Biotechnology and Bioengineering

Waste-Free Animal Agriculture that Co-Produces Biogas Energy and Organic Fertilizer: A Holistic Approach

>Manuscript Summary<

Manuscript No.:	
Full Title:	Waste-Free Animal Agriculture that Co-Produces Biogas Energy and Organic Fertilizer: A Holistic Approach
Type of Manuscript:	Articles
Category:	Environmental biotechnology
Keywords	anaerobic digestion, hog waste, biogas, organic fertilizer, sustainable animal agriculture
Corresponding Author	Jason Chia-Hsing Shih, Ph.D. President, Holistic Farming, Inc. 100 Planter Wood Lane Cary, NC27518, USA Tel: 1-919-851-8817 Email: jasonshih.bri@gmail.com
Corresponding Author's Institution	Holistic Farming Inc., (address see above)
Corresponding Author's Secondary Institution	Professor Emeritus, Department of Poultry Science, North Carolina State University, Raleigh, NC27695, USA
First Author:	Jason Chia-Hsing Shih, Ph.D.
Order of Authors:	Jason C.H. Shih, Ph.D. Jay J. Cheng, Ph.D. Eric van Heugten, Ph.D.
Manuscript Region of Origin:	North Carolina, USA
Abstract:	A novel anaerobic digester system called Holistic Digester™ System (HDS) was developed. The pilot prototype was constructed and tested twice (4 months each) at the NCSU Field Laboratory for raising 60 feeder pigs to market age for each test. The structure and operation of HDS, the performance of live animal growth, chemical analyses of biogas and the resulting digestate, and the production of a potential organic fertilizer, are presented in this communication. It was concluded that: 1) this operation demonstrated the feasibility of HDS with live animals on farm; 2)

	daily biogas (approximately 50% methane) was produced consistently during each of the two studies; 3) animals grew well in the modified house with a pit for manure slurry collection. The weight gain of the pigs and feed conversion rate met the top 25% of the industrial average; and 4) the liquid digestate of the primary digester flowed into the secondary digester preloaded with dry switchgrass, which absorbed the liquid and incubated into a final product. Chemical analysis indicated that NPK values were retained and enriched in the final product, potentially, an organic fertilizer. The new prototype HDS that co-produced biogas and fertilizer was successful and, furthermore, it left no waste nor wastewater on farm. It is believed that HDS will not only improve the cyclic bioeconomy, but also enforce the environmental and economic sustainability of animal agriculture.
Suggested Reviewers:	**Herbert H.P. Fang**, Ph.D. Emeritus Professor and founder of Environmental Biotechnology Laboratory at the University of Hong Kong. He is an international renown expert applying anaerobic technology for waste and wastewater control. Email: hrechef@hku.hk **Chenlin Li,** Ph.D. Technology Manager at Bioenergy Technologies office, Office of Energy Effciency and Renewable Energy, US Department of Energy. Email: Chenlin.Li@ee.doe.gov **Jun Zhu**, Ph.D. Director of Experiment Station and Professor of Biological and Agricultural Engineering, College of Engineering at University of Arkansas, AR, USA Email: junzhu@uark.edu **C.M. Mike Williams**, Ph.D. Professor Emeritus, Former Head of NCSU Prestage Department of Poultry Science and the Founding Director of the NC State Animal and Poultry Waste Management Center. Email: c.m.mike.williams@gmail.com **Kelly D. Zering**, Ph.D. Professor of Agricultural Economics at NCSU, has 36 years of experience studying North Carolina agriculture and agribusiness,

	state and national policy and commodity markets. Email: kzering@ncsu.edu

Title: Waste-Free Animal Agriculture that Co-Produces Biogas Energy and Organic Fertilizer: A Holistic Approach

Running Title: Digester System Coproducing Biogas and Fertilizer

Jason C. H. Shih[1], Jay J. Cheng[2] and Eric van Heugten[3]

[1]Professor Emeritus, North Carolina State University, Raleigh, NC, and, President, Holistic Farming Inc., Address: 100 Planters Wood Lane, Cary, NC 27518, USA; Email: jasonshih.bri@gmail.com

[2]Department of Biological & Agricultural Engineering, North Carolina State University, Raleigh NC 27695, USA; Email: jay_cheng@ncsu.edu

[3]Department of Animal Science, North Carolina State University, Raleigh, NC 27695, USA; Email: Eric_vanHeugten@ncsu.edu

Footnote: This publication is the result of a Collaborative Research Agreement between Holistic

Farming Inc. (HFI) and College of Agriculture and Life Sciences, NC State University. It was conceptualized by the senior author with partial funding from HFI.

