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Potential for Anaerobic Digestion of Crop Residues

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Abstract. *A project was initiated to investigate the potential for anaerobic digestion as a means of dealing with the large amounts of organic residue generated on Ontario farms. The main focus is on field vegetable crops but other organic materials will be considered. Most of the testing to date has involved a small (2.4 m^3), trailer-mounted anaerobic digester. The digester is a complete mixed system, operating in the mesophilic temperature range. The potential for the technology will be discussed as well as results of the early testing, involving sugar beets, sweet potatoes, swine manure and dried tobacco. Identified design considerations for handling these materials will be discussed.*

Keywords. Treatment, biogas, methane

Background

Traditionally, the majority of the revenue vegetable growers receive is from the sale of their crop to the fresh or processing use markets. Increasingly, competition from both domestic and foreign producers keeps the price of vegetable crops low, and this presents a major economic challenge to many of Ontario's fresh vegetable growers. One solution to this is to develop additional sources of revenue from the waste material generated during the growing season. For example, up to 40% of a sweet potato crop may be unsuitable for fresh market sales due to poor visual appearance or size. Some of these "seconds" may be sold to the food processing industry, but a better use may be as a feedstock for the production of methane (a major component of biogas) through the process of anaerobic digestion. Other potential feedstocks include crucifer crops, root, bulb and leafy vegetables, sweet corn, corn silage, tobacco residues, field tomatoes, or any spoiled or low-quality vegetable matter.

Most of the on-farm interest in anaerobic digesters in North America has involved livestock manure. However, materials such as animal fats, which are high in volatile solids, can produce large amounts of methane very quickly. In addition, presently in Europe, many digesters are receiving corn silage and ground grains, as these materials yield high amounts of biogas.

A literature review by Van Haren and Fleming (2005) documented several types of systems (e.g. covered lagoon, complete mixed, etc.). It also listed several design considerations: a) the potential methane yield for livestock manure is in the order of 500 L CH_4 / kg Volatile Solids (VS), b) fresh manure yields more methane than aged manure, c) biogas typically contains 60 to 65% methane, 35 to 40% carbon dioxide and trace amounts of H_2S, NH_3 and H_2.

Anaerobic digestion involves the microbial breakdown of organic compounds in the absence of oxygen - that results in the production of a biogas consisting mainly of methane and carbon dioxide. The biogas may then be: a) converted into electrical energy and heat through combustion in a generator, b) burned directly to produce heat, or c) purified and pumped directly into existing natural gas pipelines (i.e. as methane gas). Although agricultural uses of anaerobic digesters are most often associated with livestock manure treatment, many of these units are operating successfully in Europe using forage or field crops, or horticultural by-products as their main inputs (Scherer *et al.* 2003; Parawira *et al*. 2004). Biogas production from animal wastes is limited by the relatively low carbon to nitrogen ratio of the feedstock. The higher carbon content of plant-based inputs often translates into higher biogas production, although this varies with the input type. For example, one study looked at biogas production from wheat, tomato, peanut, sweet potato, potato, rice, cabbage, carrot, lettuce, onion, radish and red chard, and found biogas production rates varied from 140 to 360 L/kg VS (Chynoweth 2005). Research in this area consistently shows that biogas production is elevated when plant material is incorporated into the input mix compared to when manure is used alone ((Hills and Roberts 1981; Kaparaju 2004; Kaparaju 2002)

The establishment of anaerobic digesters has the potential to positively impact rural development in several ways. Economically, these units provide a new opportunity for previously unmarketable waste horticultural products, with revenue being generated through energy production, possible tipping fees for off-farm wastes (e.g. food processing waste), and the production of a high quality effluent. During the digestion process, only the readily available carbon (40 to 50%) is removed as the organic compounds are broken down. The levels of all other nutrients remain relatively unchanged, but the digestion process alters the nutrients (especially nitrogen) to forms more readily available for crop uptake. This results in the production of a nutrient-rich effluent that can reduce the need for commercial fertilizers. Furthermore, anaerobic digestion destroys pathogens and weed seeds, and is relatively odour-free.

Statistics for the 2005 growing season show that over 54,000 ha in Ontario were planted into vegetable crops. These varied crops produced a combined yield of about 1.7 million tonnes, but no figures are presented detailing the amount of waste material generated on this land. The number of hectares planted in sweet potatoes in 2007 was 415. Although this is relatively small, this crop is an excellent example of the large, untapped energy potential that could be exploited through the use of crop residues to produce biogas. Conservative estimates of sweet potato yields are 34,000 kg/ha. With a cull rate of 50%, this represents 7000 t of waste material, the bulk of which is currently ploughed back into the soil. Using horticultural wastes to produce energy and a nutrient-rich effluent has the potential to provide a new source of revenue to these growers. Relatively few studies have been conducted on the use of plant material as a feedstock for this process, and the majority of these studies are from Europe.

