -2,075,209 | -3,100,313 | -4,125,418 | -5,427,740 | -6,175,627 | -7,200,731 | -8,225,836 | -9,250,940 | -10,276,044 |
| | 80:20 | 79.6 | 11.4 | -587,129 | -1,149,258 | -1,711,387 | -2,273,516 | -3,112,862 | -3,397,774 | -3,959,903 | -4,522,032 | -5,084,161 | -5,646,290 |
| | 60:40 | 80.2 | 6.4 | -1,188,026 | -2,351,052 | -3,514,078 | -4,677,104 | -6,117,347 | -7,003,156 | -8,166,182 | -9,329,208 | -10,492,234 | -11,655,260 |
| | 40:60 | 76.4 | 5.6 | -1,318,279 | -2,611,559 | -3,904,838 | -5,198,117 | -6,768,614 | -7,784,676 | -9,077,955 | -10,371,234 | -11,664,513 | -12,957,793 |
| MT | 100:0 | 70.3 | 4.7 | -1,466,811 | -2,908,623 | -4,350,434 | -5,792,245 | -7,511,274 | -8,675,868 | -10,117,679 | -11,559,491 | -13,001,302 | -14,443,113 |
| | 90:10 | 68.8 | 6.0 | -1,341,208 | -2,657,416 | -3,973,623 | -5,289,831 | -6,883,256 | -7,922,247 | -9,238,454 | -10,554,662 | -11,870,870 | -13,187,078 |
| | 80:20 | 71.1 | 4.9 | -1,439,401 | -2,853,802 | -4,268,202 | -5,682,603 | -7,374,221 | -8,511,405 | -9,925,806 | -11,340,207 | -12,754,607 | -14,169,008 |
| | 60:40 | 71.6 | 3.3 | -1,610,313 | -3,195,625 | -4,780,938 | -6,366,250 | -8,228,780 | -9,536,875 | -11,122,188 | -12,707,500 | -14,292,813 | -15,878,125 |
| | 40:60 | 73.8 | 2.8 | -1,655,499 | -3,285,997 | -4,916,496 | -6,546,995 | -8,454,711 | -9,807,992 | -11,438,491 | -13,068,990 | -14,699,488 | -16,329,987 |
| PT | 100:0 | 53.5 | 1.4 | -1,856,336 | -3,687,673 | -5,519,009 | -7,350,346 | -9,458,899 | -11,013,018 | -12,844,355 | -14,675,691 | -16,507,027 | -18,338,364 |
| | 90:10 | 26.2 | 1.9 | -1,894,632 | -3,764,264 | -5,633,895 | -7,503,527 | -9,650,376 | -11,242,791 | -13,112,423 | -14,982,055 | -16,851,686 | -18,721,318 |
| | 80:20 | 25 | 2.3 | -1,882,863 | -3,740,725 | -5,598,588 | -7,456,451 | -9,591,531 | -11,172,176 | -13,030,039 | -14,887,901 | -16,745,764 | -18,603,627 |
| | 60:40 | 15 | 3.2 | -1,897,345 | -3,769,691 | -5,642,036 | -7,514,382 | -9,663,945 | -11,259,073 | -13,131,418 | -15,003,763 | -16,876,109 | -18,748,454 |
| | 40:60 | 13 | 2.3 | -1,924,939 | -3,824,878 | -5,724,817 | -7,624,756 | -9,801,912 | -11,424,633 | -13,324,572 | -15,224,511 | -17,124,450 | -19,024,389 |

**Table 4.13**. Cost analysis on AD systems considering $1,000/cow based on laboratory test results.

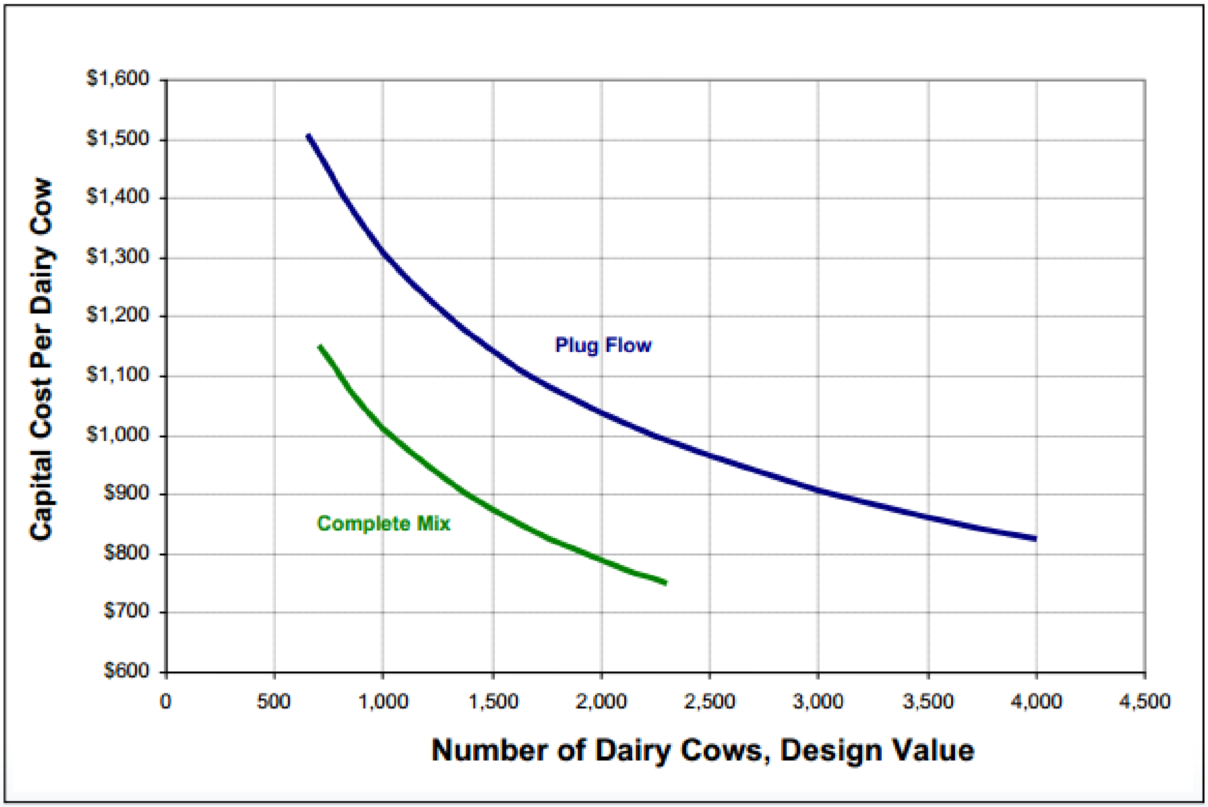
| Temperature | Ratios (DM: PW) | VS reduction (%) | Conversion (L $g^{-1}$ VS to cf/lb VS) | **Cost analysis for ten year**<br>(Net present value with zero terminal value in Excel sheet)<br>**Calculations are based on $1,000/cow** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **1,000 cows ($)** | **2,000 cows ($)** | **3,000 cows ($)** | **4,000 cows ($)** | **5,000 cows ($)** | **6,000 cows ($)** | **7,000 cows ($)** | **8,000 cows ($)** | **9,000 cows ($)** | **10,000 cows ($)** |
| TT | 100:0 | 75.4 | 4.6 | -887,329 | -1,749,658 | -2,611,987 | -3,474,316 | -4,336,645 | -5,198,975 | -6,061,304 | -6,923,633 | -7,785,962 | -8,648,291 |
| | 90:10 | 80.5 | 7.5 | -495,670 | -966,339 | -1,437,009 | -1,907,679 | -2,378,349 | -2,849,018 | -3,319,688 | -3,790,358 | -4,261,028 | -4,731,697 |
| | 80:20 | 79.6 | 11.4 | -32,694 | -40,389 | -48,083 | -55,777 | -63,471 | -71,166 | -78,860 | -86,554 | -94,248 | -101,943 |
| | 60:40 | 80.2 | 6.4 | -633,591 | -1,242,183 | -1,850,774 | -2,459,365 | -3,067,956 | -3,676,548 | -4,285,139 | -4,893,730 | -5,502,322 | -6,110,913 |
| | 40:60 | 76.4 | 5.6 | -763,845 | -1,502,689 | -2,241,534 | -2,980,378 | -3,719,223 | -4,458,067 | -5,196,912 | -5,935,757 | -6,674,601 | -7,413,446 |
| MT | 100:0 | 70.3 | 4.7 | -912,377 | -1,799,753 | -2,687,130 | -3,574,507 | -4,461,883 | -5,349,260 | -6,236,636 | -7,124,013 | -8,011,390 | -8,898,766 |
| | 90:10 | 68.8 | 6.0 | -786,773 | -1,548,546 | -2,310,319 | -3,072,092 | -3,833,865 | -4,595,638 | -5,357,411 | -6,119,184 | -6,880,958 | -7,642,731 |
| | 80:20 | 71.1 | 4.9 | -884,966 | -1,744,932 | -2,604,898 | -3,464,864 | -4,324,831 | -5,184,797 | -6,044,763 | -6,904,729 | -7,764,695 | -8,624,661 |
| | 60:40 | 71.6 | 3.3 | -1,055,878 | -2,086,756 | -3,117,634 | -4,148,511 | -5,179,389 | -6,210,267 | -7,241,145 | -8,272,023 | -9,302,901 | -10,333,778 |
| | 40:60 | 73.8 | 2.8 | -1,101,064 | -2,177,128 | -3,253,192 | -4,329,256 | -5,405,320 | -6,481,384 | -7,557,448 | -8,633,512 | -9,709,576 | -10,785,640 |
| PT | 100:0 | 53.5 | 1.4 | -1,301,902 | -2,578,803 | -3,855,705 | -5,132,607 | -6,409,508 | -7,686,410 | -8,963,312 | -10,240,213 | -11,517,115 | -12,794,017 |
| | 90:10 | 26.2 | 1.9 | -1,340,197 | -2,655,394 | -3,970,591 | -5,285,789 | -6,600,986 | -7,916,183 | -9,231,380 | -10,546,577 | -11,861,774 | -13,176,971 |
| | 80:20 | 25 | 2.3 | -1,328,428 | -2,631,856 | -3,935,284 | -5,238,712 | -6,542,140 | -7,845,568 | -9,148,996 | -10,452,424 | -11,755,852 | -13,059,280 |
| | 60:40 | 15 | 3.2 | -1,342,911 | -2,660,821 | -3,978,732 | -5,296,643 | -6,614,554 | -7,932,464 | -9,250,375 | -10,568,286 | -11,886,197 | -13,204,107 |
| | 40:60 | 13 | 2.3 | -1,370,504 | -2,716,008 | -4,061,513 | -5,407,017 | -6,752,521 | -8,098,025 | -9,443,529 | -10,789,034 | -12,134,538 | -13,480,042 |

