EFFECT OF CO-DIGESTION OF SOURCE SEPARATED ORGANICS AND MANURE ON METHANE PRODUCTION

By

Devarshi Sevak

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Abstract

Anaerobic co-digestion (AcoD) is more advantageous than conventional mono-digestion, because of higher gas production rate. This study was aimed to study the effect of mixture ratio in co-digestion of manure and source separated organics (SSO) in mesophilic condition.

Manure and SSO at different mixture ratios of 9:1, 7:3, 5:5, 3:7, and 1:9 on a volumetric basis were used to determine the effect of the mixture ratios on methane production in biomethane potential assay (BMP). Results showed that co-digestion of SSO and manure at the ratio of 1:9 (V/V) resulted in the highest biomethane production rate of 46 mL CH_4 /day. In comparison, the maximum methane production rate for anaerobic digestion of manure alone was 43 mL CH_4 /day. When manure is mixed with SSO at a ratio of 5:5, about 15% higher cumulative methane production has been achieved. This research also verified the advantages of co-digestion over mono-digestion.

Keywords: Anaerobic Digestion, Co-digestion, Source Separated Organics (SSO), Manure

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1. Introduction

Nowadays many countries facing the most crucial problems for the disposal of many types of wastes like Municipal Solid Waste (MSW), Sewage Sludge (SS), Dairy Manure (DM) and crop residues. There are different types of methods available for the proper disposal and recycling of these kind of wastes. Among all these methods, Anaerobic Digestion (AD) is one of the most successful method because of its minimum impact on the environment. It is one of the most suitable treatment techniques, because it converts such a waste in methane-rich biogas, which can be used as a valuable source of energy for heating and electricity generation.

Anaerobic digestion is a natural biological process. In this process anaerobic microbes break down the organic matters of the waste, release the gas and leave the non-biodegradable waste as a residue. This whole process operated in a closed reactor known as a 'Digester', in the absence of oxygen (O_2) with elevated temperature. Biogas, digestate and water are the three principal products of the AD process. Digestate is a nutrient rich by-product, which can be used as a fertilizer and soil improver.

Biogas is a mixture of CH_4, CO_2 and water, that can be used as a natural gas substitute and can be used to produce electricity and heat. Biogas typically contains 60% to 70% methane (by volume), 30% to 40% carbon dioxide and minor quantities of nitrogen, hydrogen, ammonia and hydrogen sulfide (usually less than 1% of the total gas volume). Among all these gases, methane is the most valuable gas, because it is a source of hydrocarbon fuel. Figure 1 shows the components of AD system.

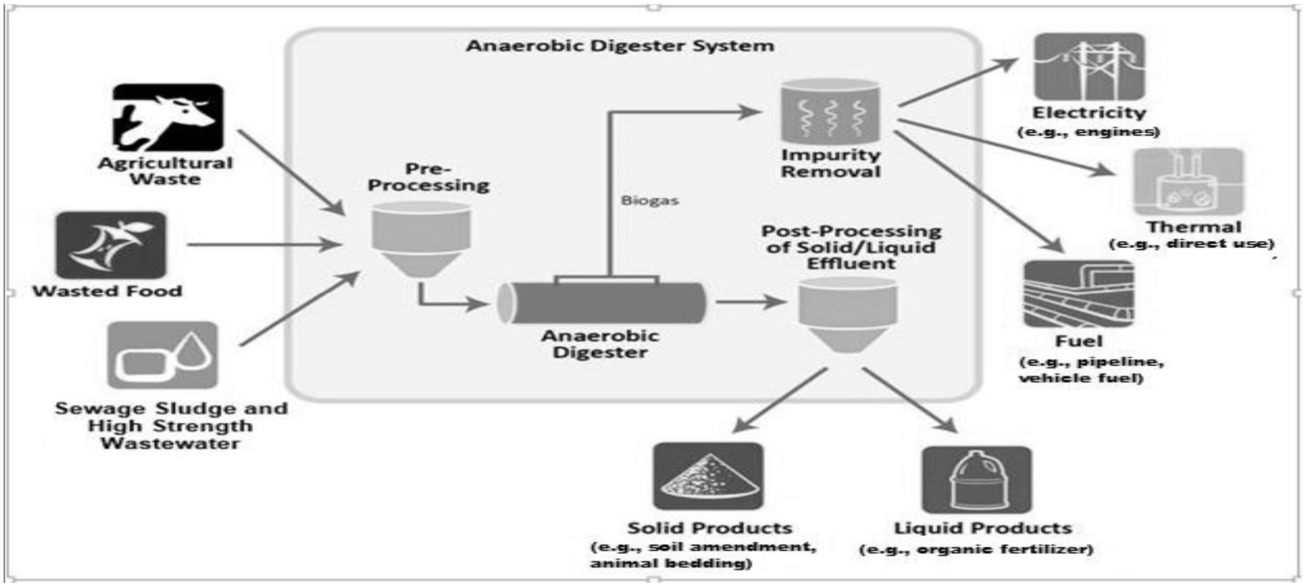

Figure 1. Anaerobic digestion system components (https://www.tn.gov/environment/program-areas/sw-mm-organics/anaerobic-digestion.html)

In AD process complex organic substrates are break down by anaerobic microorganisms and converted to CO_2, CH_4 and digested solid compost. This biodegradation process goes through four different phases named hydrolysis, fermentation (acidogenesis), acetogenesis and methanogenesis. Figure 2 shows the breakdown of complex organic matters through the four phases of the AD process.

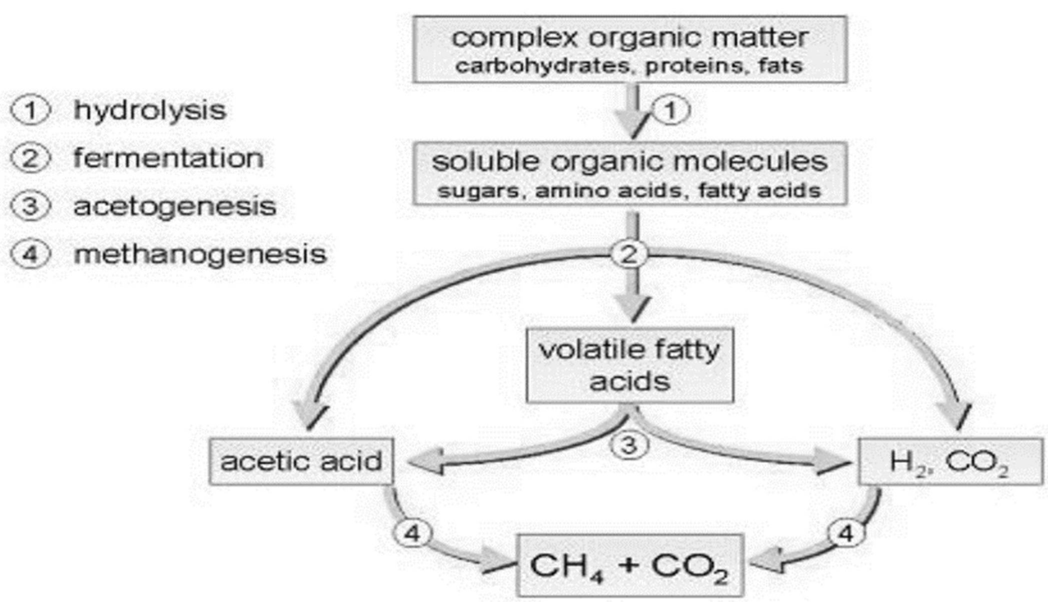

Figure 2. The pathway of AD process (http://www.appropedia.org/Arcata_Marsh_digester)

There are many advantages of using AD process as a treatment method for the waste management. Some of the major advantages are listed below.