Abstract

A novel anaerobic digester system called Holistic Digester™ System (HDS) was developed. The pilot prototype was constructed and tested twice (4 months each) at the NCSU Field Laboratory for raising 60 feeder pigs to market age for each test. The structure and operation of HDS, the performance of live animal growth, chemical analyses of biogas and the resulting digestate, and the production of a potential organic fertilizer, are presented in this communication. It was concluded that: 1) this operation demonstrated the feasibility of HDS with live animals on farm; 2) daily biogas (approximately 50% methane) was produced consistently during each of the two studies; 3) animals grew well in the modified house with a pit for manure slurry collection. The weight gain of the pigs and feed conversion rate met the top 25% of the industrial average; and 4) the liquid digestate of the primary digester flowed into the secondary digester preloaded with dry switchgrass, which absorbed the liquid and incubated into a final product. Chemical analysis indicated that NPK values were retained and enriched in the final product, potentially, an organic fertilizer. The new prototype HDS that co-produces biogas and organic fertilizer was successfully tested and, furthermore, HDS left no waste nor wastewater on farm. It is believed that HDS will not only improve the cyclic bioeconomy, but also enforce the environmental and economic sustainability of animal agriculture.

Keywords

Anaerobic digestion, Hog waste, Biogas, Organic fertilizer, Sustainable animal agriculture

Introduction

Anaerobic digestion is one of the oldest environmental technologies for the treatment of animal wastes. It breaks down organic matter and produces biogas as a source of renewable energy. However, two major issues still remain challenging that hamper its applications and commercial development. First, conventional large stir-tank digester systems for large animal farms are expensive in construction and complex in operation. Second, the large volume of daily effluent or digestate requires storage and proper treatment for safe discharge.

During the last 40+ years, a novel system has been systematically studied and developed at North Carolina State University (NCSU). Thermophilic anaerobic digestion (TAnD) of poultry manure at higher rates at 50-60ºC was pioneeringly and systematically studied first in the laboratory (Huang & Shih, 1981), and a simple plug-flow type digester was demonstrated on the NCSU Field Laboratory for 4,000 hens (Steinsberger and Shih, 1987). A scale-up TAnD for a hen house of 50,000 hens was demonstrated with Dr. Shih's supervision in Beijing, China in 1992 (Zhao et al., 1993) and operated for 20 years. While studying the microbiology in TAnD, a feather-degrading bacterium was discovered and isolated (William et al.1990). Subsequently, the enzyme called keratinase was purified (Lin et al., 1992) and the *ker* gene was isolated in (Lin et al., 1995). In applications, the keratinolytic activity can help process feather meal and, as a feed additive in small amounts, can improve protein digestibility and growth of young poults and piglets (Odetallah et al., 2003). This series of studies were narrated in reviews at different stages (Shih, 1987, 2012, 2015 and 2019). More recently, a two-stage TAnD for hog waste was set up in the laboratory at NCSU (Zang et al., 2019). The primary digester was a liquid phase stir tank digester for manure slurry treatment. The secondary digester was a solid-phase incubation of chopped switchgrass with the liquid digestate from the primary digester. Interestingly, the dry biomass of switchgrass not only absorbed the liquid for incubation to produce more biogas, but also resulted in a residue that retained all nitrogen, phosphorus and potassium (NPK) value, potentially useful as an organic fertilizer. Therefore, the concept of a novel technology called the Holistic Digester™ System (HDS) was developed. Consequently, from TAnD, keratinase technology to HDS, a total of 13 patents were generated, 6 of them are relevant to the development of HDS (Shih, 1996-2020).