**Table 4.14**. Cost analysis on AD systems considering $600/cow based on laboratory test results.

| **Temperature** | **Ratios (DM: PW)** | **VS reduction (%)** | **Conversion – L $g^{-1}$ VS to cf/lb VS** | **Cost analysis for ten year** (Net present value with zero terminal value in Excel sheet) **Calculations are based on $600/cow** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **1,000 cows ($)** | **2,000 cows ($)** | **3,000 cows ($)** | **4,000 cows ($)** | **5,000 cows ($)** | **6,000 cows ($)** | **7,000 cows ($)** | **8,000 cows ($)** | **9,000 cows ($)** | **10,000 cows ($)** |
| TT | 100:0 | 75.4 | 4.6 | -332,894 | -640,789 | -948,683 | -1,256,578 | -1,564,472 | -1,872,366 | -2,180,261 | -2,488,155 | -2,796,050 | -3,103,944 |
| | 90:10 | 80.5 | 7.5 | **58,765** | **142,530** | **226,295** | **310,060** | **393,825** | **477,590** | **561,355** | **645,120** | **728,885** | **812,650** |
| | 80:20 | 79.6 | 11.4 | **521,740** | **1,068,481** | **1,615,221** | **2,161,962** | **2,708,702** | **3,255,443** | **3,802,183** | **4,348,923** | **4,895,664** | **5,442,404** |
| | 60:40 | 80.2 | 6.4 | -79,157 | -133,313 | -578,230 | -241,626 | -295,783 | -349,939 | -404,096 | -458,253 | -512,409 | -566,566 |
| | 40:60 | 76.4 | 5.6 | -209,410 | -393,820 | -187,470 | -762,640 | -947,049 | -1,131,459 | -1,315,869 | -1,500,279 | -1,684,689 | -1,869,099 |
| MT | 100:0 | 70.3 | 4.7 | -357,942 | -690,884 | -1,023,826 | -1,356,768 | -1,689,710 | -2,022,652 | -2,355,594 | -2,688,535 | -3,021,477 | -3,354,419 |
| | 90:10 | 68.8 | 6.0 | -232,338 | -439,677 | -647,015 | -854,353 | -1,061,692 | -1,269,030 | -1,476,369 | -1,683,707 | -1,891,045 | -2,098,384 |
| | 80:20 | 71.1 | 4.9 | -330,531 | -636,063 | -941,594 | -1,247,126 | -1,552,657 | -1,858,189 | -2,163,720 | -2,469,251 | -2,774,783 | -3,080,314 |
| | 60:40 | 71.6 | 3.3 | -501,443 | -977,886 | -1,454,329 | -1,930,773 | -2,407,216 | -2,883,659 | -3,360,102 | -3,836,545 | -4,312,988 | -4,789,431 |
| | 40:60 | 73.8 | 2.8 | -546,629 | -1,068,259 | -1,589,888 | -2,111,517 | -2,633,147 | -3,154,776 | -3,676,405 | -4,198,035 | -4,719,664 | -5,241,293 |
| PT | 100:0 | 53.5 | 1.4 | -747,467 | -1,469,934 | -2,192,401 | -2,914,868 | -3,637,335 | -4,359,802 | -5,082,269 | -5,804,736 | -6,527,203 | -7,249,670 |
| | 90:10 | 26.2 | 1.9 | -785,762 | -1,546,525 | -2,307,287 | -3,068,050 | -3,828,812 | -4,589,575 | -5,350,337 | -6,111,099 | -6,871,862 | -7,632,624 |
| | 80:20 | 25 | 2.3 | -773,993 | -1,522,987 | -2,271,980 | -3,020,973 | -3,769,966 | -4,518,960 | -5,267,953 | -6,016,946 | -6,765,940 | -7,514,933 |
| | 60:40 | 15 | 3.2 | -788,476 | -1,551,952 | -2,315,428 | -3,078,904 | -3,842,380 | -4,605,856 | -5,369,332 | -6,132,808 | -6,896,284 | -7,659,760 |
| | 40:60 | 13 | 2.3 | -816,069 | -1,607,139 | -2,398,208 | -3,189,278 | -3,980,347 | -4,771,417 | -5,562,486 | -6,353,556 | -7,144,625 | -7,935,695 |

