

Final Technical Report

Project Title: Research on Anaerobic Digestion: Optimization and Scalability of Mixed High-strength Food Processing Wastes for Renewable Biogas Energy

Award Number: GO85010

Recipient: The Ohio State University Research Foundation

Project Location(s): Ohio Agricultural Research and Development Center (OARDC), Wooster; Department of Animal Sciences, and Department of Agricultural, Environmental & Development Economics, The Ohio State University, Columbus, OH.

Project Period: 08/01/2005 – 06/30/2012

Date of Report: 12/15/2012

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Acknowledgment: This material is based upon work supported by the Department of Energy under Award Number GO85010.

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Final Scientific/Technical Report Content

Executive summary:

The central objective of this research was to investigate the technical and economic aspects of anaerobic digestion to promote its implementation to convert biomass, particularly waste biomass, such as livestock wastes and food-processing wastes, to renewable energy as methane biogas. The research project was conducted in two phases, with specific objectives for each phase. In phase 1, two research-scale digesters (1,600-gallon working volume each) of new design were acquired and installed that are particularly suitable for anaerobic digestion of wastewater streams with high organic strength but low solid particular matters. Research was conducted to evaluate these two digesters to convert food-processing wastewaters to methane biogas. To support understanding of the microbiological processes that underpin the biogas production in digesters, comprehensive studies were conducted on the microbial communities in digesters of different design and when fed different feedstocks. To determine the potential of biogas production from the biomass in Ohio, research was initiated to create an Inventory of Ohio Biomass, which was designed to contain the information on location, types, compositional properties, amounts, and the estimated biogas potential. In phase 2, besides continued research on anaerobic digestion of food-processing wastes, the Inventory of Ohio Biomass, and microbiology, research activities were expanded to adapt a new anaerobic digester design that can be implemented on small and medium-sized dairy farms to convert dairy manure to biogas.

Two pilot-scale manure digesters (1,000 gallon and 8,000-gallon working volume) that employ the induced bed reactor (IBR) design were built and installed. These digesters have a much shorter hydraulic retention time (as short as 4 days) than other types of manure digesters, substantially reducing the digester volume and footprint that are otherwise required by other types of manure digesters. Coupled with the modularity in design and simplicity in maintenance and operation, these manure digesters can be less costly to build, operate and maintain. This type of manure digesters would be probably appealing to average-sized dairy farms in the US that have about 200 cattle. Besides the above digester technologies, a temperature-phased anaerobic digestion (TPAD) was developed and optimized to digest dairy manure alone and co-digest dairy manure and whey waste from a local dairy plant. The TPAD process was shown to accomplish efficient biogas production within a shorter hydraulic retention time, thus reducing digester volume needed to digest a certain volume of dairy manure and whey wastes.

The Inventory of Ohio Biomass was developed, which details the information on the biomass from Conservation Reserve Program (CRP) lands, food-processing plants, dairy farm wastes, and wastewater treatment plants in Ohio. This Inventory will be a useful resource for the industry and government agencies to plan and establish bioenergy projects, for not only projects that use anaerobic digestion as the conversion technology, but also projects that use other technologies. In addition to the Inventory, the economic valuation was assessed and compared between electric generation from coal and electric

generation from biomass (particularly livestock waste)-based biofuels. This included not only direct cost of each technology but also some 'downstream external' cost associated with each technology. This valuation information may be useful in future planning and building of energy projects in Ohio and beyond.

A series of researches were conducted to understand the microbial communities, the driving force of anaerobic digestion, in digesters of different design and when fed different feedstocks, with a goal to improve efficiency and process stability on a rational basis. The bacteria that convert complex feedstocks to intermediates and methane-producing archaea (methanogens) were investigated with respect to digester designs, feedstocks, and digester performance. A database was developed that inventories the bacteria and methane-producing archaea involved in the anaerobic digestion process. A key group of bacteria that use a key intermediate of the biogas production process was studied in detail among digesters. A biosensor was also developed to detect this key intermediate in digesters.