- Climate change mitigation (Methane emission reduction)
- Diversion of organics from landfills
- Economic benefits
- Less sludge production
- Manure management
- Renewable energy generation
- Soil improvement opportunities
- AD systems can minimize odors and vector attraction, reduce pathogens, produce gas, produce liquid and solid digestate, and reduce waste volumes.
- Biogas can be converted to energy via a Combined Heat & Power Plant (CHP). Electricity generated from the CHP process can be used in adjacent industrial or commercial enterprises or can be fed into the national grid. Surplus heat generated can be used in industrial processes or for district heating systems.

Figure 3 shows the benefits of using AD system as a treatment method for the waste management.

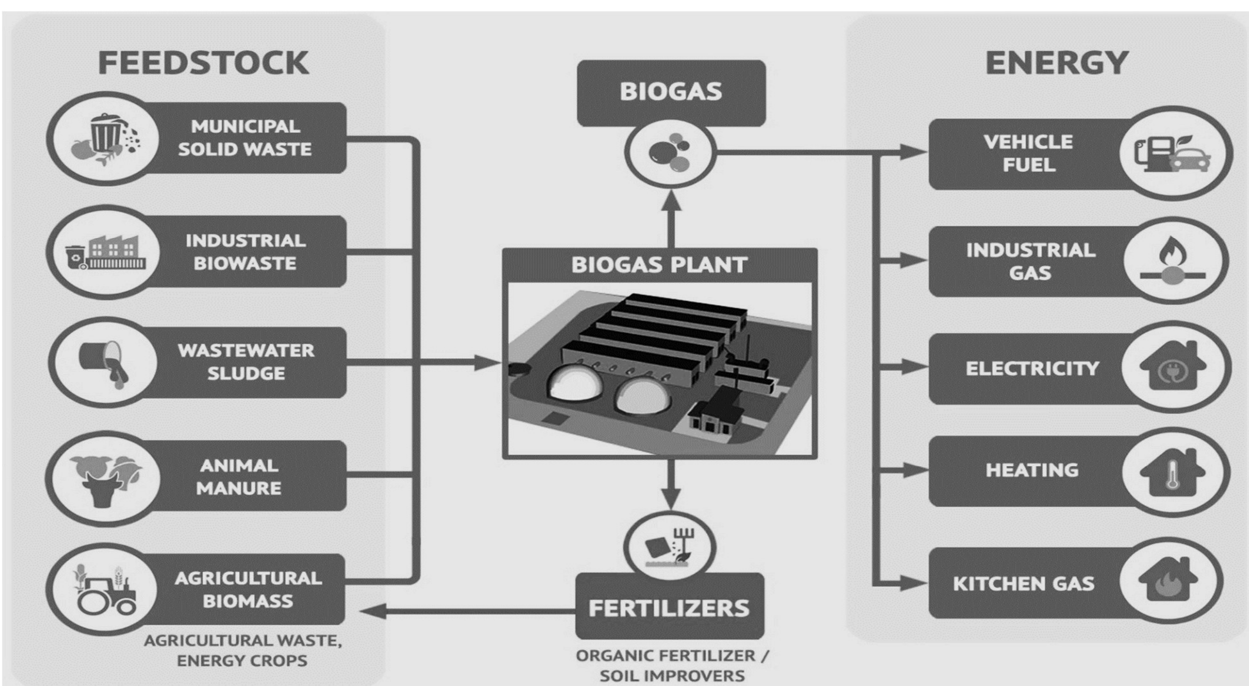

Figure 3. Advantages of AD system (https://biogts.com/products/biogas-plants/)

Although AD systems offer several advantages, there are some drawbacks of using AD system that needs to be considered. Some of the major disadvantages are listed below.

- Does not remove ammonia-nitrogen.
- Does not reduce some nutrients such as N, K and P.
- High initial capital cost; high cleaning cost.
- High operator attention is required for safety concerns because methane is an explosive gas.
- pH must be controlled along with monitoring of volatile fatty acids.
- Time consuming process because methanogenesis stage is very slow.

2. Anaerobic co-digestion

Anaerobic digestion produces renewable energy by converting the complex organic matters into biogas. However, this process takes place in completely monitored environment, because of some important parameters that affects the biogas production rate. Some important parameters need to be controlled during the process such as C: N ratio, pH value, temperature etc. to achieve better methane production rate. As in AD process only one substrate decomposes at a time; due to some factors like C: N ratio, desired production rate of biogas cannot be achieved. For example, sewage sludge is a poor feed source for AD process because it has high nitrogen and low carbon content (M. Elsayed, 2015). To avoid such type of problem, if two or more different substrates in one digester simultaneously are used; higher amount of biogas production can be achieved.

Co-digestion is the simultaneous digestion of homogenous mixture of two or more than two substrates in the same digester (A.O. Adebayo, 2014). Co-digestion has some benefits over traditional mono-digestion. The main advantage of using co-digestion is the significant improvement is the biogas production. In co-digestion, by adding two different substrates we can achieve optimum C: N ratio, which is very crucial parameter for the biogas generation. For example, an optimum C: N ratio can be obtained by adding a carbon rich waste to the sewage sludge (Richard Wickham, 2016). This project focuses on the co-digestion of Source Separated Organics (SSO) and Manure. Effects of the co-digestion of SSO and manure on methane production has been studied and analyzed in this project.

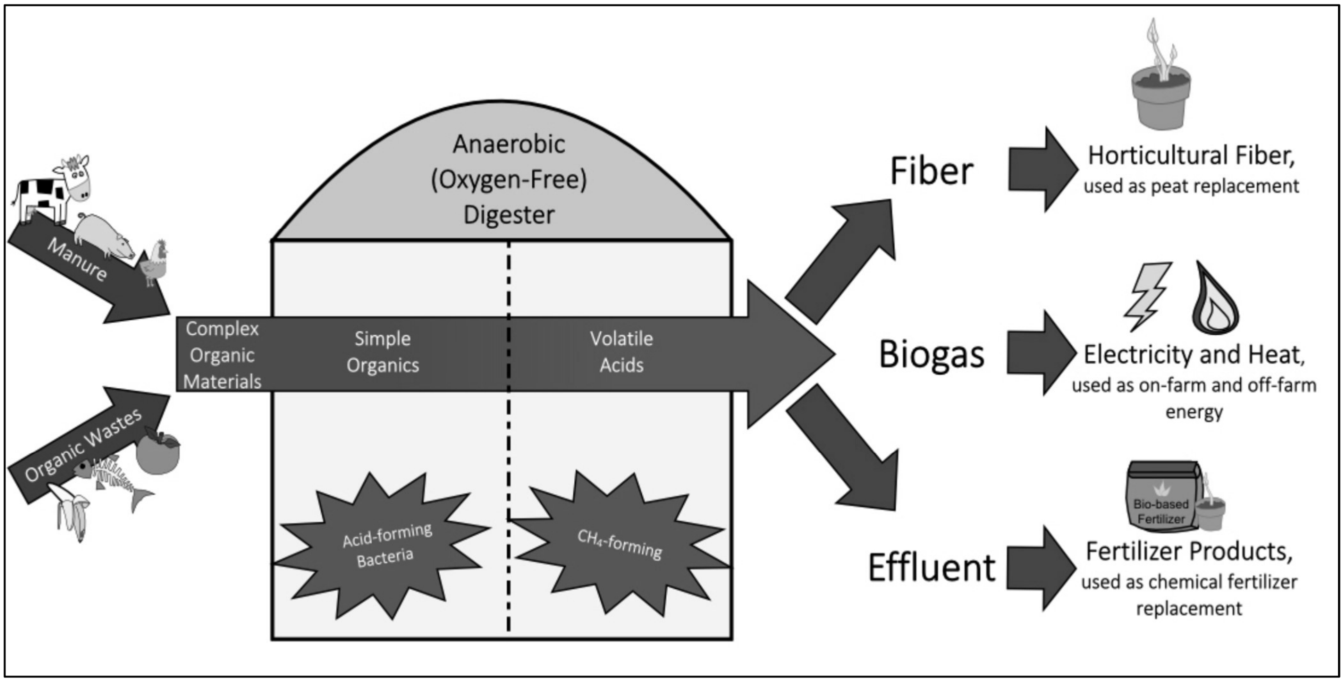

Figure 4. Anaerobic co-digestion system (Kennedy, 2015)