### 4.5.2 Summary of Part I Results.

Based on laboratory test results (for all the ratios), the cost analyses showed that we couldn’t recover the entire capital amount within a ten year time period when we invest for construction of anaerobic digestion systems on 1,000 to 10,000 cow dairy operations when \$1,400/cow or \$1,000/cow was taken. Nevertheless, when \$600/cow was taken for the analysis, it showed that the ratio of DM:PW-90:10 and 80:20 at thermophilic temperatures has positive cash flow for all capacity dairy farms (1,000 to 10,000 cows given in bold, Table 4.14). This analysis shows that the positive cash flow can be possible within a ten-year time period when $CH_4$ yield is > 7.5 cf/lb. When $CH_4$ yield is ≥ 11.4 cf/lb VS **(**ratio of DM:PW-80:20 at thermophilic temperatures, Table 4.6), a positive cash flow was possible within a ten-year time period for 1,000 to 10,000 cow dairy farms. Similarly, with the $CH_4$ yield of ≥ 7.5 cf/lb VS **(**ratio of DM:PW-90:10 at thermophilic temperatures, Table 4.6), the positive cash flow was possible within a ten-year time period for 1,000 to 10,000 cow dairy farms. Based on the laboratory results (Table 4.6), cost analysis showed that if low cost plug flow digesters (\$600/cow) are installed on dairy farms could generate a positive cash flow within a ten-year time period. However, the cost of AD systems will vary with system type and size, type of livestock operation and site-specific conditions. Based on the USEPA AgSTAR Program (2008) estimating capital cost for anaerobic digesters, the capital cost per dairy cow would be reduced when the cow numbers increase as shown in Fig. 4.1.



Source: USEPA AgSTAR Program, 2008

**Fig. 4.1.** Capital cost per dairy cow for completely mix and plug flow AD systems.

If we consider the curve indicating only the cost for plug flow digester design (Fig. 4.1), the following values (Table 4.15) can be approximately drawn for $1,400/ cow, $1,000/cow and $600/cow from Table 4.12, 4.13, and 4.14. We can see from Table 4.15 that the analysis estimates positive cash flow for $600/cow when 10,000 cow dairy farm was considered.

The study by Beddoes *et al.* (2007) showed that approximately 36% of the total capital cost is associated with electrical generation equipment. Even without the generator system, anaerobic digesters can be constructed on dairy farms and dairy farms can benefit from biogas generated and can achieve several other benefits. In part II, the cost analysis was performed by reducing 36% from the total capital cost given in Tables 4.2, 4.3, and 4.4. Additional benefits of constructing anaerobic digesters on dairy farms and cost reduction techniques for biogas collection, upgrading and on-farm use are also discussed in part II.

**Table 4.15**. Summary of cost analysis for dairies of 1,000, 2,000 and 10,000 cows.

| **Temperature** | **Ratios (DM:PW)** | **VS reduction (%)** | **Conversion (L $g^{-1}$ VS to cf/lb VS)** | **Cost analysis for ten years** (Net present value with zero terminal value in Excel sheet) | | |
|---|---|---|---|---|---|---|
| | | | | **1,000 cows** | **2,000 cows** | **10,000 cows** |
| | | | | **$1,400/cow** | **$1,000/cow** | **$600/cow** |
| TT | 100:0 | 75.4 | 4.6 | -1,441,764 | -1,749,658 | -3,103,944 |
| | 90:10 | 80.5 | 7.5 | -1,050,104 | -966,339 | **812,650** |
| | 80:20 | 79.6 | 11.4 | -587,129 | -40,389 | **5,442,404** |
| | 60:40 | 80.2 | 6.4 | -1,188,026 | -1,242,183 | -566,566 |
| | 40:60 | 76.4 | 5.6 | -1,318,279 | -1,502,689 | -1,869,099 |
| MT | 100:0 | 70.3 | 4.7 | -1,466,811 | -1,799,753 | -3,354,419 |
| | 90:10 | 68.8 | 6.0 | -1,341,208 | -1,548,546 | -2,098,384 |
| | 80:20 | 71.1 | 4.9 | -1,439,401 | -1,744,932 | -3,080,314 |
| | 60:40 | 71.6 | 3.3 | -1,610,313 | -2,086,756 | -4,789,431 |
| | 40:60 | 73.8 | 2.8 | -1,655,499 | -2,177,128 | -5,241,293 |
| PT | 100:0 | 53.5 | 1.4 | -1,856,336 | -2,578,803 | -7,249,670 |
| | 90:10 | 26.2 | 1.9 | -1,894,632 | -2,655,394 | -7,632,624 |
| | 80:20 | 25 | 2.3 | -1,882,863 | -2,631,856 | -7,514,933 |
| | 60:40 | 15 | 3.2 | -1,897,345 | -2,660,821 | -7,659,760 |
| | 40:60 | 13 | 2.3 | -1,924,939 | -2,716,008 | -7,935,695 |

### 4.6 Part II – Anaerobic digester operated without electricity generation equipment.

Based on the review of 38 case studies and on analysis of energy production costs from anaerobic digestion systems, it was determined that approximately 36% of the total capital cost is associated with electrical power generation equipment (Beddoes *et al.,* 2007). In general, the cost to produce electricity includes annualized capital cost for the digester, generator, and fuel and maintenance costs. Cost analysis can be performed by subtracting 36% from the total cost (Tables 4.2, 4.3 and 4.4) to check for positive cash flow within a ten year time period. If positive cash flow will be possible by subtracting 36% of total capital cost, dairy farmers might show interest to install anaerobic digesters on their farms.

### 4.6.1 Cost analysis for 1,000 to 10,000 cow dairy farms.

The total capital cost or budget shown in Tables 4.2, 4.3 and 4.4 using \$1,400/cow, \$1,000/cow and \$600/cow has been reduced by 36% as shown in Tables 4.16, 4.17 and 4.18 and the cost analysis was performed using the spreadsheet-based assessment tool.

### 4.6.2 Summary of Part II Results

The analysis showed that positive cash flow was achieved for some DM/PW ratios for all capital cost (\$1,400/cow, \$1,000/cow and \$600/cow) within a ten years of time. For example, at \$1,400/cow the analysis showed (Table 4.19) that only one co-digested ratio (DM:PW-80:20) at thermophilic temperature generated positive cash flow within ten year time period for capacity dairy farms (1,000 to 10,000).