Objectives

1. Assess the suitability of different agricultural by-products, mainly related to vegetable production and processing, as feedstocks for the production of biogas (containing methane).
2. Determine the appropriate handling, processing and storage requirements for different feedstocks.
3. Determine the optimum conditions to maximize methane production.
4. Collect data to assess the economic potential of using vegetable wastes as energy feedstocks.
5. Measure the nutrient quality of the effluent generated from different input crops.

Project Setup

The anaerobic digester shown in Figure 1 was used for all testing. It allowed for easy addition of test inputs, timed mixing of contents, maintenance of the appropriate temperature (mesophilic range), easy sampling of digester contents and effluent (digestate), easy sampling of gas produced, and volume measurement of gas produced.

The digester and all of the equipment to operate it were mounted on a double-axle trailer. The digester tank was custom-built of High Density Poly-Ethylene (HDPE). It is an un-insulated tank and is fitted with six rectangular Plexiglas windows for viewing. The total volume (liquid + gas) is 2.2 m^3. When the digester's target depth of 95 cm is maintained, the liquid volume is 1.84 m^3. The average hydraulic retention time for this digester was intended to be approximately 21 days. During the test period, the only gas storage was in the headspace of the digester, under the rubber membrane attached to the top of the tank. Because the digester was portable, it could also be used for on-site demonstrations and farm shows.

All input materials were added directly to the digester. The digestate was heated using an electric water heater with a pump circulating the hot water through a heating loop inside the tank. A hopper with a 5 cm auger was available to introduce solid materials into the digester. Inside the tank was an agitator (Delta Equipment Model PG mixer) for mixing the digestate, either on demand or at preset times. The digester has a thermometer mounted inside the tank to monitor the digestate temperature. Other features included an over/under pressure relief valve ("U" tube), a window washing system, a liquid drain and fill valve, a gas valve manifold for attaching gas equipment, a second liquid input valve, a desulfurization system, a small gas burner and an additional port for sample collection.

Because the unit was relatively new at the start of the project, it was still undergoing some of the initial design tweaking needed to optimize the performance. Also, the initial commissioning was still being completed. In the fall of 2007, the unit was first filled with liquid swine manure and the production of biogas began. In January, 2008, sugar beets were added to the digester.

Figure 1 - Portable 2.2 m^3 anaerobic digester

Digester Operation

It was anticipated that the microorganisms needed to make the process work would take several days to adapt to the each new recipe and reach a steady-state. A period of no less than four weeks was used for each recipe. The digester was never emptied - new materials were simply added at low daily rates. In this way, the microbial population was given a chance to slowly adapt to new feedstocks, rather than starting with an empty tank each time. Digestate was removed as needed, depending on the volume of inputs.

The procedure for adding fresh inputs was as follows:

- Run the agitator for two minutes.
- Remove the required volume of digestate.
- For liquid inputs, add the required volume of liquids either through the auger or through the liquid port in the bottom of the digester.
- For solid inputs, a variety of methods for introducing new materials was tried - outlined later in the report – for specific materials.
- Run the mixer for two more minutes.
- Return the mixer to its standard setting of 30 seconds on for every 30 minutes.

Additions were made once per day and five days per week. For this first year of testing, no additions were made on Saturday or Sunday (when the appropriate staff were not present). The amount of material added was based on a pre-determined recipe. This took into account any available information on the chemical properties of the input materials. In most cases, this recipe was created before the initial sampling results were available – using estimates of moisture levels and Volatile Solids contents, mainly. The goal was to be well under a maximum loading rate of 4.5 kg VS/ m^3 of digester capacity. In addition, the maximum volume was no greater than 90 L – which would give a minimum hydraulic retention time of 21 days (i.e. based on daily inputs).

Pre-processing was needed for some materials, mainly to reduce the input particle size. This will be discussed later. The goal was to avoid introducing solids of more than 1 cm diameter.

Monitoring and Sampling

The volume of gas production was recorded daily and gas samples were collected to determine the concentrations of methane for the various recipes. The gas was then flared off. Samples of inputs and outputs were collected for nutrient analysis.

Samples were collected of each of the following: the raw materials added to the digester, the digestate as it was removed from the digester, and the biogas. The samples of solids and liquids were composite samples.

Two methods were used for biogas sampling. Between June 5 and July 10, 2008, 21 biogas samples were collected. A 20 mL syringe was used to collect biogas from a gas sampling port on the digester. The gas was then injected into pre-evacuated sealed vials (10 mL). These vials were refrigerated until shipping to the lab. This initial gas analysis was done using Gas Chromatography by the lab of Dr Mario Tenuta, Department of Soil Science, University of Manitoba. These tests included methane, carbon dioxide and nitrous oxide. Results were reported in parts per million (by volume).

The second gas sampling method involved the use of a gas analyzer (Pronova Analysentechnik, Model SSM 6000 Continuous) which measured the levels of methane, oxygen and hydrogen sulfide in the biogas. This unit was portable and attached to the digester for continuous biogas analysis. Gas volumes were monitored using a gas flow meter (Master-Touch MPNH, EPI – Eldridge Products Inc. model 800-321-FLOW).