To prove the concept of HDS, a pilot scale prototype HDS was designed, constructed and operated to process manure slurry daily from a swine facility with 60 growing pigs, from feeder pig to market weight. The operation of the HDS, the performance of pig growth and chemical analyses of the resulted digestate, biogas and organic fertilizer are presented in this communication.

Materials and Methods

Pigs used in these studies were humanely treated and animal use protocols were approved by the North Carolina State University Institutional Animal Care and Use Committee.

A pilot-scale prototype HDS system was designed and constructed at the Swine Educational Unit of the North Carolina State University Lake Wheeler Road Field Laboratory (NCSU Field Laboratory) to test the concept of converting swine manure into biogas and organic fertilizer. The primary (5 m^3) and secondary digester (2.5 m^3) were built with a tubular metal pipe covered with 5 cm thick polyethylene for heat insulation (**Figures 1 and 2**). The prototype HDS system was designed for the treatment of the manure slurry from 60 finisher pigs.

Two studies were conducted using 60 pigs each (Smithfield Premium Genetics, Roanoke Rapids, NC). Pigs (initial body weight of 34.0 and 30.6 kg for Study 1 and 2, respectively) were housed at the Swine Education Unit of the NCSU Field Laboratory and randomly allocated to 6 pens (2.4 by 3.0 m in dimension) with 10 pigs per pen. They were housed in a mechanically ventilated room with concrete slatted floors and had *ad libitum* access to feed and water. The duration of each study was 84 days and pigs reached a market weight of 124.4 and 128.8 kg for Study 1 and 2, respectively. The first study was conducted primarily during the summer and fall (August to November) and the second study was conducted during the winter and spring (January to April). Throughout the growing period, pigs were fed a 3-phase diet program, with each diet phase being fed for 28 days. Diets were representative of commercial production practices and contained 16.5, 14.0, and 12.5% crude protein, 1.00, 0.80, and 0.67% standardized ileal digestible lysine, and 0.54, 0.49, and 0.44% total phosphorus, for Phase 1, 2, and 3 diet, respectively. Pigs were weighed intermittently at 2-week intervals and feed intake was determined from feed provided minus feed remaining in the feeders at the end of each period. Feed efficiency was calculated as average daily feed intake divided by average daily gain. Mortality and morbidity were recorded for the duration of the studies.

The swine manure slurry was collected through a retrofitted pit under the concrete slatted floor of the pig houses as shown in **Figure 3**. The manure slurry flowed through the slatted floor onto a sloped surface by gravity and ended in a collection basin. The manure slurry was then pumped from the collection basin into the 5 m^3 primary anaerobic digester for biogas production. The hydraulic retention time (HRT) of the primary digester was 12.5 days. Biogas production rate from the primary digester was measured daily and the methane content of the biogas was analyzed twice a week. After the biogas production, which happened mostly in the primary digester, the effluent or digestate flowed into a secondary 2.5 m^3 solid-state digester preloaded with chopped dry switchgrass to absorb the liquid for co-incubation or partial digestion of the switchgrass biomass to produce organic fertilizer. After 5 days, the residues were collected, dried, chemically analyzed and compared with the original switchgrass samples. They were analyzed by standard procedure for moisture content (MC), total Kjeldahl nitrogen (TKN), total phosphorus (TP), and total potassium (TK) for their potential as an organic fertilizer. The temperature in both the primary and secondary digesters was maintained at 50ºC with steam injection. The biogas generated from the secondary solid digester was not measured because of mechanical issues. Our previous study (Zang et al. 2019) in the laboratory showed approximately 10-20% of the total biogas could be generated from a secondary digester.