**Table 4.16**. Thirty six percent reduction of capital budgets allocated based on $1,400 per cow.

| Total capital cost as obtained in Table 4.2 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Number of cows** | **1,000** | **2,000** | **3,000** | **4,000** | **5,000** | **6,000** | **7,000** | **8,000** | **9,000** | **10,000** |
| **Total Capital costs (TCC)** | 1,400,000 | 2,800,000 | 4,200,000 | 5,600,000 | 7,200,000 | 8,400,000 | 9,800,000 | 11,200,000 | 12,600,000 | 14,000,000 |
| **TCC reduced by 36%** | 896,000 | 1,792,000 | 2,688,000 | 3,584,000 | 4,608,000 | 5,376,000 | 6,272,000 | 7,168,000 | 8,064,000 | 8,960,000 |

**Table 4.17**. Thirty six percent reduction of capital budgets allocated based on $1,000 per cow.

| Total capital cost as obtained in Table 4.3 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Number of cows** | **1,000** | **2,000** | **3,000** | **4,000** | **5,000** | **6,000** | **7,000** | **8,000** | **9,000** | **10,000** |
| **Total Capital costs (TCC)** | 1,000,000 | 2,000,000 | 3,000,000 | 4,000,000 | 5,000,000 | 6,000,000 | 7,000,000 | 8,000,000 | 9,000,000 | 10,000,000 |
| **TCC reduced by 36%** | 640,000 | 1,280,000 | 1,920,000 | 2,560,000 | 3,200,000 | 3,840,000 | 4,480,000 | 5,120,000 | 5,760,000 | 6,400,000 |

**Table 4.18**. Thirty six percent reduction of capital budgets allocated based on $600 per cow.

| Total capital cost as obtained in Table 4.4 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Number of cows** | **1,000** | **2,000** | **3,000** | **4,000** | **5,000** | **6,000** | **7,000** | **8,000** | **9,000** | **10,000** |
| **Total Capital costs (TCC)** | 600,000 | 1,200,000 | 1,800,000 | 2,400,000 | 3,000,000 | 3,600,000 | 4,200,000 | 4,800,000 | 5,400,000 | 6,000,000 |
| **TCC reduced by 36%** | 384,000 | 768,000 | 1,152,000 | 1,536,000 | 1,920,000 | 2,304,000 | 2,688,000 | 3,072,000 | 3,456,000 | 3,840,000 |

At $1,000/cow, the analysis showed (Table 4.20) that the ratio of DM:PW-90:10 and 80:20 at thermophilic temperature generated positive cash flow for all capacity dairy farms (i.e. 1,000 to 10,000 cow dairy farms). At $600/cow, the analysis showed (Table 4.21) that all the co-digested ratios at thermophilic temperature (DM:PW-90:10, 80:20, 60:40 and 40:60) and one co-digested ratio (DM:PW-90:10) at mesophilic temperature showed positive cash flow within ten year time period for all capacity dairy farms (i.e. 1,000 to 10,000 cow dairy farms). The analysis from part II shows that without generator equipment, the completely mixed digesters and high and low cost plug flow digesters can be constructed to generate a positive cash flow within a ten year time period for specific temperature regimes and DM/PW ratios. But, the ratios at which the positive cash flow was generated should be used while operating anaerobic digesters on dairy farms. Anaerobic digesters without generator equipment have several advantages, and the biogas generated can be used on dairy farms. However, similar to the previous discussion of Fig. 4.1, the cost of AD systems will vary with system type and size, type of livestock operation and site-specific conditions. We can draw the corresponding approximate values for the plug flow curve from Fig. 4.1 and from Table 4.19, 4.20 and 4.21 for $1,400/ cow, $1,000/cow and $600/cow as shown in Table 4.22.

**Table 4.19**. Cost analysis of AD systems based on 36% reduction of total cost (Based on Table 4.16 - $1,400/cow).

| Temperature | Ratios (DM:PW) | VS reduction (%) | Conversion (L $g^{-1}$ VS to cf/lb VS) | **Cost analysis for ten year**<br>(Net present value with zero terminal value in Excel sheet)<br>**Calculations are based on $1,400/cow** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **1,000 cows ($)** | **2,000 cows ($)** | **3,000 cows ($)** | **4,000 cows ($)** | **5,000 cows ($)** | **6,000 cows ($)** | **7,000 cows ($)** | **8,000 cows ($)** | **9,000 cows ($)** | **10,000 cows ($)** |
| TT | 100:0 | 75.4 | 4.6 | -743,176 | -1,461,352 | -2,179,528 | -2,897,704 | -3,793,299 | -4,334,056 | -5,052,233 | -5,770,409 | -6,488,585 | -7,206,761 |
| | 90:10 | 80.5 | 7.5 | -351,517 | -678,033 | -1,004,550 | -1,331,067 | -1,835,003 | -1,984,100 | -2,310,617 | -2,637,134 | -2,963,651 | -3,290,167 |
| | 80:20 | 79.6 | 11.4 | **111,459** | **247,917** | **457,186** | **520,835** | **479,875** | **793,752** | **930,211** | **1,066,670** | **1,203,129** | **1,339,587** |
| | 60:40 | 80.2 | 6.4 | -489,438 | -953,877 | -1,418,315 | -1,882,753 | -2,524,610 | -2,811,630 | -3,276,068 | -3,740,506 | -4,204,944 | -4,669,383 |
| | 40:60 | 76.4 | 5.6 | -619,692 | -1,214,383 | -1,809,075 | -2,403,766 | -3,175,877 | -3,593,149 | -4,187,841 | -4,782,532 | -5,377,224 | -5,971,916 |
| MT | 100:0 | 70.3 | 4.7 | -768,224 | -1,511,447 | -2,254,671 | -2,997,894 | -3,918,537 | -4,484,342 | -5,227,565 | -5,970,789 | -6,714,012 | -7,457,236 |
| | 90:10 | 68.8 | 6.0 | -642,620 | -1,260,240 | -1,877,860 | -2,495,480 | -3,290,519 | -3,730,720 | -4,348,340 | -4,965,960 | -5,583,580 | -6,201,200 |
| | 80:20 | 71.1 | 4.9 | -740,813 | -1,456,626 | -2,172,439 | -2,888,252 | -3,781,485 | -4,319,879 | -5,035,692 | -5,751,505 | -6,467,318 | -7,183,131 |
| | 60:40 | 71.6 | 3.3 | -911,725 | -1,798,450 | -2,685,174 | -3,571,899 | -4,636,043 | -5,345,349 | -6,232,074 | -7,118,799 | -8,005,523 | -8,892,248 |
| | 40:60 | 73.8 | 2.8 | -956,911 | -1,888,822 | -2,820,733 | -3,752,644 | -4,861,974 | -5,616,466 | -6,548,377 | -7,480,288 | -8,412,199 | -9,344,110 |
| PT | 100:0 | 53.5 | 1.4 | -1,157,749 | -2,290,497 | -3,423,246 | -4,555,995 | -5,866,162 | -6,821,492 | -7,954,241 | -9,086,989 | -10,219,738 | -11,352,487 |
| | 90:10 | 26.2 | 1.9 | -1,196,044 | -2,367,088 | -3,538,132 | -4,709,176 | -6,057,640 | -7,051,265 | -8,222,309 | -9,393,353 | -10,564,397 | -11,735,441 |
| | 80:20 | 25 | 2.3 | -1,184,275 | -2,343,550 | -3,502,825 | -4,662,100 | -5,998,794 | -6,980,650 | -8,139,925 | -9,299,200 | -10,458,475 | -11,617,750 |
| | 60:40 | 15 | 3.2 | -1,198,758 | -2,372,515 | -3,546,273 | -4,720,031 | -6,071,208 | -$,067,546 | -8,241,304 | -9,415,062 | -10,588,819 | -11,762,577 |
| | 40:60 | 13 | 2.3 | -1,226,351 | -2,427,702 | -3,629,054 | -4,830,405 | -6,209,175 | -7,233,107 | -8,434,458 | -9,635,809 | -10,837,161 | -12,038,512 |