Nutrient samples were delivered to the Laboratory Services Division of the University of Guelph, Guelph, Ontario. Digester inputs were analyzed for levels of total Carbon (C), Organic Carbon, Inorganic Carbon, Nitrogen (N), ammonium (NH_4-N), Phosphorus (P), Potassium (K), total solids (TS), Electrical Conductivity, pH and volatile solids (VS).

In addition, information was gathered for each input material that could be used to assess other logistical considerations related to the use of that material. This included data in the areas of:

- timing of availability
- handling, processing and storage considerations
- optimal operating parameters (pH, temperature, dry matter content, size of processed feedstock)
- economics – e.g. costs associated with feedstock handling, processing and storage

Materials Tested

Liquid swine manure was one of the materials used. It served as a stand-alone test but also was mixed with other materials. The rational was that the swine manure could serve as a benchmark - to which other materials could be compared. It is a material for which there have been numerous studies, making gas production comparisons easier. Also, because most digesters are designed to handle liquid materials, blending with swine manure could serve as a logical means of introducing solids to the digester.

Manure from the same swine farm was used throughout the study. This manure was tested to ensure that it was representative of Ontario swine farms. This was the first material added to the digester during the commissioning and initial testing. These early results are included here, even though the testing was done before the start of this study. Swine manure was re-visited later in the year. Another test that was performed before this project officially started looked at sugar beets as the energy source.

From there, the intention was to test a number of recipes using vegetable wastes. During the first year, the following materials were digested: a) swine manure alone, b) chipped sugar beets and swine manure, c) sweet potatoes, d) sweet potatoes mixed with swine manure, e) swine manure that was more recently produced, and f) dried green tobacco that was nicotine-free.

Special considerations for each of the input materials:

- Sugar beets are grown in the region. In some cases, spoilage prevents their use for sugar production. Sugar beets were chopped using a large wood chipper (see Figure 2) that could quickly shred the beets into small pieces. The sugar beets were first added to the digester using the attached hopper and auger. Liquid swine manure was added as well, but on a weekly basis. The manure was pumped into the bottom of the digester tank. This process proved to be less than ideal, so the liquid manure and chipped sugar beets were pre-mixed in a tank using a chopper pump. This mixture was then pumped into the digester. This also gave some problems, so the mixed sugar beets and liquid swine manure were added through the hopper and auger – which worked satisfactorily. This study ran in January and February of 2008.
- Liquid swine manure had been stored in a nearby underground tank for seven months. The swine manure was added to the digester over a 26 day period in May of 2008. It was added by pouring it into the auger while it was running.
- Sweet potatoes are grown in south-western Ontario and, each year, a significant quantity fails to meet the standards required for sale. The cull sweet potatoes typically would be returned to the field as waste. This study was started in June and ran for 24 days. The sweet potatoes were chopped in a food processor and 10 kg was added each day, five days a week. This material was mixed with fresh digestate to make inputs easier (with the auger). No new liquid manure was added with the sweet potatoes for this study and no digestate was removed since the volume of liquids didn't increase noticeably.
- Sweet potatoes were mixed with liquid swine manure. This study began in July, 2008. The same level of VS inputs was maintained – swine manure represented a small portion of the added VS. The study was run for 24 days with 40 litres of liquid swine manure combined with 8 kg of sweet potatoes each day. The liquid manure and chopped sweet potatoes were combined in a container and then poured into the auger as it ran (see Figure 3).
- Fresh swine manure was added to the digester beginning in August. This test was needed in order to compare methane production to the "older" swine manure used earlier. The manure used for this study had been placed into storage in early July. This study ran for just 11 days in August – ending with a digester mechanical failure. It was restarted in October and ran for an additional 29 days. Typically 90 L of liquid swine manure was added daily, 5 days per week. The manure was pumped into the feed auger as it was running.
- The tobacco used for this study was grown for the production of protein and small molecules. Once these were extracted, the dry biomass was available for digestion. This study ran for 25 days in November, 2008. Each day, 2 kg of dry tobacco was added (i.e. 5 days per week). The tobacco was mixed with liquid digestate drained from the digester. This material was then pumped into the feed auger as it ran. On the second day of the study the auger plugged and never was operational again. The mixture then was pumped into the drain hose at the bottom of the digester. This also created plugging problems. Finally, the mixture was pumped into the drain hose

but digestate was allowed to return to the tubs to re-liquefy the mixture. Even this method led to periodic plugging problems.

Figure 2 Wood chipper used to process sugar beets prior to digestion

Figure 3 Liquefied inputs being added to feed auger

Results and Discussion

A - General

Sugar Beets and Liquid Swine Manure

On January 9, 2008, the process of adding sugar beets was started. The sugar beets were of good quality, having only recently been harvested. The sugar beets were shredded using a wood chipper. On each of January 10, 11, 14, 15 and 16, 2008, 33 kg of shredded sugar beets were added to the digester. This period was used as a time to deal with any operational issues and to develop appropriate protocols for dealing with this solid material. Unfortunately, the auger did not handle the shredded sugar beets very effectively, so an operator had to gradually feed the sugar beets into the hopper - which was very time-consuming.