When adding two or more different substrates in the digester, some modification in the infrastructure of the digester is necessary based on the type of the substrates added. Studies have shown that biogas production is higher in co-digestion compared to mono-digestion; because in co-digestion balanced nutrients and high energy organic material is fed to the digester. The produced biogas can be used for electricity and heat generation. It can be also upgraded to Renewable Natural Gas (RNG) (Kennedy, 2015). The biogas production rate highly depends on the type and concentration of the substrates that are used in co-digestion process. It also depends on the flow rate of the substrates throughout the process. Some of the common advantages and disadvantages of co-digestion process is mentioned below (Kennedy, 2015).

2.1 Advantages of co-digestion process

- Diversion of organic matters from the landfills
- Improved overall process economics by producing higher biogas
- Reduction of the greenhouse gas (GHG) emissions
- Improved fertilizer value of the digestate due to less solids and higher degradation
- Enhanced C: N ratio and nutrients balance by substrates combinations

2.2 Disadvantages of co-digestion process

- Inorganic materials (e.g. metals, plastics etc.) can negatively impact the digester performance
- Higher biogas production leads to higher biogas contaminants (e.g. hydrogen sulfide and carbon dioxide)
- Increased nutrients such as nitrogen, phosphorous and potassium from the substrate can affect the quality of the digestate
- Possibility of digester failure due to biological inhibition process occurred within the co-digested substrates

3. Feedstocks

Feedstock can be defined as any biodegradable substrates which can be converted to biogas by anaerobic microbes. It can be easily degradable or complex high-solid waste. Using specific technologies toxic compounds can also be degraded anaerobically. Adequate organic matters must be present in the feedstock, so that they can be finally converted to biogas which is comprised mainly of methane.

Feedstocks for the AD process is derived from one major source. Initially, AD was designed for the treatment of animal manure. But due to population growth and urbanization, amount of different kind of waste material is also increased. Therefore, since 1970s industrial and municipal solid wastes are also introduced to AD applications to fulfill the demand of the new waste management strategies and renewable energy forms (Steffen, Szolar, & Braun, 1998). Figure 3 shows the eligible main sources of the feedstocks for AD process.

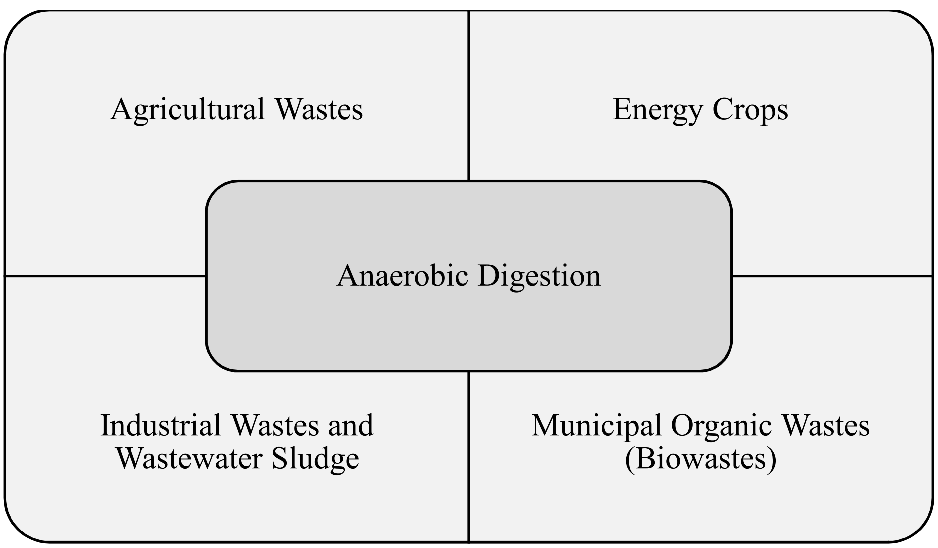

Figure 5. Sources of feedstocks for AD process (Graphic by Devarshi Sevak)

There are many types of substrates that can be used as a feedstock in AD process. The following table shows the broad classification of the main sources of the feedstocks for the AD process.

Table 1- Various feedstock from different sources (Steffen, Szolar, & Braun, 1998)

Source of Feedstock	Various Feedstocks
Agricultural Waste	Manure (cattle, pig etc.)
	Algal biomass
	Harvest remains etc.
Communities	Municipal Solid Waste (MSW)
	Sewage Sludge
	Yard Waste etc.
Industry	Food/beverage processing waste
	Dairy waste
	Pulp and Paper etc.

As mentioned earlier, the biogas production rate mainly depends on the type of substrate used and the amount of organic matters in the substrate. The following figure shows the data derived from a study at Cornell University, demonstrates a massive change in methane production based on different substrate types (Kennedy, 2015).

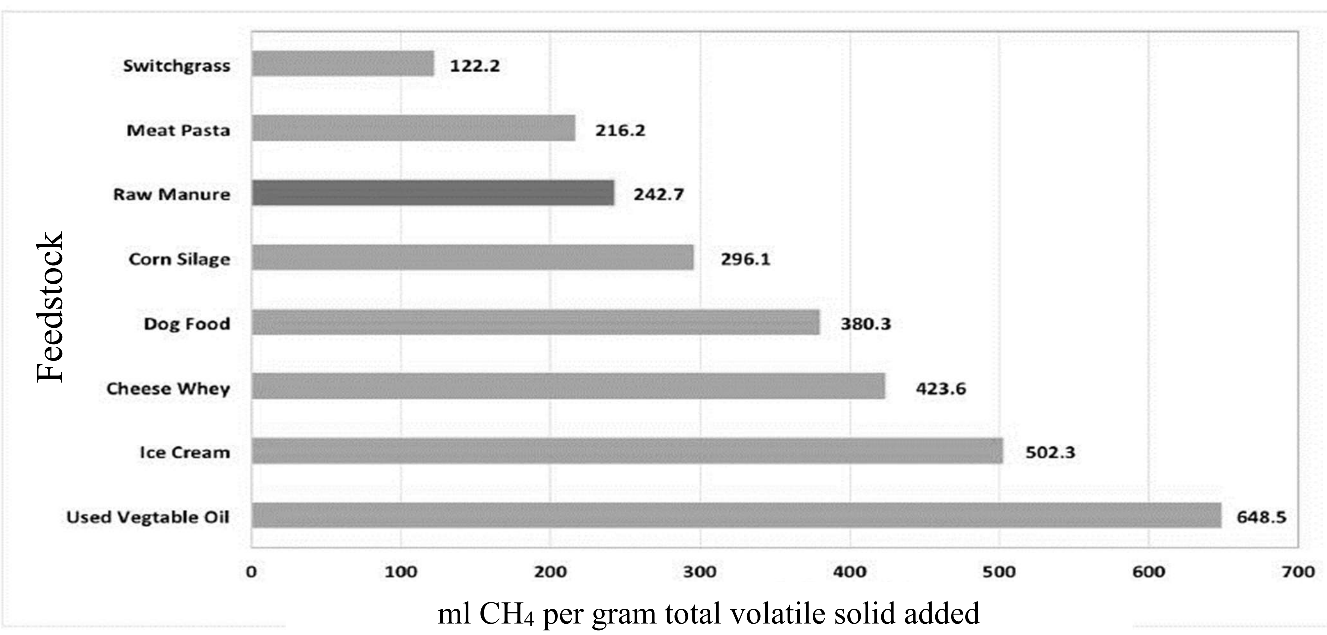

Figure 6. Methane yields of different substrates (Kennedy, 2015)

4. Co-digestion of SSO and manure

In this project, co-digestion of SSO and manure in mesophilic condition at different mixture ratios of manure and SSO has been investigated. The effects of the co-digestion of these two substrates has been analyzed through the BMP assay to evaluate the mixture ratio on improving methane production.