Results

Two studies were conducted to evaluate the HDS system and pig growth performance. Growth parameters measured for pigs during the two studies were excellent. Pigs reached market weight in 84 days, gaining 1.08 and 1.17 kg per day for Study 1 and 2, respectively, with a feed efficiency of 2.52 to 2.53 (**Table 1**). Growth performance compared favorably to published performance metrics for swine finishing farms reporting an average days to market of 110.6±8.1 days with and average daily gain of 0.93±0.05 kg/day and a feed efficiency of 2.6±0.20 kg of feed per kg of gain for farms in the top 25% percentile of production records (Stalder, 2018). The data from Stalder represented a total of 39 companies and 3,122 farms, thus providing a robust data set for comparison. Clearly, the results from the present study indicate pig performance was superior, ranking within the top 25% of commercial production records. Feeding practices and production performance in the two studies were consistent with the progressive swine industry and, thus, the composition of the manure produced and collected (from the pits underneath the pig housing floors) is expected to be representative of the manure produced on commercial farms.

Table 1. Growth performance parameters of pigs used to evaluate the waste management by the HDS.

	Study 1[1]	**Study 2**[1]	**Industry Mean**[2]	**Industry Top 25%**[2]
Weight at placement,	34.0	30.6	23.6 ± 4.5	26.7 ± 4.8

kg[3]				
Market weight, kg	124.5	128.8	123.7 ± 7.3	127.7 ± 5.1
Days to market	84	84	118.5 ± 11.4	110.6 ± 8.1
Average daily gain, kg/day	1.08	1.17	0.84 ± 0.08	0.93 ± 0.05
Feed:gain, kg/kg	2.52	2.53	2.71 ± 0.22	2.61 ± 0.20
Mortality and removed, %	8.33	4.92	5.19 ± 3.51	4.09 ± 2.77

[1]Data represent the mean of 6 pens with 10 pigs per pen for each of two studies.

Most biogas was produced in the primary digestion of daily fresh manure slurry, which had an average of 3.1% total solids (TS) concentration. The average flow rate in the primary digester was 401.2 L/day and a hydraulic retention time (HRT) of 12.5 days. The average biogas production from HDS was 1,933 L/day and the average methane content in the biogas produced in the primary digester was 50.06%. (**Table 2**).

Table 2. The operational conditions in the primary and secondary anaerobic digesters of the prototype HDS.

Operational Parameter	**Primary Anaerobic Digester**	**Secondary Anaerobic Digester**
Temperature, °C	50	50
Hydraulic Retention Time (HRT), days	12.5	5
Average Manure Slurry Flow Rate, L/day	401.2	401.2
Digester Volume, m^3	5.0	2.5
Average Biogas Production Rate, L/day	1,933	N/A

The cumulative production of biogas during the growth of the pigs used in the two tests is shown in **Figure 4**. The production of biogas was stable and consistent during the two test periods. During the winter and spring months (the 2nd study) it appeared that the biogas rate was higher than that of summer and fall months (the 1st study). This could be due to the higher feed intake and associated higher amount of excreta produced during the cold season. The effectiveness of waste reduction of the primary digestion is shown in **Table 4**.

Table 4. The performance of anaerobic digestion of the primary digester of the HDS

	Swine Manure Slurry	Primary Digestate	Removal Rate (%)
Chemical Oxygen Demand (COD)	54,730 mg/L	35,710 mg/L	41.0%
Average Total Solid (TS) Content	3.12%	1.32%	51.8%
Average Volatile Solid (VS)/TS Ratio	80.50	71.21	62.6%
pH	6.30	6.30	

The chopped switchgrass was incubated for 5 days with the primary digestate and treated by "anaerobic composting". A comparison between the treated switchgrass with the original switchgrass samples is shown in **Table 5**. Clearly, the incubated switchgrass samples had enriched values in NPK as compared with the original switchgrass samples. The increased NPK must have been retained from the original hog manure, indicating a potential value recycled from the animal manure. This is the first study of this kind of waste management. The results are encouraging. More studies and further development of the HDS technology are strongly suggested, for waste-free co-production of animals, biogas and organic fertilizer.

Table 5. Moisture, total kjeldahl nitrogen (TKN), total phosphorus (TP), and total potassium (TK) of the original switchgrass and the air-dried switchgrass after fermentation with the digestate in the secondary anaerobic digester.