**Table 4.20**. Cost analysis of AD systems based on 36% reduction of total cost (Based on Table 4.17 - $1,000/cow).

| Temperature | Ratios (DM:PW) | VS reduction (%) | Conversion (L $g^{-1}$ VS to cf/lb VS) | **Cost analysis for ten year**<br>(Net present value with zero terminal value in Excel sheet)<br>**Calculations are based on $1,000/cow** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **1,000 cows ($)** | **2,000 cows ($)** | **3,000 cows ($)** | **4,000 cows ($)** | **5,000 cows ($)** | **6,000 cows ($)** | **7,000 cows ($)** | **8,000 cows ($)** | **9,000 cows ($)** | **10,000 cows ($)** |
| TT | 100:0 | 75.4 | 4.6 | -$388,338 | -$751,676 | -$1,115,014 | -$1,478,351 | -$1,841,689 | -$2,205,027 | -$2,568,365 | -$2,931,703 | -$3,295,041 | -$3,658,379 |
| | 90:10 | 80.5 | 7.5 | **3,321** | **31,643** | **59,964** | **88,286** | **116,607** | **144,929** | **173,250** | **201,572** | **229,893** | **258,215** |
| | 80:20 | 79.6 | 11.4 | **466,297** | **957,594** | **1,448,891** | **1,940,188** | **2,431,485** | **2,922,782** | **3,414,079** | **3,905,376** | **4,396,673** | **4,887,970** |
| | 60:40 | 80.2 | 6.4 | -134,600 | -244,200 | -353,800 | -463,400 | -573,000 | -682,600 | -792,200 | -901,800 | -1,011,400 | -1,121,001 |
| | 40:60 | 76.4 | 5.6 | -264,853 | -504,707 | -744,560 | -1,578,542 | -1,224,267 | -1,464,120 | -1,703,973 | -1,943,827 | -2,183,680 | -2,423,533 |
| MT | 100:0 | 70.3 | 4.7 | -413,385 | -801,771 | -1,190,156 | -984,413 | -1,966,927 | -2,355,312 | -2,743,698 | -3,132,083 | -3,520,469 | -3,908,854 |
| | 90:10 | 68.8 | 6.0 | -287,782 | -550,564 | -813,345 | -1,076,127 | -1,338,909 | -1,601,691 | -1,864,473 | -2,127,255 | -2,390,036 | -2,652,818 |
| | 80:20 | 71.1 | 4.9 | -385,975 | -746,950 | -1,107,925 | -1,468,900 | -1,829,874 | -2,190,849 | -2,551,824 | -2,912,799 | -3,273,774 | -3,634,749 |
| | 60:40 | 71.6 | 3.3 | -556,887 | -1,088,773 | -1,620,660 | -2,152,546 | -2,684,433 | -3,216,320 | -4,064,510 | -4,280,093 | -4,811,979 | -5,343,866 |
| | 40:60 | 73.8 | 2.8 | -602,073 | -1,179,146 | -1,756,218 | -2,333,291 | -2,910,364 | -3,487,437 | -3,748,206 | -4,641,582 | -5,218,655 | -5,795,728 |
| PT | 100:0 | 53.5 | 1.4 | -802,910 | -1,580,821 | -2,358,731 | -3,136,642 | -3,914,552 | -4,692,463 | -5,470,373 | -6,248,284 | -7,026,194 | -7,804,105 |
| | 90:10 | 26.2 | 1.9 | -841,206 | -1,657,412 | -2,473,618 | -3,289,824 | -4,106,029 | -4,922,235 | -5,738,441 | -6,554,647 | -7,370,853 | -8,187,059 |
| | 80:20 | 25 | 2.3 | -829,437 | -1,633,874 | -2,438,310 | -3,242,747 | -4,047,184 | -4,851,621 | -5,656,057 | -6,460,494 | -7,264,931 | -8,069,368 |
| | 60:40 | 15 | 3.2 | -843,920 | -1,662,839 | -2,481,759 | -3,300,678 | -4,119,598 | -4,938,517 | -5,757,437 | -6,576,356 | -7,395,276 | -8,214,195 |
| | 40:60 | 13 | 2.3 | -871,513 | -1,718,026 | -2,564,539 | -3,411,052 | -4,257,565 | -5,104,078 | -5,950,591 | -6,797,104 | -7,643,617 | -8,490,130 |

**Table 4.21**. Cost analysis of AD systems based on 36% reduction of total cost (Based on Table 4.18 - $600/cow).

| **Temperature** | **Ratios (DM:PW)** | **VS reduction (%)** | **Conversion L $g^{-1}$ VS to cf/lb VS** | **Cost analysis for ten year**<br>(Net present value with zero terminal value in Excel sheet)<br>**Calculations are based on $600/cow** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **1,000 cows ($)** | **2,000 cows ($)** | **3,000 cows ($)** | **4,000 cows ($)** | **5,000 cows ($)** | **6,000 cows ($)** | **7,000 cows ($)** | **8,000 cows ($)** | **9,000 cows ($)** | **10,000 cows ($)** |
| TT | 100:0 | 75.4 | 4.6 | -33,500 | -41,999 | -50,499 | -58,999 | -$67,498 | -$75,998 | -$84,498 | -$92,997 | -$101,497 | -$109,997 |
| | 90:10 | 80.5 | 7.5 | **358,160** | **741,319** | **1,124,479** | **1,507,639** | **1,890,798** | **2,273,958** | **2,657,118** | **3,040,278** | **3,423,437** | **3,806,597** |
| | 80:20 | 79.6 | 11.4 | **821,135** | **1,667,270** | **2,513,405** | **3,359,541** | **4,205,676** | **5,051,811** | **5,897,946** | **6,744,081** | **7,590,216** | **8,436,352** |
| | 60:40 | 80.2 | 6.4 | **220,238** | **465,476** | **710,714** | **955,953** | **1,201,191** | **1,446,429** | **1,691,667** | **1,936,905** | **2,182,143** | **2,427,382** |
| | 40:60 | 76.4 | 5.6 | **89,985** | **204,970** | **319,955** | **434,939** | **549,924** | **664,909** | **779,894** | **894,879** | **1,009,864** | **1,124,849** |
| MT | 100:0 | 70.3 | 4.7 | -58,547 | -92,094 | -125,642 | -159,189 | -192,736 | -226,283 | -259,830 | -293,378 | -326,925 | -360,472 |
| | 90:10 | 68.8 | 6.0 | **67,056** | **159,113** | **251,169** | **343,226** | **435,282** | **527,338** | **619,395** | **711,451** | **803,507** | **895,564** |
| | 80:20 | 71.1 | 4.9 | -31,137 | -37,273 | -43,410 | -49,547 | -55,683 | -61,820 | -67,957 | -74,093 | -80,230 | -86,367 |
| | 60:40 | 71.6 | 3.3 | -202,048 | -379,097 | -556,145 | -733,194 | -910,242 | -1,087,290 | -1,264,339 | -1,441,387 | -1,618,436 | -1,795,484 |
| | 40:60 | 73.8 | 2.8 | -247,235 | -469,469 | -691,704 | -913,938 | -1,136,173 | -1,358,408 | -1,580,642 | -1,802,877 | -2,025,111 | -2,247,346 |
| PT | 100:0 | 53.5 | 1.4 | -448,072 | -871,144 | -1,294,217 | -1,717,289 | -2,140,361 | -2,563,433 | -2,986,506 | -3,409,578 | -3,832,650 | -4,255,722 |
| | 90:10 | 26.2 | 1.9 | -486,368 | -947,735 | -1,409,103 | -1,870,471 | -2,331,838 | -2,793,206 | -3,254,574 | -3,715,942 | -4,177,309 | -4,638,677 |
| | 80:20 | 25 | 2.3 | -474,599 | -924,197 | -1,373,796 | -1,823,394 | -2,272,993 | -2,722,591 | -3,172,190 | -3,621,788 | -4,071,387 | -4,520,985 |
| | 60:40 | 15 | 3.2 | -489,081 | -953,163 | -1,417,244 | -1,881,325 | -2,345,407 | -2,809,488 | -3,273,569 | -3,737,650 | -4,201,732 | -4,665,813 |
| | 40:60 | 13 | 2.3 | -516,675 | -1,008,350 | -1,500,024 | -1,991,699 | -2,483,374 | -2,975,049 | -3,466,723 | -3,958,398 | -4,450,073 | -4,941,748 |