4.1 Source separated organics (SSO)

Source Separated Organics (SSO) is the compostable organic waste which is segregated from other waste materials at the source. SSO refers to mostly food waste which is separated from the residential waste for separate collection and processing (Kelleher & Robins, 2013). For the separate collection and processing of SSO, many municipalities (Ottawa, Toronto etc.) introduced the concept of using 'Green Bins' for the food waste. Following figure shows the separate collection bins of different wastes.

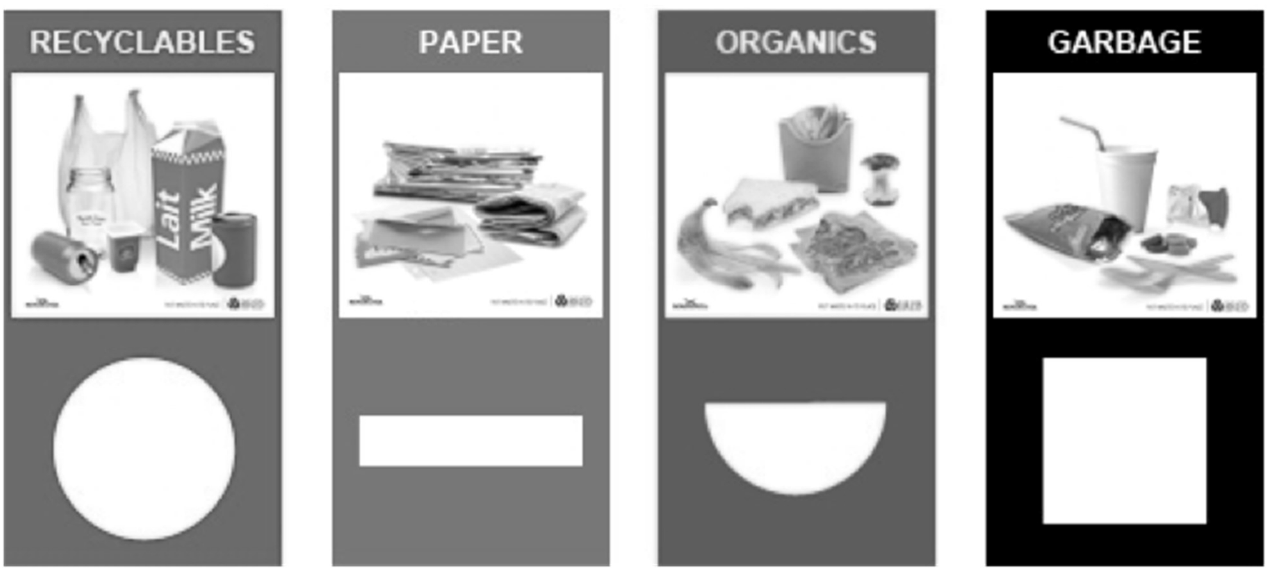

Figure 7. Waste separation at source (https://divertns.ca/resources/bins-signage/bin-guidelines)

Organic matters such as wood waste, food scraps, yard trimmings, paper and cardboard products, typically make up about 33% (by weight) of the municipal solid waste stream. Generally, SSO programs depend on the composition of waste material, acceptance criteria of organics processing units and the collection method. So, the different types of organic matters include the following wastes.

- **Yard and Landscaping debris-** Tree trimming, grass, leaves etc.
- **Food Waste-** vegetables, meat, seafood, bones, rice, eggshells, bakery items etc.
- **Paper Fibers-** napkins, paper towels, tea bags, coffee filters etc.
- **Wood Waste-** urban wood waste, rural forestry residuals etc.

4.1.1 SSO from residential sources

The most common wastes generated at residents include food waste, paper waste, yard waste etc. Separating food waste from other garbage has significant benefits at the landfill or disposal site, as organics break down in landfills and generate strong greenhouse gases and leachate which is acidic and precipitates metals from the landfilled material. So, the segregation of food waste from other wastes is very important. There are some benefits of AD of Residential SSO and are as follows:

- **Green House Gases and other Air Emissions**
  Anaerobic digestion of residential SSO produced less air and water pollution than aerobic composting and landfilling of residential SSO. It has positive net energy balance; while other methods including landfilling with gas collection- consume energy over their lifetime.
- **Air Quality Impacts**
  AD system produces lower gas emissions. It has a significant air quality benefit compared to composting. AD of Green Bin material (residential SSO) occurs in a tightly controlled environment, where all the produced gas is cleaned through a biofilter; so that odors do not occur.

4.1.2 SSO from industrial, commercial and institutional sources

Waste composition studies carried out for several communities by Kelleher Environmental have indicated that about 23% of waste generated by the non-residential industrial, commercial and institutional sector (IC&I) is food waste generated by businesses and institutions in all communities across Canada. Restaurants, hotels, hospitals and different food processing facilities generate most of the food waste. Food wastes from these different sources can generate considerable amount of biogas through the AD process.

4.2 Manure

Animal manure is a valuable source of nutrients and renewable energy. However, majority of the manure is collected in lagoons or left to decompose in the open which results in a significant environmental and ecological risk. The air contaminants emitted from manure include methane, nitrous oxide, ammonia, hydrogen sulfide, volatile organic compounds and particulate matter, which can cause serious environmental concerns and health problems.

All animal manures are valuable sources of crop nutrients and manure represents a substantial bioenergy recourse if processed by anaerobic digestion. Anaerobic digestion is a unique treatment solution for animal manure as it can deliver positive benefits related to multiple issues, including renewable energy, water pollution, and air emissions. Although, there are some important factors including pH, temperature and C: N ratio which must be considered for enhance biogas recovery. Neutral pH, mesophilic temperature of around 35°C and C: N ratio of 25:1 is considered ideal for maximum gas production.

The fresh animal manure is stored in an accumulation tank before its processing to the homogenization tank which is equipped with a mixer to facilitate homogenization of the waste stream. The consistently mixed waste is passed through a macerator to obtain uniform particle size of 5-10 mm and pumped into suitable-capacity anaerobic digesters where stabilization of organic waste happens.

5. Anaerobic co-digestion technology-review

The usage of different mixture of waste in anaerobic co-digestion for biomethane recovery has been studied and some of them are discussed in the following sections. Below is summary of some studies on anaerobic co-digestion.

5.1 Anaerobic co-digestion of organic wastes (G. Esposito, 2012)

The study carried out in the paper focused on three important aspects;

(1) the analysis of the organic substrates typically co-digested to exploit their complementary characteristics;

(2) the need of pre-treating the substrates before their digestion to change their physical and/or chemical characteristics;

(3) the usefulness of mathematical models simulating the anaerobic co-digestion process.

This study verified that combination of different organic wastes results in a better-balanced and assorted substrate in terms of nutrients. It demonstrated that pre-treatments make the organic solid wastes more accessible and degradable to microbes. A mathematical model was also developed, which can be useful externally to predict the performance of co-digestion process and as a result, it can be useful in selecting the best suitable substrates to mix and proper pretreatment methods to be applied. The pretreatment methods which were applied in this study included 'Physical pre-treatment', 'Biological and physical–chemical pre-treatment' and 'Thermal pre-treatment'.