As noted, the digester had a gas meter that could measure the concentration of methane on a continuous basis. When the digester was loaded at the intended rate of 33 kg sugar beets per day, the quality of the biogas declined. Previously-measured methane levels were in the order of 70% - achieved using liquid swine manure. When sugar beets were added to the digester at 33 kg/day, methane levels dropped to a low of 37%. When loading was interrupted over the weekend (i.e. two days with no loading), the methane levels rose to around 70% by Monday.

On January 21, the blending of manure and sugar beets began. Manure and/or sugar beets were added on several occasions until February 8. On January 24, liquid swine manure and shredded sugar beets were mixed in a tub using the chopper pump and the resulting liquid was pumped into the digester (i.e. the hopper was not used). However, there were problems getting all the solids into the digester using this method, so the remaining material was added through the hopper and auger. This appeared to work well, so this method was used to add sugar beets for the remainder of the study. On the days when loading took place, loading rates were 16.5 kg sugar beets per day along with 90 L of liquid swine manure.

By February 11, pumps to move the initial liquid manure had frozen in the nearby manure storage. As a result, no more material was added to the digester. Gas production was monitored until February 27, when it was apparent the pumping equipment was not going to thaw out. At this point, the sugar beet test was ended.

During the study, a few leaks were discovered in the digester and in one case a valve was accidently partly opened, allowing oxygen to enter the digester. Methane concentrations continued to be quite variable during the entire study, with values in the range of 25.5% to 72.1%. The average methane content in the biogas during this study was 56.7% (STD = 9.6).

Even with the addition of blanket insulation on the exterior of the digester tank, the system still was not well-insulated. It was very difficult to maintain the target temperature of 37^{o}C when the ambient winter temperatures were much colder. The digester temperature dropped to as low as 28^{o}C on one occasion. The average daily temperature during the test was 34.2^{o}C (STD = 3.1).

This study ran for a total of 48 days. However, the period of greatest interest ran from January 21 to February 8 – a total of 18 days. The average daily loading rates were 5.5 kg of sugar beets and 31.1 L of liquid swine manure. The average daily biogas production was 0.756 m^3/day, at 54.7% methane (on average).

Liquid Swine Manure

This testing ran throughout May 2008. The average daily loading of swine manure was 50 L/day. The average daily biogas production was 0.55 m^3 per day (range 0.11 to 0.89, STD=0.25) and the average methane content 64.0% (STD=5), with a range of 57% to 74%.

The digester performed satisfactorily during this portion of the study but had difficulty maintaining the proper temperature. The average temperature in the digester was 33.7^oC throughout this period (range 28^oC to 39^oC; STD=2.51). Ambient air temperatures varied widely during this period. Bio-gas production fell when the digester temperature fell, and rose when the temperature was in the desired range (i.e. a low of 0.11 m^3 per day when the temperature was 28^oC and 0.89 m^3 per day when the temperature was 36^oC). The digester did not have any insulation on it for this study since the insulation had to be removed for demonstrations.

Sweet Potatoes

Sweet potatoes were tested in June 2008. In total, 180 kg of sweet potatoes were digested with an average of 10 kg added per day. No digestate was removed from the system during this study since there was no noticeable increase in the digestate volume. It appeared to take about a week to reach a steady state operation. On Day 22 a pressure relief valve blew. This was the result of higher than expected gas production overnight. This occurred again on each of the next two nights. As a result, some gas production data were not available.

The average daily biogas production was 1.57 m^3 per day (range 0.99 to 2.12; STD=0.40). The average methane content was 48.0% (range 45% to 53%; STD=3).

The digester performed well during this portion of the study maintaining the proper temperature. The average temperature in the digester was 35.9^oC throughout this period (STD 1.52). The digester did not have any insulation on it for this study.

Sweet Potatoes and Fresh Liquid Swine Manure

As a result of the low methane concentrations in the previous test, the decision was made to combine sweet potatoes with regular additions of swine manure. Throughout this test, an average of 8 kg/day of sweet potatoes was digested. In addition, an average 40 L/day of fresh liquid swine manure was added. Digestate was removed daily during this study (i.e. 40 L/per day). It appeared to take only three days to reach a steady-state operation, transitioning from the previous study. On Day 10, a pressure relief valve blew due to high gas production overnight.

The average daily biogas production was 2.26 m^3 per day (STD=0.47). The average methane content was 56.0% (STD=3). The digester performed well during this portion of the study. The average temperature in the digester was 37.2^oC throughout this period (STD=2.53). The digester did not have any insulation on it for this study, causing a certain amount of the variability in temperature.