**Table 4.22**. Summary of cost analysis for a dairy of 1,000, 2,000 and 10,000 cows based on 36% reduction of total cost.

| **Temperature** | **Ratios (DM:PW)** | **VS reduction (%)** | **Conversion (L $g^{-1}$ VS to cf/lb VS)** | **Cost ($) analysis for ten years** (Net present value with zero terminal value in Excel sheet) | | |
|---|---|---|---|---|---|---|
| | | | | **1,000 cows** | **2,000 cows** | **10,000 cows** |
| | | | | **$1,400/cow** | **$1,000/cow** | **$600/cow** |
| TT | 100:0 | 75.4 | 4.6 | -743,176 | -$751,676 | -$109,997 |
| | 90:10 | 80.5 | 7.5 | -351,517 | **31,643** | **3,806,597** |
| | 80:20 | 79.6 | 11.4 | **111,459** | **957,594** | **8,436,352** |
| | 60:40 | 80.2 | 6.4 | -489,438 | -244,200 | **2,427,382** |
| | 40:60 | 76.4 | 5.6 | -619,692 | -504,707 | **1,124,849** |
| MT | 100:0 | 70.3 | 4.7 | -768,224 | -801,771 | -360,472 |
| | 90:10 | 68.8 | 6.0 | -642,620 | -550,564 | **895,564** |
| | 80:20 | 71.1 | 4.9 | -740,813 | -746,950 | -86,367 |
| | 60:40 | 71.6 | 3.3 | -911,725 | -1,088,773 | -1,795,484 |
| | 40:60 | 73.8 | 2.8 | -956,911 | -1,179,146 | -2,247,346 |
| PT | 100:0 | 53.5 | 1.4 | -1,157,749 | -1,580,821 | -4,255,722 |
| | 90:10 | 26.2 | 1.9 | -1,196,044 | -1,657,412 | -4,638,677 |
| | 80:20 | 25 | 2.3 | -1,184,275 | -1,633,874 | -4,520,985 |
| | 60:40 | 15 | 3.2 | -1,198,758 | -1,662,839 | -4,665,813 |
| | 40:60 | 13 | 2.3 | -1,226,351 | -1,718,026 | -4,941,748 |

From Table 4.22, it is evident that a positive cash flow can be achieved within a ten year time period for 1,000, 2,000 and 10,000 cow dairy farm. As the cow numbers increase, a positive cash flow was possible for all the co-digested ratios at thermophilic digestion and the ratio of

DM:PW - 90:10 at mesophilic digestion. This shows that bigger dairy farms can generate a more positive cash flow than smaller dairy farms for installing an anaerobic digester.

## 4.7 On-farm biogas use

Direct combustion is the simplest method for biogas consumption (Walsh *et al.* 1988). The cost of cleaning the biogas for storage, handling, and transport is eliminated by using biogas directly on the facility. There are several options for direct utilization of biogas produced through anaerobic digestion. These include combustion to provide space heating, combustion in a boiler to provide hot water, and use as fuel for either stationary or mobile engines.

### 4.7.1 Direct combustion in boilers

Biogas can be burned directly through boilers to produce hot water for the facility and to heat the anaerobic digester and/or manure influent. To date, the primary direct use of biogas on farm settings has been to fire boilers used to heat water. These systems have primarily been employed by dairies due to the year round requirement for hot water to clean and sanitize milking pipelines and equipment. Since dairies will typically milk two to three times daily and clean after each milking, there is a consistent requirement for hot water on these facilities. Boilers require very little biogas cleaning and conditioning prior to use, and boiler efficiency has been reported to average 75 percent when burning biogas (NETL 2000).

Boilers will operate on very low gas pressures in the range of 5 to 10 inches of water. While burning biogas with large amounts of $H_2S$ will decrease the useful life and increase the operation and maintenance of the equipment. The cleaner the biogas in relation to $H_2S$, the longer the boiler life. To clean the biogas (to remove $CO_2$ and $H_2S$) various technologies are available such as water and polyethylene glycol scrubbing, chemical absorption, pressure swing adsorption, membrane separation, biofilter, and cryogenic separation. According to De Hullu *et al.* (2008), the cost of water scrubbing is \$0.18/Nm$^3$ (Nm$^3$ means Normal Cubic Meter of a gas or the volume of that gas measured under the standard conditions of 0 degrees Celsius and 1 atmosphere of pressure). The cost of scrubbing using chemical absorption, pressure swing adsorption, membrane separation, cryogenic separation is 0.23\$/Nm$^3$, 0.34\$/Nm$^3$, 0.17\$/Nm$^3$, 0.61\$/Nm$^3$ biogas, respectively. However, there are other techniques to burn the biogas without removing $H_2S$.

To successfully burn biogas that has not had the $H_2S$ removed, the boiler should be operated continuously. When biogas containing $H_2S$ is burned, the $H_2S$ is converted into oxides of sulfur (S) (primarily sulfur dioxide ($SO_2$) and sulfur trioxide ($SO_3$)). These sulfur compounds are regulated as air pollutants in the United States, and air emission permits are required depending on the amount released by a facility. When exhaust gases containing $SO_2$ and $SO_3$ cool below the dew point temperature, the moisture that condenses in the gas stream will combine with these compounds to form highly corrosive sulfuric acid ($H_2SO_3$). It is the formation of $H_2SO_3$ following the combustion of biogas that contains $H_2S$ that results in severe equipment corrosion.