Sample	Moisture Content, %	TKN, mg/kg (dry weight)	TP, mg/kg (dry weight)	TK, mg/kg (dry weight)
Original switchgrass	9.35	3,964	258	436

Air-dried residue after incubation in the secondary digester	19.77	18,980	7,395	3,537

Discussion

Environmental sustainability is a top priority for animal production systems to ensure the responsible production of high quality protein sources for a growing global population (Steinfield, 2006). Numerous methods and technologies for manure handling have been used and developed in past decades. They were extensively reviewed, evaluated and documented (Williams, 2009). Among all technologies, anaerobic digestion is not only emerging but also maturing toward commercial development because it co-produces biogas energy. Nevertheless, it faces two major challenges. First, the conventional stir-tank digester system for large animal farms is expensive in construction and complex in operation. Second, the large volume of daily effluent or digestate still requires storage lagoons and further treatment for safe discharge.

Based on the present study, the HDS may be able to deal with these challenges for the following reasons: 1. New design and low-cost: At thermophilic (50-60^{o}C) high-rate anaerobic digestion, a compact (100 m^3) plug-flow digester is able to process manure slurry, 10 tons/day from 2,000 pigs to produce biogas. It is simple to build and simple to operate; 2. New product: In the secondary digester pre-loaded dry biomass, such as switchgrass or other agricultural and forestry residues, can be converted into organic fertilizer. The secondary solid-state digester can be a 20-50 m^3 tank (data not shown), depending on the duration of the incubation; 3. New income: In addition to meat production, HDS on farm can generate income not only from fertilizer, but also from carbon credits of the production and utilization of biogas, a renewable source of energy; 4. Modularization: The size and configuration of the HDS can be modularized and prefabricated in a central manufacturing facility. The size of an animal farm will dictate the number of HDS that need to be installed. For example, a 10,000-head hog farm can install 5 units of the standard HDS. Biogas pipelines can facilitate the collection, purification and utilization of biogas, for example, to generate electricity. Prefabrication of standard size HDS should be able to largely reduce the cost of HDS. A schematic diagram of the HDS system is presented in **Figure 5**; 5. Importantly, installation of HDS will assist in rendering the animal farm virtually free of waste and wastewater. Our current work using anaerobic digestion technology with multiple benefits reflected in a document, *Biogas Opportunities Road Maps*, jointly published by USDA, EPA and DOE (2014).

Previously, an egg farm with one million hens was projected on paper for a large conventional anaerobic digester (Shih, 2019). Due to the additional income from organic fertilizer, it was estimated that a $6.6 million investment may have a return of investment (ROI) in 4 years. If we can develop prefabrication of HDS for 2,000 hogs with a \$4.8 million investment, a shorter ROI of 3.7 years would be achievable (**Table 6**). However, these estimates are predicative and for discussion only. In conclusion, the result of this current piece of work is so encouraging, that a scale-up work with 2,000-hog house for verification is strongly recommended.

Table 6. Estimated return of investment (ROI) for a 2,000-hog HDS

Investment (million \$):	
General construction	0.40
Major equipment (HDS, steam injectors, piping, etc.)	1.00*
Other facilities (de-grit, de-sulfur, post-treat, dryers, etc.)	1.00
Power generator system (1 MegaW)	1.00
Design, adjustment, service, etc.	0.40
Operational, 1st year	1.50
Total:	5.30
Income: per year (million \$)	
Power generation (20,000 KWH/day)	0.70
CDM (40,000 ton CO_2 eq/year)	0.40
Organic fertilizer, (10 tons/day)	0.70
Saving from waste management fee, per year	0.50
Operational, per year.	(1.00)
Net:	1.30
ROI: *HDS construction on site, \$1.00M:	5.3/1.3 = 4.1 years breakeven
HDS prefabricated, \$0.50M:	4.8/1.3 =3.7 years breakeven

Notes:

1) Assuming a farm with 2,000 pigs; 5.0 kg manure slurry per pig per day.

2) Electricity, \$0.10 per kWh.

3) Organic fertilizer, \$100 per ton

4) All estimates in US dollars.

Acknowledgements

This work was supported by a 50-50 Cost-sharing Collaborative Agreement between Holistic Farming Inc. (HFI) in Cary, NC and the College of Agriculture and Life Sciences, North Carolina State University in Raleigh, NC. The authors wish to thank Dr. Ellis Cowling, Dr. Mike Williams and Dr. Giles Shih for their preview and suggestions for this manuscript. To Mr. Tim Shih, we appreciate his artistic vision of the HDS (**Figure 5**).