5.2 Anaerobic digestion of dairy manure: design and process considerations (Wilkie, 2005)

Ann W. discussed in the study about the benefits of using AD system for dairy farms. In this study four different types of digester designs are described as an existing design which includes Covered lagoon, Plug-flow, Complete mix and Fixed film. This study also provided the information about different parameters for each types of digester which is summarized in Table-2.

Table 2- Digester operating parameters (Wilkie, 2005)

Digester Type	Total solids	HRT (days)	Temperature
Covered lagoon	<2%	35-60	Ambient
Fixed film	<2%	2-4	Ambient/Mesophilic
Complete-mix	3-10%	20-25	Mesophilic
Plug-flow	10-14%	20-30	Mesophilic

Note; Ambient temp.= 15-20°C and Mesophilic temp.= 30-40°C

Impact of manure characteristics were also evaluated in this study. The most important parameters for characterizing manure were reported to be total solids (TS) and volatile solids (VS) contents. The process flow for flushed manure and scraped manure digestion was also investigated in this study. The author concluded the following two main points from the study:

- AD is a unique treatment solution for animal agricultural waste. It has positive advantages in terms of renewable energy, air and water pollution.
- AD offers an environmentally sustainable solution for livestock manure management.

5.3 Biomethane potential evaluation of co-digestion of sewage sludge and organic wastes (Richard Wickham B. G., 2016)

In the study conducted by Richard Wickham B. G., 2016, it was confirmed that the suitability of the organic rich waste depends on its ability to produce biogas as well as its influence on the overall anaerobic digestion process. They used seven different organic wastes and dehydrated algae for the biomethane potential evaluation. After performing all the experiments, based on the results they obtained, they concluded that all co-substrates increased the bio-methane yield by three to six times compared with conventional anaerobic digestion of sewage sludge.

Maximum co-digestion ratios were identifiable for most solid co-substrates including algae (6% wt/wt), undiluted food waste (5% wt/wt), bakery waste (5% wt/wt), and diluted commercial food waste (10% wt/wt). The maximum co-digestions ratio of beverage rejects, and sewage sludge was 10% (wt/wt). The increase in COD removal when co-digesting wastewater sludge and liquid waste was from 2 to 41%.

5.4 Anaerobic co-digestion of cattle slurry with maize stalk at mesophilic temperature (A.O. Adebayo, 2014)

A study carried out by A.O. Adebayo, 2014 on anaerobic co-digestion of dairy manure (DM) and maize stalk. The experiment performed by authors at mesophilic temperature (37°C) by mixing cow slurry and maize stalk in the batch digester with different mixing ratios. The two substrates were co-digested at different ratios of 3:1, 1:1 and 1:3 using the percentage volatile solid of each substrate. The experiment was performed in a laboratory scale in batch mode. The biogas yields for all three samples were analyzed. The measured biogas yields for the samples with the ratios 3:1, 1:1 and 3:1 at mesophilic temperature were 0.426, 0.385 and 0.391 m^3/kg_{DM} respectively, while the methane yields were 0.297, 0.270 and 0.262 m^3 CH_4/kg_{DM} respectively. The maximum biogas yields of 0.426 m^3/kg_{DM} was obtained for the mixing ratio of 3:1 (dairy manure to maize stalks). Methane concentration for the ratios of 3:1, 1:1 and 1:3 were 69.66, 70.24 and 66.98% respectively. So, the study verified that mixing ratio of 3:1 is the optimal for the co-digestion of cattle slurry (dairy manure) and maize stalks at 37°C i.e. mesophilic temperature.

6. Material and methodology

Co-digestion of SSO and manure with different mixing ratios has been studied through a BMP assay. The experiment was performed with batch reactors in the laboratory at mesophilic temperature (37°C) as it is the most favorable temperature for methanogenic microbes according to the literatures. The batch reactors operated in working volume of 0.2L (200mL) for 52 days. During the whole process, speed of 150 RPM was applied for proper mixing. The main objective of this project was to find out the optimum mixing ratio of SSO and manure to achieve higher methane production.

6.1 Feedstocks and inoculum

Cow manure was obtained from a manure pit of a dairy farm located in New market, Ontario. SSO sample was collected from Disco Road Organics Processing Facility, Toronto, Ontario. The inoculum (seed) was obtained from Ash Bridges Bay Wastewater Treatment Plant, Toronto, Ontario. Samples were transported and preserved according to Standard Methods for the Examination of Water and Wastewater.

6.2 Characteristics of substrates and inoculum

For the design of batch reactor, characterization of the substrates and inoculum is necessary. TSS and VSS concentration was measured in triplicates corresponding to the Standard Methods for the Examination of Water and Wastewater (1999). To measure the TCOD, high range (20-1500 mg/L) COD reagent vials and HACH DR 3900 spectrophotometer were used. The TCOD analysis was conducted according to the procedure specified by HACH. Table-3 shows some of the characteristics of the substrates and the inoculum in summary.

Table 3- Characteristics of substrates and inoculum

Sample	TCOD (mg/L)	TS (mg/L)	VS (mg/L)	TSS (mg/L)	VSS (mg/L)
Inoculum	17167	16590	10180	15400	9500
Manure	106733	73727	38647	86520	47698
SSO	206267	68187	47493	56899	39478

6.3 Sample preparation

Manure slurry was prepared by addition and homogenization of cow manure with deionized distilled water using a blender. SSO samples also were homogenized using a blender and mixed with the manure slurry and the inoculum at different mixing ratios. The reactors were fed with the mixtures immediately after preparation.

6.4 Design of the batch reactors

Batch tests were carried out at five different mixing ratios in triplicates. Manure and SSO alone as control reactors, and inoculum (seed) without any feedstock were used as blank reactors in triplicates as well. Co-digestion of manure with SSO was conducted at the mixing ratios of 9:1, 7:3, 5:5, 3:7, and 1:9 on a volumetric basis. The COD equivalent for these samples are shown in the Table 4.

Table 4- TCOD of different samples

Samples	TCOD (COD eq.) (mg/L)	TCOD (COD eq.) (g/L)
Manure only	106733	107
SSO only	206267	206
M: S = 9:1	116686	117
M: S = 7:3	136593	137
M: S = 5:5	156500	157
M: S = 3:7	176406	176
M: S = 1:9	196313	196

Total sample of 200ml was filled in the reactors. The value of Food to micro-organisms ratio (F/M) was 2. The volume of the substrates and seed were calculated using the following equation. Table-5 shows the calculated volume of substrates and seed.

$$\frac{F}{M} = \frac{gTCODsubstrate}{gVSSseed} = \frac{Vsub.*TCODsub.}{Vseed*VSSseed} \qquad \text{Eq. 1}$$

$$Total\ Volume = Vsubstrate + Vseed \qquad \text{Eq. 2}$$

$$Vseed = Total\ Volume - Vsubstrate \qquad \text{Eq. 3}$$

Table 5- Design volumes of substrates and seed

Samples	Substrate Volume	Manure Volume	SSO Volume	Seed Volume
Manure only	30	30	0	170
SSO only	17	0	17	183
M: S = 9:1	28	25	3	172
M: S = 7:3	24	17	7	176
M: S = 5:5	22	11	11	178
M: S = 3:7	19	6	13	181
M: S = 1:9	18	2	16	182

Note: unit of the volume= ml

6.5 Biochemical methane potential (BMP) assay

An experimental study, using anaerobic batch reactors were carried out at mixing speed of 150 RPM, in triplicates under mesophilic temperature, which is most favorable condition for methanogenic microbes. To achieve the best mixing ratio of SSO and manure for effective biogas production five different mixing ratios were tested in triplicates. Manure and SSO were also tested alone as a control reactor in triplicates. The experimental setup is shown in Figure 8. The following table shows the details about the bioreactors.