A method commonly employed when operating boilers on biogas containing $H_2S$ is to operate the boiler continuously at a temperature above dew point. By maintaining the boiler temperature above the dew point of the gas stream, $H_2SO_3$ is not formed inside the boiler and corrosion is avoided. Since $SO_2$ will reduce the dew point of the gas stream, the greater the $H_2S$ level of a biogas, the higher the boiler temperature that must be maintained to avoid $H_2SO_3$ formation. Biogas with a 1,000 parts per million of $H_2S$ concentration will require exhaust gas stream temperatures of around 150˚C (302ºF) to remain above dew point (IEA Bioenergy 1999). Of course, wherever the exhaust gas stream cools to dew point outside of the boiler, $H_2SO_3$ will be formed. Thus, it is very important to direct exhaust gases away from any equipment, personnel, or livestock. Since $H_2SO_3$ will form when the boiler is shut down, cautionary measures must be taken to avoid any cycling of the boiler on and off when burning $H_2S$-laden biogas to avoid corrosion.

### 4.8 Additional benefits of constructing anaerobic digesters on dairy farms.

Electricity and heat production are direct monetary benefits of the AD projects. Key non-energy benefits and byproducts from anaerobic digestion of manures such as digested dairy solids, odor control, mineralization of organic nitrogen, weed seed destruction, pathogen reduction and improved manure handling are non-monetizable benefits demonstrated by existing digestion systems (Topper *et al.,* 2006; Wright *et al.,* 2008). These factors are increasingly important in sustaining farm viability and are appreciated and desired by farm owners.

### 4.8.1 Nitrogen

Nitrogen in the manure enters the digester mainly in two forms: ammonium or organic N. Ammonium is formed from the reaction of the urease enzyme in the feces with the urea in the urine. Ammonium formation is fairly rapid, with about 95% of the reaction complete in the first 12 hours, often before the manure is collected. Ammonium is not destroyed during the digestion process, but rather, organic N is converted to ammonium during protein degradation. Hence, the ammonium level in the digester effluent is typically higher than raw manure. A negligible amount of ammonia gas will escape with the biogas. As a result, the digester effluent ammonium content can be up to two times higher than in stored manure. When digester effluent is field applied, much of the ammonium will be released as a gas (ammonia) unless it is incorporated into the soil. When incorporated, microorganisms can convert the ammonia to nitrite, which is then rapidly converted to nitrate, the nitrogen form most readily taken up by plants (Topper *et al.,* 2006).

### 4.8.2 Pathogens

In a  study through a plug-flow digester over a 14-month period which was tested for fecal coliform and Mycobacterium avium paratuberculosis (MAP), it was found that anaerobic digestion has the potential to significantly reduce the number of fecal indicator bacteria and MAP CFU/gram in dairy effluent as shown in Table 4.23 (Wright *et al.,* 2008)..

**Table 4.23**. Pathogen reduction from dairy manure through anaerobic digestion process.

| | **Fecal Coliform** (Colony forming units - CFU)/Gram | **MAP** CFU/Gram |
|---|---|---|
| Raw Manure | 3,836,400 | 20,640 |
| Digested Effluent | 3,400 | 136 |

Source: Wright *et al.,* 2008

Communications with several dairy farmers indicated a number of user-reported benefits due to operation of anaerobic digesters (Karmer, 2004). According to Karmer, the benefits were sparsely recorded by farmers and often not quantified. The benefits described were not always separable and mutually exclusive, and were often not easily monetized. Farm owners reported the following benefits they received through operating AD systems on dairy farms (Table 4.24).

**Table 4.24**. Benefits of operating AD systems on dairy farms.

| **Name of the Farm** (location of the farm)<br>(# of cows; type of digester; temperature at which the digester was operated – according to 2004 report) | **Annual benefits savings or revenues** |
|---|---|
| **Baldwin and Emerald Dairies** (Baldwin and emerald, Wisconsin)<br>(1,600; covered lagoon; psychrophilic) | Odor controlled, volume needing treatment reduced due to precipitation exclusion, easier handling of digested manure. |
| **Double S Dairy** (Markesan, Wisconsin)<br>(1,020; plug-flow; mesophilic) | $30,000 savings using digested solids for bedding. |
| **Gordondale Farms** (Nelsonville, Wisconsin)<br>(725; plug-flow; mesophilic) | $23,000 in biogas sales (based on kWh of electricity generated), $30,000 savings replacing commercial fertilizer with digested manure, $28,800 savings using digested solids instead of sand, reduced need for pest |

| | |
|---|---|
| | control in barns saving $5,000 per year, $2,000 in reduced propane use, herbicide savings (not yet calculated), less lime needed to balance pH in soil, significant odor control, extra heat allows use of warm flush flumes and daily scraping throughout the year |
| **Haubenschild Farms** (Princeton, Minnesota) (1,000; plug-flow; mesophilic) | $66,000 in electricity sales and offsets, $50,000 savings replacing commercial fertilizer with digested manure, $30,000 savings in reduced herbicide use, $4,000 in reduced propane use, less stirring needed, better neighbor relations, improved operational flexibility |
| **New Horizons Dairy** (Elmwood, Illinois) (1,100 plug flow, mesophilic) | $40,700 in electricity sales and offsets, process heat allows use of hydroponics system, odor greatly reduced |
| **Stencil Farm** (Denmark, Wisconsin) (1,000; plug flow; mesophilic) | electricity offsets, bedding cost savings, odor reduction, improved fertilizer quality of manure |
| **Tinedale Farm** (Kaukauna, Wisconsin) (2,400; completely mixed; mesophilic) | $75,000 saved using digested solids for bedding |

Source: Karmer, 2004.

## 4.9 Conclusions

### 4.9.1 Part I

- The analysis showed that the anaerobic digesters connected with electricity generation equipment generated positive cash flow within a ten year time period when capital costs of $600/cow were used for analysis.
- Positive cash flow was generated only when the volatile solids conversion rate was higher, i.e. when ≥ 7.5 cubic foot of biogas produced per pound of volatile solid.

### 4.9.2 Part II

- The analysis showed that for all capital costs considered ($1,400/cow, $1,000/cow and $600/cow), positive cash flow can be generated for some DM/PW ratios within a ten years of time.
- Using $1,400/cow, the completely mixed digesters can be constructed without electricity generation equipment. The ratio of DM:PW-80:20 with thermophilic temperature is the recommended ratio and temperature to generate positive cash flow.
- Using $1,000/cow, the high cost plug flow digesters can be constructed without electricity generation equipment. At this cost, the ratios of DM:PW-90:10 and 80:20 with anaerobic digester operating at thermophilic temperature are recommended.

- The low cost plug flow digesters (which cost $600/cow) can be operated in both temperatures (thermophilic and mesophilic) to generate positive cash flow within a ten year time period. For low cost plug flow digesters operated at thermophilic temperatures, dairy manure and potato waste should be mixed to generate positive cash flow. If low cost plug flow digesters are operated at mesophilic temperature, the ratio of DM:PW-90:10 is recommended to generate a positive cash flow.

### 4.9.3 Conclusions

- This analysis suggests that direct use of biogas on site could provide significant non-electrical energy uses and also decrease the payback period of capital investment.
- The anaerobic digesters provide other important benefits such as odor control, savings from bedding cost improved fertilizer quality of manure, reduced need for pest control, herbicide savings, and reduction of solid content of manure.