References

Huang, J.J.H. and Shih, J.C.H. 1981. The potential of biological methane generation from chicken manure. *Biotechnology Bioengineering.* 23:2307-2314.

Lin, X., Kelemen, D.W., Miller, E.S. and Shih, J.C.H. 1995. Nucleotide equence and expression of *KerA,* the gene encoding a keratinolytic protease of *Bacillus licheniformis* PWD-1. *Applied & Environmental Microbiology,* 61:1469-1474.

Lin, X., Lee, C.G., Casale, E.S. and Shih, J.C.H. 1992. Purification of a keratinase from a feather-degrading *Bacillus licheniformis. Applied & Environmental Microbiology,* 58:3271-3275.

Odetallah, N.H., Wang J.J., Garlich, J.D. and Shih, J.C.H. 2003. Keratinase in start diets improves growth of broiler chicks. *Poultry Science,* 82: 664-670.

Shih, J.C.H. 1987. From Anaerobic Digestion to Holistic Farming. In: Wise, D.L., Ed., *Bioenvironmental System, Vol. II.* CRC Press, Boca Raton, Florida, Chapter 1:1-16.

Shih, J.C.H. 2012. From Biogas Energy, Feed Enzyme to New Agriculture. *World Poultry Science Journal* 68:409-416. Erratum: 68:803-806.

Shih, J.C.H. 2015. Development of Anaerobic Digestion of Animal Waste: From Laboratory Research and Commercial Farms to a Value-Added New Product. In: Fang, H.H.P. and Zhang, T., Eds., *Anaerobic Biotechnology: Environmental Protection and Resource Recovery.* Imperial College Press, London, Chapter 14:339-352.

Shih, J.C.H. 2019. The core technology for the sustainability of animal production, environment and green energy. *Zootecnica International*, No. 9:28-31, Scandicci (FI) Italy.

Shih, J.C.H. 1996-2020. Six relevant patents: US 5,525,229 (1996), US 9,242,881(2016), TW I656,109 (2019), US Application 0235139 (2018), US Application 0310467 (2018).

Stalder, K. 2018. Pork industry productivity analysis. National Pork Board, Des Moines, IA. Available at: https://www.pork.org/blog/2018-pork-industry-productivity-analysis/

Steinfield, H. 2006. *Livestock's Long Shadow,* published by Food and Agriculture Organization of United Nation.

Steinsberger, S.C. and Shih, J.C.H. 1987. Construction and Operation of a Low-Cost Poultry Waste Digester. *Biotechnology Bioengineering.* 26:537-543.

US Department of Agriculture, Environment Protection Agency and Department of Energy 2014. *Biogas Opportunities Road Map: voluntary actions to reduce methane emission and increase energy independence.*

Williams, C.M. 2009. Development of environmentally superior technologies in the

US and policy. *Bioresource Technology,* 100:5512-5518.
Williams C.M., Richter, C.S., MacKenzie, Jr., and Shih, J.C.H. 1990. Isolation, identification and characterization of a feather-degrading Bacterium. *Applied & Environmental Microbiology,* 56:1509-1515.
Zang, J., Shih, J.C.H., Cheng, J.J., Liu, Z., Liu, Y. and Lu, W. 2019. Thermophilic solid state anaerobic digestion of switchgrass for liquid digestate reuse and organic fertilizer production. *Renewable Agriculture and Food Systems* 1-10. https://doi.org/10.1017/S1742170519000139
Zhao, L.J., Lin, J.I. and Yang X.S. 1993. Beijing Anaerobic Digestion of Poultry Waste (in Chinese), *Report submitted to United Nations Development Program*, Part 2, pp. 73-109.