Collectively, this research project developed and improved anaerobic digestion technologies, created a comprehensive Inventory of Ohio Biomass and a database of microorganisms of anaerobic digesters, and advanced knowledge and understanding of the underpinning microbiology of the anaerobic digestion process. The results and finding of this research project may be useful for future development and implementation of anaerobic digesters, especially at livestock farms. Policy makers and investors may also find the information on the biomass availability in Ohio and valuation of energy projects useful in policy making and making of investment decisions. The public may benefit from the information on biogas as an energy source and the potential impact of anaerobic digester projects on their neighborhoods.

Actual accomplishments:

The actual accomplishments were detailed in comparison with the original project objectives and planned tasks.

Two sand bed filter digesters (1,600-gallon working volume each) were designed and installed. The sand bed filter placed at the bottom of each digester retains the microbial cells and prevents washout at high hydraulic loading rates. Thus, this digester design decouples hydraulic retention time from solid retention times and thus can be operated at high hydraulic loading rates. The high microbial cell mass inside of the digesters also allow high organic loading rates. Thus, this digester technology is suitable for wastewater streams with high organic strength but low solid suspended solid content. This achieved Objective A of the project Phase 1 (P1.Obj A). This technology overcomes some of the limitations of other digester designs, such as the most popular upflow anaerobic sludge bed (UASB) reactors, which have high risk of microbial washout and long startup period. However, the sand bed filter design is more expensive to build.

Research was conducted on operation of anaerobic digestion of biomass wastes and optimum conversion of biomass wastes to biogas (Objective B of Phase 1), to define

biochemical parameters and indicator metabolite for key metabolic pathways, and biogas yield and composition associated with positive or negative digester performance (Sub-objective D2 in Phase 2), and to determine the range of feedstock strength and composition that can be reliably utilized and the loading rates that can be tolerated (Sub-objective D3 in Phase 2). A series of experiments were conducted using digesters at three different scales: batch, bench, and pilot scales. A wide range of feedstocks were evaluated, including off-spec chips from a local chip snack manufacturer, wastewater streams from a local dairy product company, thin stillage from a corn ethanol plant, and dairy manure. The research focused on optimization with respect to organic loading rate, hydraulic retention time, pH, biogas yield and composition. Two TPAD processes were also evaluated to determine the optimal temperature and pH of the thermophilic first stage that result in maximal biogas production and solid destruction. The ratio of livestock manure and waste whey, organic loading rates, and hydraulic retention time were determined for co-digestion in a TPAD process. The above objectives were achieved.

A series of researches were conducted to investigate population dynamics in anaerobic digesters in responses to feedstock versatility, digestion efficiency, process stability or reliability, and biogas yield (Sub-objective B2 in Phase 1); and to determine microbial speciation and community structure (Sub-objective D1 in Phase 2) in different digesters. The diversity and composition of bacteria and methane-producing archaea (methanogens), population dynamics of important groups of bacteria (including syntrophic acetogens) and methanogens (including different genera of methanogens that convert acetate and hydrogen and carbon dioxide to methane) were investigated in different types of anaerobic digesters, including a UASB digester fed the wastewater of a local jelly and jam manufacturer; sand bed filter digesters fed cheese whey wastes, off-spec chip snack and related wastewater from a commercial company, and thin stillage from a corn-ethanol plant; a constant stirred tank reactor (CSTR) digester fed municipal sludge; TPAD digesters fed dairy manure or mixture of dairy manure and waste whey; a mixed plug-flow loop reactor (MPFLR) digester fed livestock manure; and solid-state digesters fed crop residues. Some bacteria and methanogens were found to be correlated with feedstocks, operation temperature, pH, and performance. Bacteria that are potentially important to different phases of the digestion process, i.e., hydrolysis, acidogenesis, syntrophic acetogenesis, and methanogenesis, were also identified. A database was developed that archives the global diversity of bacteria and methanogens found in anaerobic digester.