## 4.10 References

AgSTAR, 2010. Anaerobic Digestion Capital Costs for Dairy Farms. Chemical Engineering, Vol. 117, No. 1. Reterived from http://www.epa.gov/agstar/documents/digester_cost_fs.pdf on Feb 11th, 2013.

Hullu, J. d., Maassen, J. I. W., van Meel, P. A., Shazad, S., Vaessen, J. M. P. (2008). Comparing different biogas upgrading techniques. Eindhoven University of Technology, The Netherlands. Retrieved from http://students.chem.tue.nl/ifp24/BiogasPosterWEB.pdf on March 27th, 2014.

Dhanya, M. S., Prasad, S., & Singh, A. (2013). Biogas technology for developing countries. *Bioenergy Production by Anearobic Digestion*, 397.

Dixon, J. E., J. E. Ojala, L. E. Sandval, and S. L. Hafez. (1987). Disposal of cull and waste potatoes. Current Information Series – Cooperative Extension Service, Univ. Idaho, Moscow. No. 814.

Enahoro, D. K. and Gloy, B. A. (2008). "Economic Analysis of Anaerobic Digestion Systems and the Financial Incentives provided by the New York State Renewable Portfolio Standard (RPS) Customer-Sited Tier (CST) Anaerobic Digester Gas (ADG)-to-Electricity Program." Extension Bulletin 4 (2008). 23 pages. Department of Applied Economics and Management, Cornell University.

IEA Bioenergy. 1999. Biogas upgrading and utilisation. Task 24: Energy from biological conversion of organic waste.

Karmer, J. M. (2004). Agricultural biogas casebook Resource Strategies, Inc. Madison, WI.

Krich, K. *et al.* (2005). Biomethane from Dairy Waste: A Sourcebook for the Production and

Use of Renewable Natural Gas in California. Report for Western United Dairymen.

Martin, J. H. "An Evaluation of a Mesophilic, Modified Plug Flow Anaerobic Digester for Dairy Cattle Manure." Eastern Research Group, Inc. EPA Contract No. GS 10F-0036K Work Assignment/Task Order No. 9.

National Energy Technology Laboratory (NETL). (2000). Pleasant Hills Sewage Treatment Plant Project on Alternative Energy Generation. http://www.netl. doe.gov/energy-analyses/pubs/PHA%20Final%20 Report.pdf

National Greenhouse Gas Inventories Programme. Intergovernmental panel on climate change (IPPC-1996). Reterived from website: http://www.ipcc.ch/graphics/speeches/sbsta-19-statement-revision-1996.pdf on April 22nd, 2013.

Nelson, M. L. (2010). Utilization and application of wet potato processing co-products for finishing cattle. *Journal of Animal Science, 88,* 13, 133-42.

Pailthorp, R. E., J. W. Filbert, and G. A. Richter. (1987). Treatment and disposal of potato wastes. Pages 747–788 in Potato Processing. W. F. Talburt and O. Smith, ed. AVI Publ. Co., Westport, CT.

Smith, J. H. (1986). Decomposition of potato processing wastes in soil. J. Environ. Qual. 15:13–16.

Standley & Company, Irrigation Companies in Jerome, ID.

Topper, P., Graves, R., Richard, T. (2006). The Fate of Nutrients and Pathogens during Anaerobic Digestion of Dairy Manure. Penn State Cooperative Extension. Agriculture and Biological Engineering. Extension Bulletin. Reterived from http://extension.psu.edu/natural-resources/energy/waste-to-energy/resources/biogas/projects/g-71 Feb 17th, 2014.

USDA, Potatoes summary. (2011). National Agricultural Statistics Service. Reterived from website: http://usda01.library.cornell.edu/usda/current/Pota/Pota-09-20-2012.pdf on June 6th, 2012.

USEPA (U.S. Environmental Protection Agency). (2012). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010 (publication No. EPA 430-R-12-001). Washington, DC: Author. Retrieved from http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2012-Main-Text.pdf on July 18th, 2013.

Wright, P. E., Inglis, S. F., Stehman, S. M., Bonhotal, J. (2008). Reduction of selected pathogens in anaerobic digestion. Retrieved from http://www.renewwisconsin.org/biogas/AD/Pathogen%20Reduction%20Article.pdf Feb 17th, 2014.

Idaho Power, Idaho Business Rates. Retrieved from https://www.idahopower.com/AboutUs/RatesRegulatory/Rates/grcBusiness.cfm Feb, 20th, 2014.

# CHAPTER 5 - OVERALL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

## 5.1 Conclusions drawn from this research:

1. The important process parameters affecting the co-digestion process is optimum mixing ratio, C/N ratio, and temperature. The co-digestion process avoided potential inhibitors such as pH drops and volatile fatty acids accumulation due to the high buffer capacity of manures.
2. In the co-digestion study of dairy manure (DM) with potato waste (PW), the biogas and $CH_4$ production was enhanced by 157% and 158% for the mixing ratio of 80:20 (DM:PW) at thermophilic temperatures and 12% and 26% for the mixing ratio of 90:10 (DM:PW) at mesophilic temperatures compared to the digestion of DM alone. At ambient temperatures, digestion of DM alone (100:0) achieved the highest biogas and $CH_4$ production of 33 L and 8 L, respectively. This study showed that higher operating temperatures allowed high percentage of PW in the mixture to be anaerobically digested.
3. In cases of anaerobic digesters with electricity generators, it is recommended to invest in low cost plug flow digesters (capital cost of $600/cow) operated at thermophilic temperatures. The ratio of DM:PW-90:10 or 80:20 is recommended while the low cost plug flow digesters are operated at thermophilic temperatures.
4. In cases of anaerobic digesters without electricity generators: 1) It is favorable to use completely mixed digesters or high or low cost plug flow digesters. 2) It is recommended to use the ratio of DM:PW-80:20 at thermophilic temperatures in a

completely mixed digester ($1,400/cow) to generate positive cash flow within ten years. 3) It is recommended to use the ratio of DM:PW-90:10 or 80:20 at thermophilic temperatures in high cost plug flow digesters ($1,000/cow) to generate positive cash flow within ten years of time period. 4) All of the four ratios (i.e. DM:PW-90:10 or 80:20 or 60:40 or 40:60) are recommended at thermophilic temperatures or the ratio of DM:PW-90:10 at mesophilic temperatures to generate positive cash flow within the ten year time period. The conversion of volatile solids to biogas is important, anaerobic digester connected with electricity generators showed that the positive cash flow can be generated only when the volatile solids conversion rate is higher than 7.5 cf/lb VS. Similarly, an anaerobic digester operated without electricity generation equipment can generate positive cash flow when the volatile solids conversion rate is higher than 5.6 cf/lb VS. It is concluded that an anaerobic digester operated without electricity generation equipment leads to a quicker payback period than an anaerobic digester operated with electricity generation equipment.

## 5.2 Recommendations for future research:

1. According to this study, digestion at ambient temperatures showed that the ratio of DM:PW-100:0 obtained higher biogas productions than other co-digested ratios tested (DM:PW-90:10, 80:20, 60:40 and 40:60), so further studies are needed to explore the reasons for decrease of biogas and methane productions for co-digested ratios at ambient temperatures.

2. More studies on co-digestion of dairy manure with waste from biofuel industry are needed.
3. There is a need to develop software based tools like the spreadsheet-based tool used in this study for analysis of economic feasibility of anaerobic digesters.