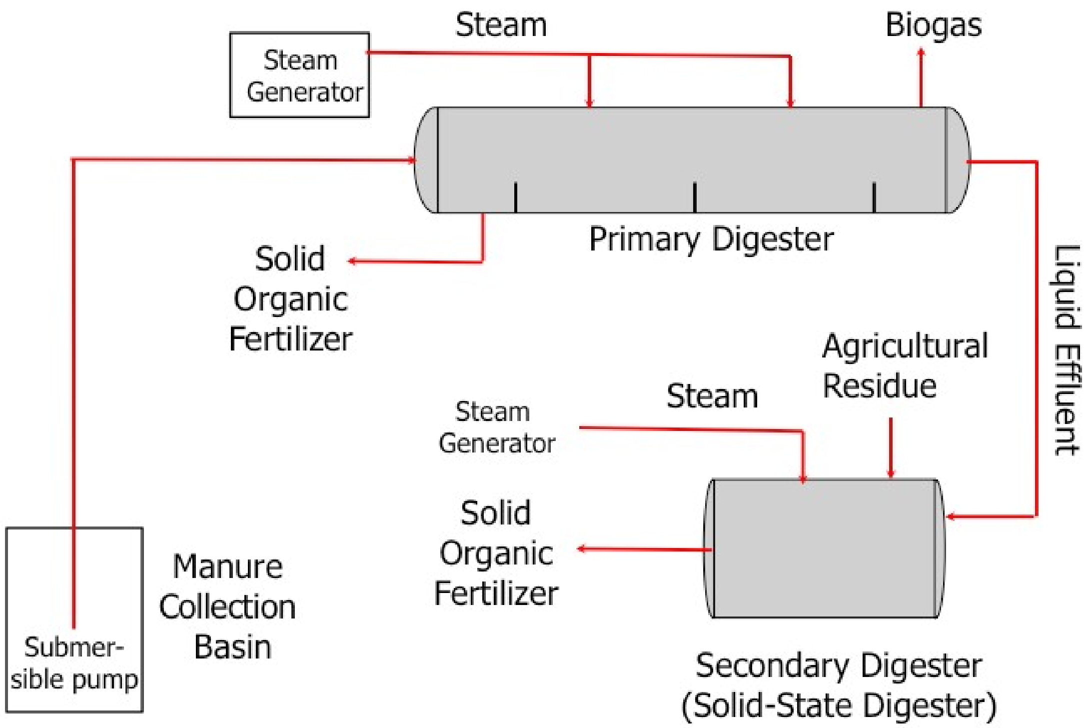

Figure 1. A two-stage anaerobic digestion system to convert pig manure and agricultural residue or switchgrass into biogas and organic fertilizer.

Figure 2. Primary and secondary anaerobic digesters of the Holistic Digester^{TM} System (HDS) at the NCSU Field Laboratory.

Figure 3. A sloped hog manure slurry collection system under the slatted floor of the pig house.