An Inventory of Ohio Biomass was created in both Phase 1 (Sub-objective B3) and Phase 2 (Sub-objective D6). The Inventory archived the following information: locations and amounts of dairy wastes, biomass potential of conservation reserve program (CRP) lands, types and estimated amounts of food-processing wastes, and wastes sludge of municipal wastewater treatment plants. The biogas potential of each biomass source was also estimated. The economic valuation was included to compare coal-based electricity and biomass-based electricity, with external costs, air pollution, and potential social cost being considered. A detailed, holistic case study of the profitability, renewable energy, air emissions and downstream externalities of a large conventional vs. simulated anaerobic

digestion of dairy operation in Wayne County, Ohio was completed. This study included (1) a large hedonic pricing and spatial econometric model of proximity of dairy farms and resulting impacts on downstream residential housing values in four Ohio counties, (2) assessment of air emissions from livestock and waste storage, and (3) financial analysis of a simulated anaerobic digestion system. Thus, our original goals and objectives for this part of the project have been achieved.

Objective C in Phase 2 was to develop and test an anaerobic digester system able to utilize low-strength lignocellulosic fibrous biomass wastes, including sand-laden manure, with or without augmentation with high-strength biomass wastes for increased biogas yield. Two digesters (1,000-gallon working volume and 8,000-gallon working volume) were built using the induced bed reactor (IBR0 design. The 1000-gallon unit was designed to serve as a prototype/pilot digester while the 8,000-gallon unit was built to digest about 50% of the manure from a research dairy farm located on the OARDC campus in Wooster. These digesters feature short hydraulic retention time due to high microbial cell mass retained inside the digesters and reduce capital, operation and maintenance cost. Due to delay by the subcontractor and completion of the auxiliary components, these two digesters have not been started up. We planned to complete the auxiliary components and start both digesters up in next year (2013).

Research was conducted to develop sensors and controls to monitor performance of digesters (Sub-objective D4 in Phase 2). In collaboration with Rockwell Automation, one programmable logic control program was developed to control feeding to bench-scale digesters. We also developed the genetic construct for a biosensor that can monitor the concentration of a key intermediate of the digestion process. Future research is needed to construct a biosensor that can be used in inline monitoring of anaerobic digestion process.

Another sub-objective in Phase 2 (Sub-objective D5) was to determine suitability of biogas for direct and scalable conversion to electricity using the solid-oxide fuel cell technology developed by a partner company (this company received funding from the Ohio Department of Development Ohio to develop and provide us an operable fuel cell). With the assumption that this partner company would provide us an operable fuel cell as planned, we built one biogas cleaning system, one biogas compression system, and other auxiliary components. Unfortunately, we did not receive an operable fuel cell from this partner company. This sub-objective was not achieved. Other options to utilize biogas were explored, including compression as vehicle fuel and combined power and heat.

Summary of project activities:

The research project was conducted by three groups of scientists. One group was led by Dr. Floyd Schanbacher (from the beginning of the project until November 2010) to design and built digesters and conduct operational research on digesters. Since November 2010, Dr. Zhongtang Yu continued the research by this group. The second group was led by Dr. Fredrick Hitzhusen to develop the Inventory of Ohio Biomass. The third group was led by Dr. Zhongtang Yu to investigate the microbiology underpinning performance and stability of anaerobic digesters. Most of the original plans and approaches were

followed, but there were unexpected setbacks that forced us to change plans and approaches. The most significant departure from the initial plan was caused by the fuel cell company that did not deliver the fuel cell as planned. Without a fuel cell, we were not able to evaluate the feasibility to convert biogas to electricity using fuel cells.

Another unexpected hurdle stemmed from the unwillingness of private food-processing companies to share the data on their wastes or wastewaters due to their concerns of revealing information that may damage their business operation. Thus, the information on the amounts of wastes and wastewaters from the Ohio food-processing companies were estimated from information that were available in the public domain, such as the product output from individual companies. As such, the information on the biomass of the food-processing companies are just estimates. Considering that companies change production from time to time, the estimated outputs of wastes and wastewaters will still be useful in future planning.

It was planned to develop sensors and controls that can improve monitoring of the anaerobic digestion process. In the early stage of the project, two private partner companies expressed interest in collaborating with us to develop sensors and control. These two companies changed their priority and thus only one PLC program was developed that controls feeding of digesters. Unplanned but achieved is the development of a biosensor that can be used to monitor the concentration of a key intermediate of the anaerobic digestion process. This biosensor may be instrumented and used for inline monitoring of anaerobic digestion process.