Table 6- Designed ratios for manure and SSO

Bottle No.	M: S ratios
1, 2, 3	Manure only
4, 5, 6	SSO only
7, 8, 9	M: S = 9:1
10, 11, 12	M: S = 7:3
13, 14, 15	M: S = 5:5
16, 17, 18	M: S = 3:7
19, 20, 21	M: S = 1:9

Figure 8. Experimental setup for BMP test

6.6 Data collection and analysis

The experiment has been carried out on a laboratory scale. Gas measurement was carried out on daily basis. The gas was measured by using 100 ml Gastight Luer-Lock syringe at the initial stage of the experiment, because of higher gas production. But, in the final stage of the experiment (i.e. last 10-15 days); the gas production was lower so, gas was measured using 50 ml Gastight Luer-Lock syringe for the most accurate readings. Then, the measured biogas data was analyzed to find the most suitable mixing ratio of manure and SSO; for maximum methane production rate.

For the data analysis, amount of daily methane production is required. Theoretical approach was used to find methane production on the daily basis. For the first five days, the amount of methane produced is 10, 20, 30, 40 and 50% of the biogas respectively. From the 6th day onwards, the amount of methane is 60% of the biogas. Then, this data of methane production was used for the analysis of cumulative methane production, maximum methane production rate and different kind of methane yields. The data for the biogas production is shown in table 7. The table shows the average biogas measurement on daily basis with respect to different mixing ratios.

Table 7- Average biogas measurement at different mixture ratio(mL)

Day	Manure only	SSO only	M:S = 9:1	M:S= 7:3	M:S=5:5	M:S = 3:7	M:S=1:9
1	126	97	124	130	110	117	99
2	133	120	90	115	67	136	124
3	119	138	76	93	62	135	142
4	72	91	62	62	61	80	90
5	68	83	56	58	51	73	82
6	72	75	72	70	69	76	77
7	57	57	56	55	55	58	61
8	37	44	39	37	38	38	44
9	36	47	37	36	39	35	43
11	42	47	47	42	52	39	45
12	24	22	31	26	37	22	22
14	31	20	39	31	47	24	22
15	16	11	25	18	28	14	12
16	11	8	19	14	21	9	8
17	10	7	17	12	20	8	7
18	11	7	17	13	19	9	7
20	16	11	25	20	29	14	12
21	11	8	19	15	20	9	8
22	8	5	14	10	16	7	6
23	7	6	11	9	12	6	5
24	7	4	11	9	12	6	5
25	8	6	11	9	13	8	6
26	8	4	11	9	12	6	5
28	13	7	16	12	16	10	8
29	7	5	11	9	12	6	6
30	7	4	10	8	10	6	5
31	3	3	7	5	9	3	2
32	6	4	8	7	8	6	3
35	11	7	15	13	17	10	8
37	13	9	10	11	7	7	15
40	11	7	15	12	16	10	8
43	12	8	16	13	18	11	8
46	10	5	13	12	14	9	8
49	10	4	12	10	13	9	7
52	9	6	12	10	12	8	7

Using theoretical approach methane measurement was calculated. So, the methane measurement on the daily basis is presented in table 8.

Table 8- Average methane measurement at different mixture ratio (mL)

Day	Manure only	SSO only	M:S =9:1	M:S =7:3	M:S = 5:5	M:S =3:7	M:S =1:9
1	13	10	12	13	11	12	10
2	27	24	18	23	13	27	25
3	36	41	23	28	19	41	43
4	29	36	25	25	24	32	36
5	34	42	28	29	26	37	41
6	43	45	43	42	41	46	46
7	34	34	34	33	33	35	37
8	22	26	23	22	23	23	27
9	22	28	22	22	23	21	26
11	25	28	28	25	31	23	27
12	15	13	19	15	22	13	13
14	19	12	23	19	28	14	13
15	9	7	15	11	17	8	7
16	7	5	11	8	13	6	5
17	6	4	10	7	12	5	4
18	7	4	10	8	11	6	4
20	10	7	15	12	17	8	7
21	7	5	11	9	12	6	5
22	5	3	8	6	9	4	4
23	4	4	6	5	7	4	3
24	4	3	7	6	7	4	3
25	5	4	7	5	8	5	4
26	5	3	7	5	7	4	3
28	8	4	9	7	10	6	5
29	4	3	6	5	7	4	3
30	4	3	6	5	6	4	3
31	2	2	4	3	5	2	1
32	4	2	5	4	5	3	2
35	7	4	9	8	10	6	5
37	8	5	6	7	4	4	9
40	7	4	9	7	10	6	5
43	7	5	9	8	11	6	5
46	6	3	8	7	8	5	5
49	6	2	7	6	8	5	4
52	5	3	7	6	7	5	4

Table 9 shows the methane production rate.

Table 9- Methane production rate at different mixture ratio (mL/day)

Day	Δt	Manure only	SSO only	M:S = 9:1	M:S = 7:3	M:S=5:5	M:S = 3:7	M:S = 1:9
1	1	13	10	12	13	11	12	10
2	1	27	24	18	23	13	27	25
3	1	36	41	23	28	19	41	43
4	1	29	36	25	25	24	32	36
5	1	34	42	28	29	26	37	41
6	1	43	45	43	42	41	46	46
7	1	34	34	34	33	33	35	37
8	1	22	26	23	22	23	23	27
9	1	22	28	22	22	23	21	26
11	2	13	14	14	13	16	12	14
12	1	15	13	19	15	22	13	13
14	2	9	6	12	9	14	7	7
15	1	9	7	15	11	17	8	7
16	1	7	5	11	8	13	6	5
17	1	6	4	10	7	12	5	4
18	1	7	4	10	8	11	6	4
20	2	5	3	8	6	9	4	4
21	1	7	5	11	9	12	6	5
22	1	5	3	8	6	9	4	4
23	1	4	4	6	5	7	4	3
24	1	4	3	7	6	7	4	3
25	1	5	4	7	5	8	5	4
26	1	5	3	7	5	7	4	3
28	2	4	2	5	4	5	3	2
29	1	4	3	6	5	7	4	3
30	1	4	3	6	5	6	4	3
31	1	2	2	4	3	5	2	1
32	1	4	2	5	4	5	3	2
35	3	2	1	3	3	3	2	2
37	2	4	3	3	3	2	2	5
40	3	2	1	3	2	3	2	2
43	3	2	2	3	3	4	2	2
46	3	2	1	3	2	3	2	2
49	3	2	1	2	2	3	2	1
52	3	2	1	2	2	2	2	1

7. Results and discussion

The measured data was analyzed to find methane production rate, cumulative methane production and methane yields. The results of the experiment are discussed in the following sections.

7.1 Methane production rate

The methane production rate for manure, SSO and different mixing ratios are shown in figure 9. All the samples have similar behavior for the methane production. The samples with higher content of manure have gradual increase in the methane production rate at initial stage. But, the samples with higher SSO content have sudden increase in the methane production in the initial stage. For all the different mixtures the maximum methane production occurred after 6 days.

Figure 10 shows the maximum methane production rate for the different mixing ratios. The samples with the ratio of M: S= 1:9 and M: S= 3:7 have the maximum methane production rate of 46 mL/day. The sample with mixing ratio of M:S=5:5 has the lowest methane production rate of 41 mL/day among all other samples. As the amount of SSO is more, the methane production rate is higher. By adding manure with the SSO, we can increase the methane production rate.