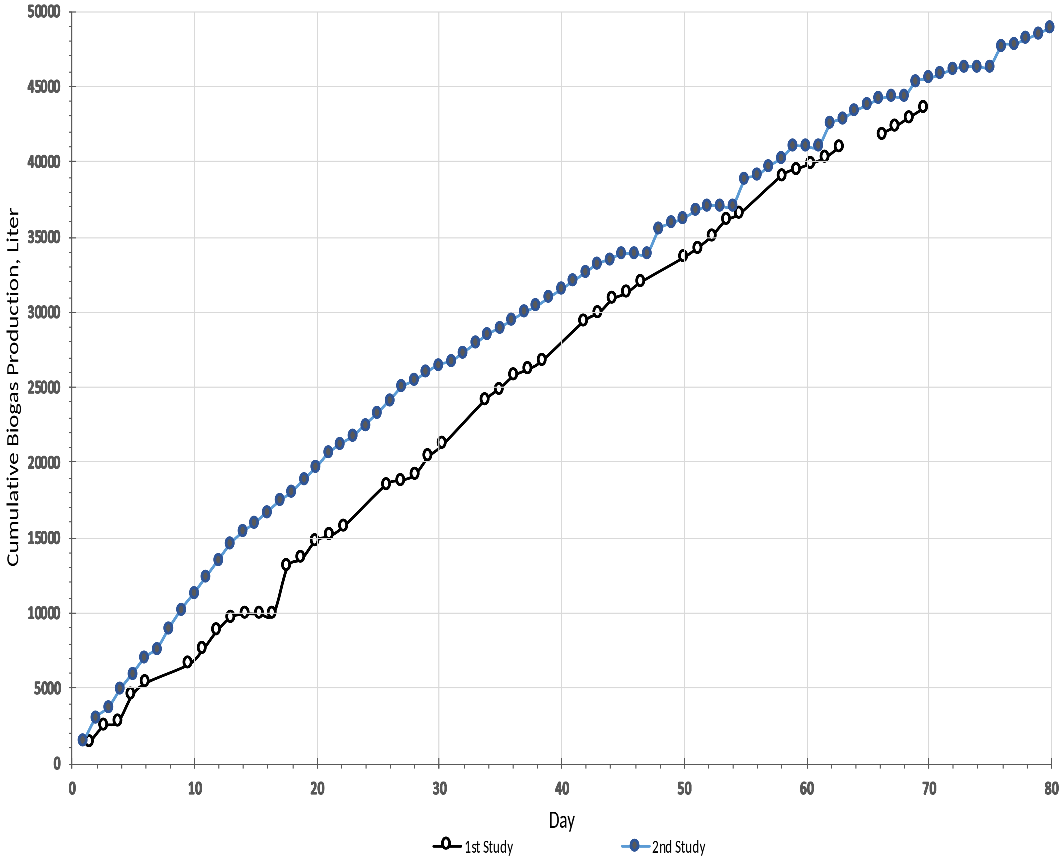

Figure 4. Cumulative biogas production from the primary digester of HDS of two separate tests with hog growth from weaning to market age.

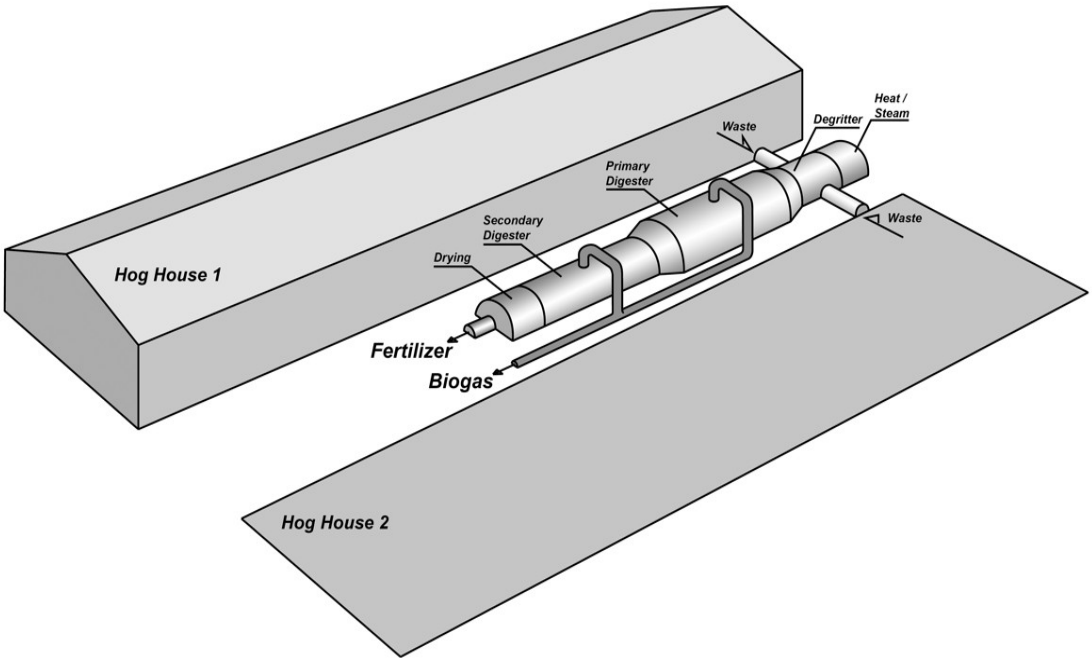

Figure 5. Schematic diagram of the Holistic Digester^{TM} System.