Products and outcomes:

a. Publications:

- Jeanty, P.W., D. Warren, and F. Hitzhusen. Assessing Ohio's Biomass Resources Using GIS, AEDE, OSU, research report to Ohio Dept. of Develop., Nov. 2004, p. 128.
- Shakya, Bibhakar. Application of OH-MARKAL as an Electric Sector Energy Policy Instrument for Ohio. Consulting Report to Ohio Dept. of Develop. and Public Util. Comm. of Ohio, 2008.
- Nelson, M., M. Morrison, F.L. Schanbacher, and Z. Yu. Phylogenetic analysis of the microbial communities in anaerobic digester treating three distinct food processing wastes. 108th ASM General Meeting. 2008. Boston, MA.
- Kiger, Sarah. Potential of Lignocellulosic Biomass Feedstocks from CRP Land in Ohio. Poster/Paper for University Clean Energy Alliance of Ohio (UCEAO) Conference, March, 2008, Columbus, Ohio.
- Nelson, M., M. Morrison, F.L. Schanbacher, and Z. Yu. Microbial diversity sampled in anaerobic digestion reactors. ISME 12, Cairns, 2008. Australia.

- Dabrowska, Kora. Assessing the Social, Economic and Environmental Costs and Benefits of Anaerobic Digestion. Poster/Paper for University Clean Energy Alliance of Ohio (UCEAO) Conference, March 18, 2008, Columbus, OH.
- Rismani-Yazdi, H., N. Pashmi, S.M. Carver, Z. Yu, O.H. Tuovinen, and A.D. Christy. Evaluation of methane production in microbial fuel cells generating electricity from cellulose. 1st international Symposium on Microbial Fuel Cells. 2008. Philadelphia, PA.
- Gossom, John. Hauling Mass: Modeling the Effect of Transport on the Greenhouse Gas Impact of Anaerobic Digestion. MS thesis, OSU, 2009.
- Kiger, Sarah. Environmental and Energy Benefits from CRP Lands vs. Returns from Row Crops, M.S. thesis, OSU, 2009.
- Mishra, Shruti. Estimation of Social Costs of Coal-Based Electricity Generation: An OH-MARKAL Extension, PhD dissertation, OSU, 2009.
- Hitzhusen, Fred, and Bibhakar Shakya. Benefit-Cost Analysis of Energy: Toward a More Renewable and Cleaner Fossil Fuel Based Electric Power Sector in Ohio. AEDEcon White Paper, OSU.
- Dabrowska, K. and Hitzhusen (2010). Measuring the Impact of Livestock Operations on Local Communities and Estimating the Demand for Environmental Quality: A Spatial Econometrics Approach, submitted to Land Economics.
- Mishra, Shruti, and Fred Hitzhusen. Downstream Recreation Benefits and Costs of Coal Strip Mine Reclamation. Poster/paper, 2010 Land Grant and Sea Grant National Water Conference, Feb. 21-25, 2010, Hilton Head, SC.
- Dabrowska, Kora. Linking Profitability, Renewable Energy and Externalities: A Spatial Econometric Assessment of the Socio-Economic Impact of Ohio Dairies, PhD Dissertation, OSU, 2010.
- Yu, Z., M. Morrison, and F.L. Schanbacher. Production and utilization of methane biogas as renewable fuel. P. 403-433. In A. Vertes, N. Qureshi, H. Blaschek, and H. Yukawa (eds.), Biomass to Biofuel: Strategies for global industries. 2010. Wiley & Sons, Hoboken, NJ.
- Lv, W., F.L. Schanbacher, Z. Yu. Put microbes to work in sequence: recent advances in temperature-phased anaerobic digestion processes. Bioresource Technology, 2010. 101(24): 9409-9414.
- Yu, Z. and F.L. Schanbacher. Production of methane biogas through anaerobic digestion. p. 105-127. In O.V. Singh and S.P. Harvey (eds.), Sustainable Biotechnology: renewable resources and new perspectives. 2010. Springer, The Netherlands.