Fresh Liquid Swine Manure

Liquid swine manure had been tested earlier but it had been in storage for an extended period of time before input to the digester. We needed to determine if more recently produced swine manure would give similar biogas yields. This test ran for part of August 2008 but an electrical failure in the digester ended the study. It was re-started in October and ran for 29 days. An average of 90 L/day was digested. The average daily biogas production was 0.97 m^3/per day (range 0.63 to 1.52; STD=0.23) and the average methane content was 63.0% (STD=2).

The digester performed well during this study. A new thermostat had been installed to better control the digester temperature. The average temperature in the digester was 36.0°C throughout this period (STD=1.62). Ambient air temperatures varied but the digester was now able to maintain the desired temperature. The digester was re-insulated partway through the study (October 23), which led to a more stable digester temperature.

Dried Nicotine-Free Tobacco

Dried nicotine-free tobacco (Figure 4) was tested to determine if tobacco used for protein and small molecule production could then be digested to produce biogas. This would potentially provide a means to extract further value from the biomass. The study ran for 25 days in November 2008. There were a number of problems getting the tobacco fed into the digester, since it plugged both the feed auger and the drain hose. In spite of this, the tobacco was tested with the desired feed rate of 2 kg/day dried material. Higher feed rates were not practical because it was so difficult to add the material using the existing equipment configuration. No digestate was drained from the digester since there was no noticeable increase in the volume. The tobacco tended to float on the liquid surface, so agitation time was increased when the tobacco was added to the digester.

The average daily biogas production was 1.1 m^3/day (range 0.36 to 3.4; STD=0.70) and the average methane content was 49.0% (STD=2). The average temperature in the digester was 36.5°C throughout this period (STD=1.62). Ambient air temperatures varied widely during this test.

B - Chemical Analysis

Results of the chemical analysis of inputs and outputs are summarized in Tables 1 to 6. In the case of sugar beets and swine manure (Table 1), while the N content was similar on an “as is” basis, a much higher percentage of this N was in the NH_4-N form in the swine manure than in the sugar beets. The sugar beets had a higher Volatile Solids content (84.9%, on a DM basis) and a higher C:N ration (20:1).

One of the characteristics of the digestate shown in these tables is that the NH_4-N represents a higher percentage of total N than it does in the inputs. This has implications for farmers who will rely on this liquid as a source of crop nutrients.

As expected, values of total N, P and K in the digestate are somewhat similar to levels in the inputs – the digestion process should have no impact on these nutrient totals. In those cases where only a small amount of relatively dry material is first mixed with digestate, it is hard to see this trend. Where very little, if any, digestate is actually removed from the system, one would expect levels of N, P and K to gradually rise to the point where the system is not sustainable. These tests were not run long enough to notice any problems with high levels of N or salts. In addition, the C:N ratio in the digester was low in all cases, well below the desirable ratio of 20:1.

The Dry Matter content of the digestate was typically lower than that of any of the inputs. Also, the concentration of C in the digestate was typically lower than for any of the inputs, confirming that C is removed from the system in the form of methane (CH_4) and carbon dioxide (CO_2).

The chemical results for the “aged” swine manure (Table 2) appear to be similar to those reported in Table 5, for the much more “fresh” swine manure. The gas production efficiency was different, however, as discussed later.

Figure 4 Shredded tobacco prior to addition to digester

Table 1 - Average chemical characteristics of inputs and outputs - Sugar Beets and Swine Manure

Parameter	**Units**	**Swine Manure**	**Sugar Beets**	**Digested Sugar Beets and Swine Manure**
NH_4-N	mg/kg (as is)	3470	54.0	2830
Total N	% (as is)	0.45	0.50	0.39
Total P	% (as is)	0.11	0.07	0.10
Total K	% (as is)	0.23	0.39	0.25
pH	pH units	7.4	4.5	8.10
Dry Matter	% (as is)	4.43	20.1	3.12
O.M. (VS)	% (DM basis)	65*	84.9	NA
E.C.	mS/cm	9.2	NA	NA
Total C	% (DM basis)	43	39	34.3
C:N	ratio	4.2	20	2.73

* Values for Organic Matter (i.e. Volatile Solids), determined by Loss on Ignition, were missing for the swine manure. The value was assumed to be equal to that obtained for a previous study, using swine manure from the same source.

Table 2 - Average chemical characteristics of inputs and outputs - Swine Manure

Parameter	**Units**	**Swine Manure**	**Digested Swine Manure**
NH_4-N	mg/kg (as is)	1,668	2,018
Total N	% (as is)	0.20	0.24
Total P	% (as is)	0.05	0.05
Total K	% (as is)	0.18	0.20
pH	pH units	7.35	8.0
Dry Matter	% (as is)	1.86	1.71
O.M. (VS)	% (DM basis)	65*	NA
E.C.	mS/cm	6.59	7.78
Total C	% (DM basis)	33.1	27.3
C:N	ratio	3.05	1.94

* Values for Organic Matter (i.e. Volatile Solids), determined by Loss on Ignition, were missing for the swine manure. The value was assumed to be equal to that obtained for a previous study, using swine manure from the same source.