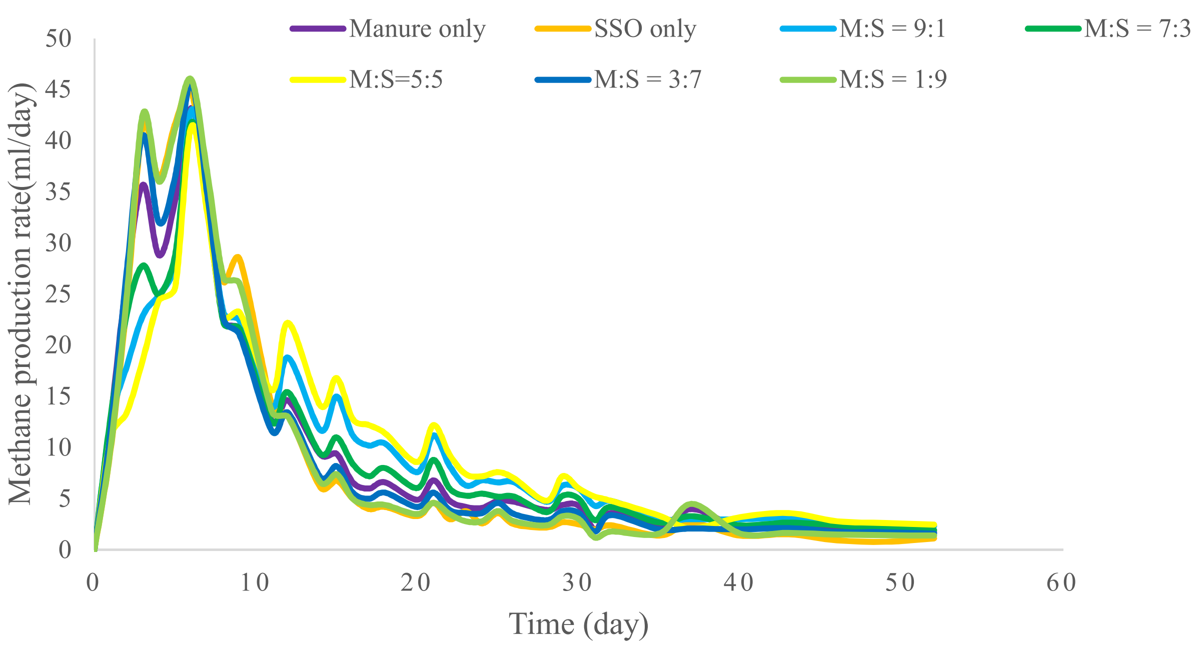

Figure 9. Methane production rate at different mixture ratio

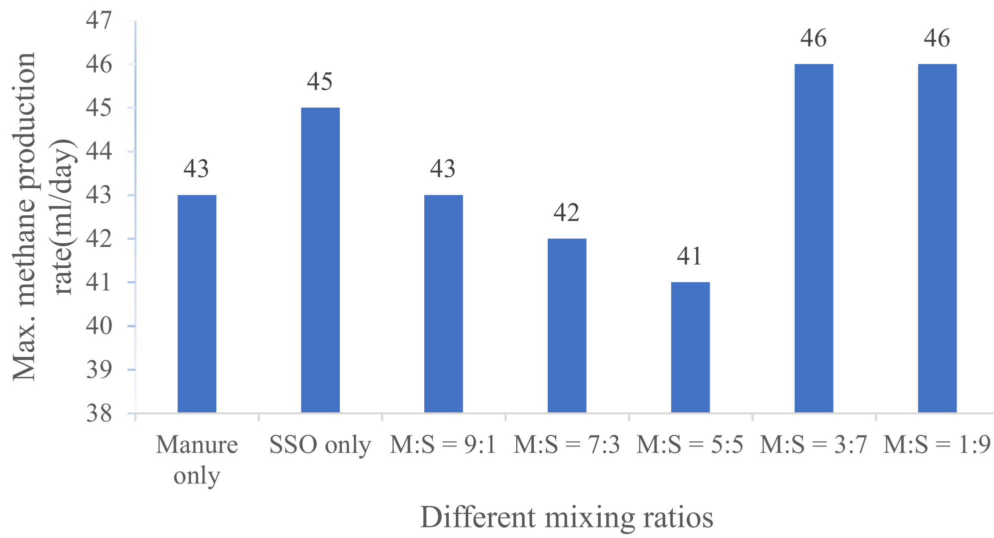

Figure 10. Maximum methane production rate

7.2 Cumulative methane production

The cumulative methane production is presented in the figure below. Figure shows the comparison of cumulative methane production at different co-digestion ratios of manure/SSO. The ultimate cumulative methane production of 507 mL CH_4 for M: S = 5:5, while this value was 453 mL CH_4 for manure and 428 mL CH_4 for SSO alone.

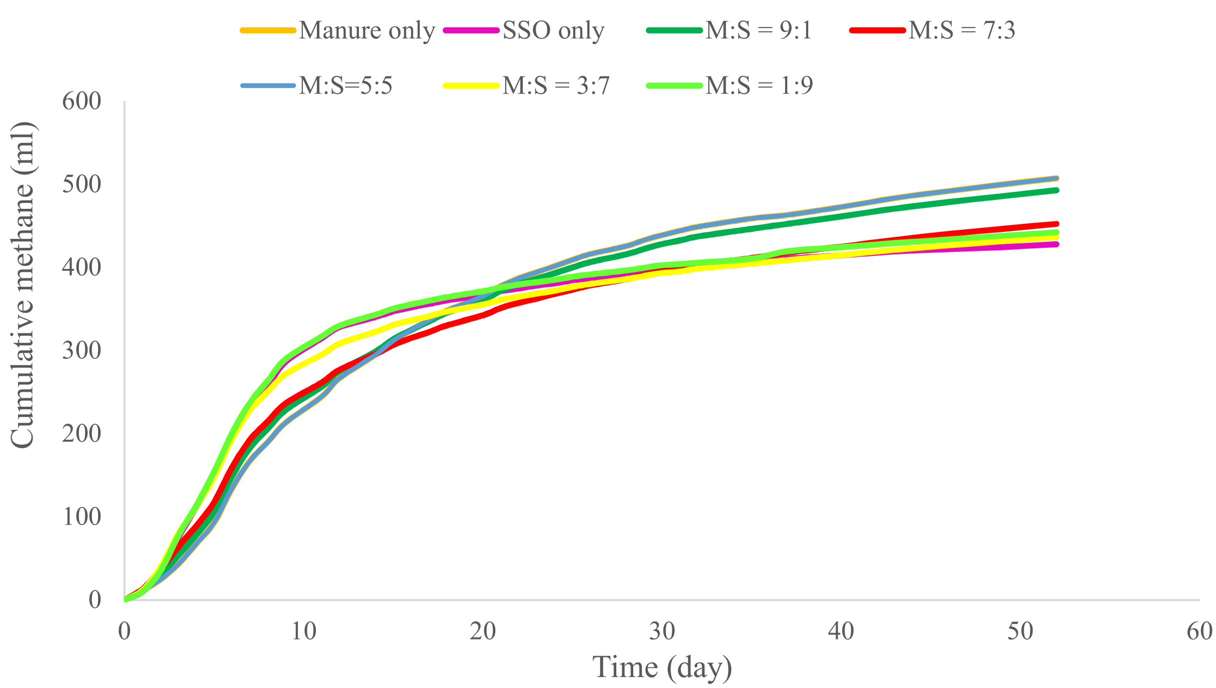

Figure 11. Cumulative methane production at different mixing ratios

7.3 Methane yields

Different types of methane yields were calculated. The following figures shows the methane yields in form of mL CH4/ mL substrate added, mL CH4/g VSS added and mL CH4/ g TCOD added. Methane yield as mL CH4/ mL substrate added was lowest for manure only sample. As the amount of SSO added with manure increased the methane yield as mL CH4/ mL substrate also increased. Same kind of behavior was observed for the methane yield as mLCH4/g VSS added, with the maximum value of 653.58 mLCH4/g VSS added for SSO only sample.