- M. Farren, F. Hitzhusen, P. Jeanty. Waste is a Terrible Thing to Waste. Posters at University Clean Energy Alliance of Ohio (UCEAO) Conference (<http://uceaoconference.info/>), April 16, 2011, Columbus, OH.
- Nelson, M.C., M. Morrison, and Z. Yu. A meta-analysis of the microbial diversity observed in anaerobic digesters. *Bioresource Technology*, 2011. 102:3730-3739.
- Maturana F, D. Carnahan, C. Abraham, J. Jay. Case study: Control Design of An Anaerobic Digestion System Using Simulation-based Synchronization. *Industrial Technology (ICIT)*, 2011 IEEE International Conference on. 14-16 March 2011, Auburn, AL.
- Nelson, Morrison M M, and Yu Z. Bacterial and archaeal diversity in anaerobic digesters as affected by feedstocks and digester designs. *First International Conference on Biogas Microbiology*. 2011. Leipzig, Germany.
- Dabrowska K, M. Farren, F. Hitzhusen, P. Jeanty, N. Mundhada, and A. Prakash. Cow Power. Posters at University Clean Energy Alliance of Ohio (UCEAO) Conference (<http://uceaoconference.info/>), April 16, 2011, Columbus, OH.
- Nakul Mundhada. Cow Power: An Ohio Case Study on Externalities and Renewables in Electricity Production. Master thesis, 2011, OSU.
- Nelson, Michael. An Integrated Investigation of the Microbial Communities Underpinning Biogas Production in Anaerobic Digestion Systems. Ph.D. Dissertation, 2011. OSU.
- Farren, Michael. An Analysis of Anaerobic Digestion of Dairy Manure on Assessed Residential Property Values. Term Paper, AEDE 831 Econometrics, May 1, 2012.
- Mishra, Shruti. Estimation of Externalities Associated with Coal: A Case Study on Damages to Lakes in Ohio. *US Geological Survey Webinars*, Feb. 16, 2012 on USGS website.
- Lv W and Yu Z. Isolation and characterization of two thermophilic cellulolytic strains of *Clostridium thermocellum* from a compost sample. *Journal of Applied Microbiology*, 2012. in press.
- Nelson MC, Schanbacher FL, Morrison M, and Yu Z. Shifts in microbial community structure of granular and liquid biomass in response to changes to infeed and digester design in anaerobic digesters receiving food-processing wastes. *Bioresource Technology*. 2012. 107:135-143.
- Xu F, Shi J, Lv W, Yu Z, and Li Y. Comparison of Different Anaerobic Digestion

Effluents as Inoculum and Nitrogen Sources for Solid-State Anaerobic Digestion of Corn Stover. Waste Management. 2013. 33(1): 26-32.

b. Web site or other Internet sites that reflect the results of this project:

The earlier Ohio biomass inventory and OH-MARKAL policy model are available on the Ohio Department of Development Website. The analysis of the downstream lake recreation economic impacts from unreclaimed coal stripmines is available on the U.S. Geological Survey website.

c. Networks or collaborations fostered:

Collaborations with several state and local government agencies were established to accomplish the OH-MARKAL model update and expand the Ohio biomass inventory. We also established collaborations and partnership with engineers at the Utah State University, Rockwell Automation, and a local dairy product company. These relationships may help future research of mutual interest.

d. Technologies/Techniques:

A biosensor that monitors a key intermediates of the anaerobic digestion process.

Two temperature-phase anaerobic digestion (TPAD) processes that improve digestion process of dairy manure.

A manure digester design that is suitable for average-sized dairy farms in the US.

e. Inventions/Patent Applications, licensing agreements:

No patent has been filed.

f. Other products:

An ARB database dedicated to the microbial diversity of anaerobic digesters was developed, which archived the bacteria and methanogens that have been detected in all the anaerobic digesters that have been analyzed. This database serves as a global phylogenetic framework of microbial diversity underpinning the anaerobic digestion process.