NA = Not Available

Table 3 - Average chemical characteristics of digester inputs and outputs - Sweet Potatoes

Parameter	**Units**	**Sweet Potatoes**	**Digested Sweet Potatoes**
NH_4-N	mg/kg (as is)	208	1,809
Total N	% (as is)	0.47	0.22
Total P	% (as is)	0.05	0.04
Total K	% (as is)	0.53	0.22
pH	pH units	3.13	7.9
Dry Matter	% (as is)	15.2	1.42
O.M. (VS)	% (DM basis)	89.8	46.2
E.C.	mS/cm	4.4	7.3
Total C	% (DM basis)	41.7	25.7
C:N	ratio	18.58	1.64

Table 4 - Average chemical characteristics of digester inputs and outputs - Sweet Potatoes plus Liquid Swine Manure

Parameter	**Units**	**Sweet Potatoes**	**Liquid Swine Manure**	**Digested Sweet Potatoes and Liquid Swine Manure**
NH_4-N	mg/kg (as is)	228	2682	1970
Total N	% (as is)	0.28	0.39	0.30
pH	pH units	4.66	6.48	7.71
Dry Matter	% (as is)	12.62	4.72	2.16
O.M. (VS)	% (DM basis)	86.9	68.3	55.3
Total C	% (DM basis)	40.5	36.6	28.0
C:N	ratio	18.78	4.16	2.03

Table 5 - Average chemical characteristics of digester inputs and outputs - Liquid Swine Manure

Parameter	**Units**	**Liquid Swine Manure**	**Digested Liquid Swine Manure**
NH_4-N	mg/kg (as is)	NA	NA
Total N	% (as is)	0.28	0.24
Total P	% (as is)	0.10	0.03
Total K	% (as is)	0.18	9.82
pH	pH units	7.8	7.5
Dry Matter	% (as is)	1.89	1.18
O.M. (VS)	% (DM basis)	53.2	46.2
E.C.	mS/cm	NA	NA
Total C	% (DM basis)	29.6	33.4
C:N	ratio	2.01	1.62

Table 6 - Average chemical characteristics of digester inputs and outputs - Dried Nicotine-Free Tobacco

Parameter	**Units**	**Dried Nicotine-Free Tobacco**	**Digested Dried Nicotine-Free Tobacco**
NH_4-N	mg/kg (as is)	NA	NA
Total N	% (as is)	2.02	0.30
Total P	% (as is)	0.30	0.10
Total K	% (as is)	3.62	0.21
pH	pH units	5.46	7.76
Dry Matter	% (as is)	87.86	2.18
O.M. (VS)	% (DM basis)	84.47	53.16
E.C.	mS/cm	NA	NA
Total C	% (DM basis)	40.83	29.29
C:N	ratio	18.57	2.10

C - Digester Performance

A plot of the daily methane production over time for sweet potatoes and liquid swine is shown in Figure 5. This was typical of the graphs for the other inputs in the 2008 testing. It shows that the daily methane production varied and that the variation seems to have been influenced, at least in part, by the timing of addition of inputs (represented here by Volatile Solids inputs). The methane production appeared to drop off over the weekends when there were no additions of fresh materials. The 2009 testing will attempt to remove this possible source of variability by ensuring that inputs and measurements continue daily throughout the test period. While there are full-scale systems (e.g. in Germany) where inputs are added every 30 minutes, this was not feasible for this project.

These daily variations are not nearly as obvious when the cumulative methane production is plotted for the same two inputs (see Figure 6). Figure 6 demonstrates a strong correlation between the cumulative VS loadings and methane production. The fact that the lines representing cumulative methane production are relatively straight (at least after the first few days) suggests that the rate of methane production has leveled off and that there is no need to run the tests longer than the test period used. This will be further assessed in the 2009 trials.

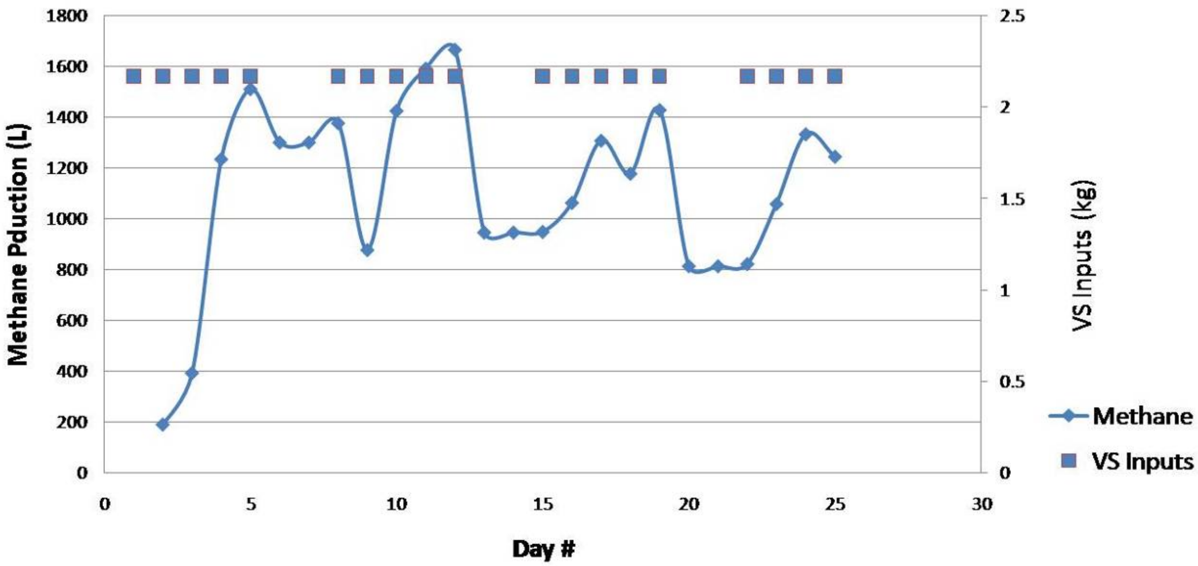

Figure 5 Daily methane production and VS inputs - Sweet Potatoes and Swine Manure

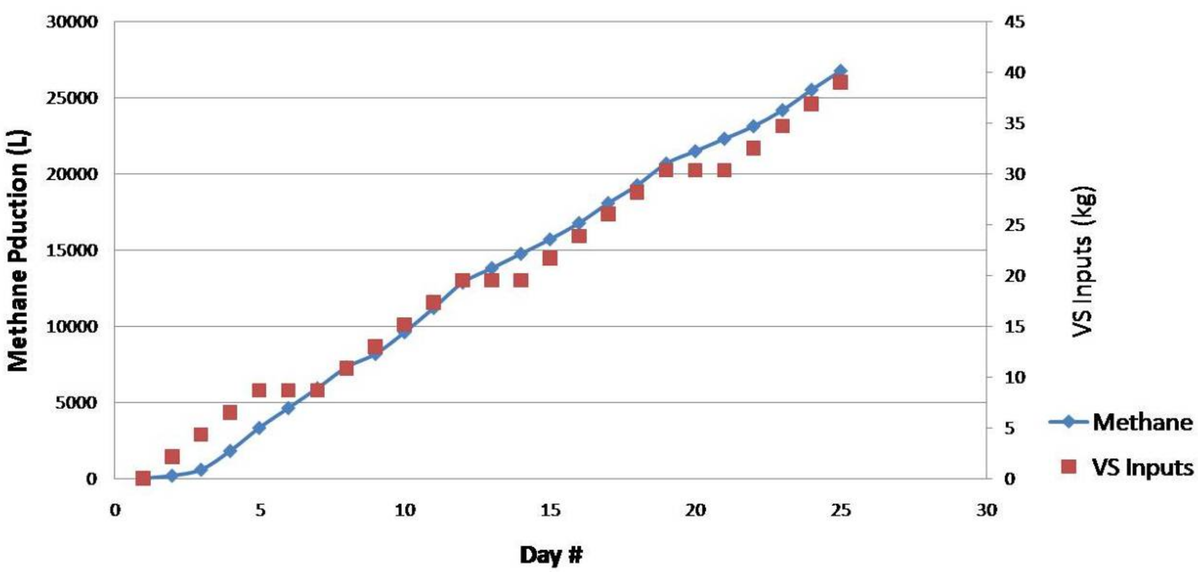

Figure 6 Cumulative methane production and VS inputs - Sweet Potatoes and Swine Manure

A number of standard performance indicators are typically used in the evaluation of anaerobic digesters. Several of these are summarized in Table 7. They help to make meaningful comparisons between the various trials. The normal target for the hydraulic retention time for this digester design is in the range of 20 to 35 days. In all cases except for Fresh Liquid Swine Manure, the mass of daily inputs could have been increased (thus reducing the Hydraulic Retention Time). Because the swine manure was so dilute initially, when the proper liquid loading rate was achieved, the Average Loading Rate (expressed as kg VS/m^3 digester capacity) was quite low. The generally accepted rule of thumb is to not exceed a value of 4.5. In the study, values ranged from 0.49 (for fresh swine manure) to 1.17 (for sweet potatoes and swine manure).

The concentration of methane in the biogas was highest (64%) for the swine manure. When looking at gas production expressed as L/kg VS, fresh swine manure yielded the highest value. Somewhat surprisingly, the lowest value was for the sugar beets and manure mixture. However, this test likely does not represent a fair assessment of the potential, since it was an early test carried out in cold weather, with no digester insulation.

In the cases where small amounts of solids were mixed with digestate to assist with input of materials (i.e. sweet potatoes and tobacco), there is a potential that the hydraulic retention time could be so long that salt accumulation in the digester will start to limit microbial activity. While this was not expected to cause problems for the test period selected, it is something that needs to be considered when “scaling up” the results from this study.

Table 7 – Performance indicators for the 6 Anaerobic Digester trials

	Units	**Sugar Beets + Swine Manure***	**Swine Manure**	**Sweet Potatoes**	**Sweet Potatoes + Fresh Swine Manure**	**Fresh Swine Manure**	**Dried Nicotine-Free Tobacco**
Length of trial	days	18	26	24	24	29	25
Average Loading Rate	kg/day	5.5 (SB) + 31.1 (Man.)	50	10	8 (SP) + 40 (Man.)	90	2
Average Hydraulic Retention Time	days	39.6	36.8	No digestate removed	46	21	No digestate removed
Volatile Solids added	kg/day	1.84	0.61	1.37	2.17	0.91	1.48
Average Loading Rate**	kg VS/m^3 digester capacity	1.00	0.89	0.74	1.17	0.49	0.80
Biogas produced	m^3/day	0.76	0.55	1.57	2.26	0.97	1.09
Methane Content	%	57	64	48	56	63	49
Methane Produced	m^3/day	0.43	0.35	0.75	1.27	0.61	0.53
Methane Produced	L/kg VS	233	336	547	585	670	358

* - this test had the greatest temperature variation due to winter operation in an un-insulated digester – less than ideal conditions

** - Based on a digester liquid volume of 1.84 m^3

Handling, Processing and Storage Requirements

General observations were made in order to give guidance on the handling, storage and processing requirements for the materials tested. For liquid swine manure, it is desirable to use fresh manure so the digester should be close to the manure source. It should be sized to handle the daily production of the swine operation. The storage for digestate would need to be similar to what otherwise would have been used for the operation.

The solid materials such as sugar beets, sweet potatoes and tobacco would have to be stored using appropriate facilities. Sugar beets and sweet potatoes would be used seasonally since storage for long periods of time in warm weather results in rapid deterioration. The sweet potatoes and sugar beets would have to be stored whole and chipped or shredded just prior to digestion. During the testing, when sugar beets were shredded and stored for a week or two in cold weather, some composting and break down took place. The tobacco would have to be stored dry and protected from moisture and monitored for spoilage and heating.

Economic Analysis

A number of factors were identified that should be considered in performing an economic analysis. These include:

- On-site storage may be needed for materials that are available only on a seasonal basis.
- While labour inputs are minimal, regular supervision and monitoring of the digester is essential.
- There should be no loss of plant nutrients from the inputs (e.g. livestock manure) during digestion.
- It is anticipated that the cull sugar beets, sweet potatoes, tobacco and liquid swine manure would be supplied at no cost to the digester. There would normally be some transportation and storage costs, however.
- Ontario's Standard Offer Contract guarantees a minimum price for electricity sold onto the grid and this arrangement covers a number of years into the future.
- In certain situations, a value may be placed on odour reduction or on possible pathogen reduction (not measured in this study but documented by others).
- Inputs that have relatively low moisture contents may need to be blended with a liquid (in most current digester designs). Liquid manure is a possible candidate. .

Summary

During 2008, a series of tests was performed using a pilot-scale anaerobic digester at the Ridgetown Campus of the University of Guelph. Methane production was measured using the following inputs: a) Sugar beets and liquid swine manure, b) liquid swine manure, c) sweet potatoes, d) sweet potatoes and fresh swine manure, e) fresh swine manure, f) dried nicotine-free tobacco. In each case the length of trial was approximately four weeks, during which time the system appeared to reach a steady-state production of methane. The main findings of the study are as follows:

- The mix of swine manure and sugar beets produced only 233 L methane per kg VS. Almost certainly, this value underestimates the true potential, as there were problems in maintaining digester temperature during the winter-time trials. Methane represented 56.7% of the total biogas production.

- The “older” swine manure (1.86% D.M.) produced 336 L methane per kg VS. Methane comprised 64% of the total biogas production (the highest concentration for the input materials tested).
- The sweet potatoes produced 547 L methane per kg VS. Methane represented 48% of the total biogas production (an undesirably low concentration).
- The mixture of sweet potatoes and fresh swine manure produced 585 L methane per kg VS. Methane represented 56% of the total biogas production.
- The fresh swine manure yielded 670 L methane per kg VS (the highest yield of the materials tested). Methane represented 63% of the total biogas production. This swine manure had been in storage for considerably less time that the “older” swine manure tested earlier. The methane yield (volume of methane per kg VS) was double the value reached for the older manure. This verified that it is much better to use freshly-produced swine manure in a digester, rather than manure from a long-term storage.
- The dried nicotine-free tobacco produced 358 L methane per kg VS. Methane was 49% of the total biogas production (a lower concentration than what is required to ignite).
- In most cases, the average hydraulic retention time ranged from 21 to 46 days. In two trials, no digestate was removed throughout the test period. The addition of inputs did not increase the volume in the digester.
- The study ran into a certain level of difficulty handling all of the solids and also introducing liquids into the digester. Numerous methods were tried to add these materials to the digester. Typically, either liquid manure or digestate were added to the solids and then this slurry was introduced using the feed auger. Even this method failed at times (notably for the tobacco test) and alternative methods were used. This design issue will be solved prior to the 2009 testing.

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