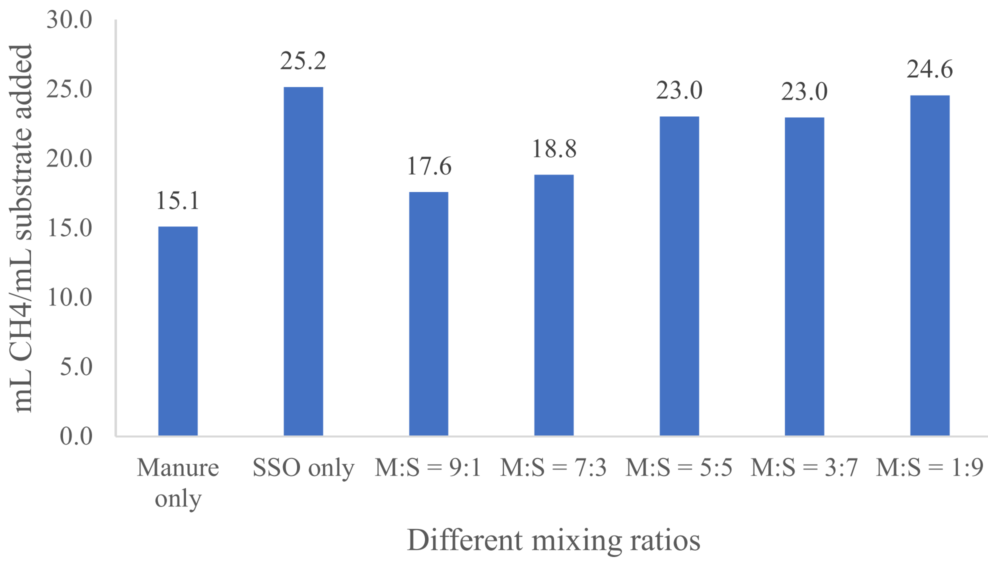

Figure 12. Methane yield (mLCH4/mL substrate added)

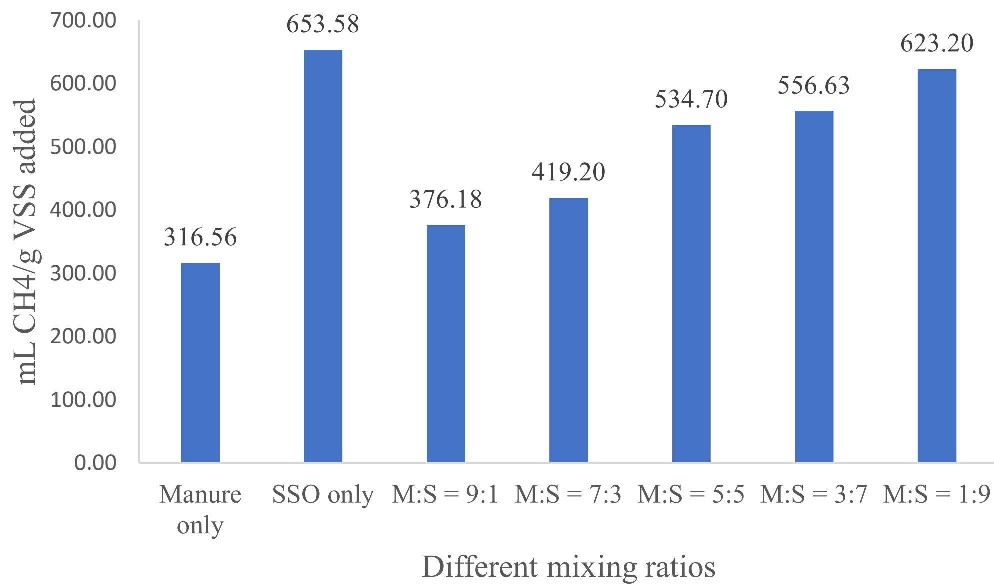

Figure 13. Methane yield (mLCH4/g VSS added)

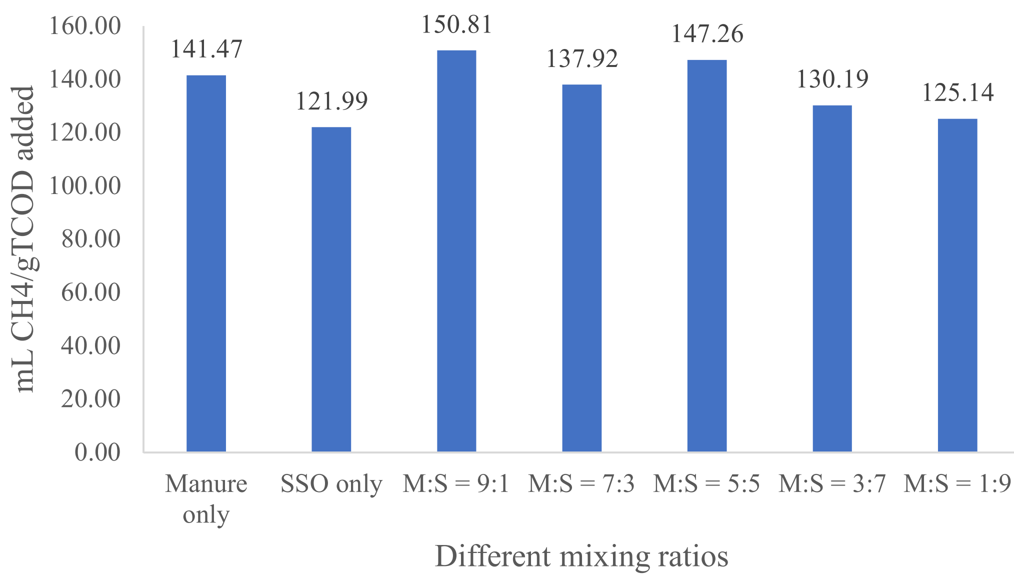

Figure 14. Methane yield (mLCH4/g TCOD added)

The maximum methane yield of about 150 mLCH4/g TCOD added was observed for the manure and SSO ratio of 9:1. As the amount of manure decrease in the sample, that value was also decreased to 125 mLCH4/g TCOD added.

7.4 Percentage increase in methane production

The following table shows the % increment in the cumulative methane production for the different mixing ratios. For the mixing ratio of M: S= 9:1, the cumulative methane production was increased to 10% and for the M: S= 5:5 it was 15%.

Table 10- % increase in cumulative methane production

Mixture Ratio	Measured cumulative CH4 production	Calculated cumulative CH4 production	% increase (%)
Manure only	453	N/A	N/A
SSO only	428	N/A	N/A
M:S = 9:1	493	450.9	9.3
M:S = 7:3	452	445.8	1.4
M:S = 5:5	507	440.7	15.1
M:S = 3:7	436	435.6	0.1
M:S = 1:9	442	430.5	2.7

8. Conclusion

Co-digestion can result in a significant increase of the bio-methane potential when the substrates mixture is prepared with proper percentages of the different organic substrates to be digested. Co-digestion results higher methane yields and improves the quality and quantity of methane content when compared to the single waste digestions. A constant rate for the digestion process can be sustained and it avoids the digester to be underloaded or overloaded. By using co-substrates more gas can be produced and subsequently more electricity will be obtained at only marginal cost. The excess of electricity produced can be utilized to supply the energy demands of waste water treatment avoiding extra cost.

The ultimate cumulative methane production of 507 mL CH_4 for M: S = 5:5, while this value was 453 mL CH_4 for manure and 428 mL CH_4 for SSO alone. The ultimate cumulative methane production of 493 mL was observed for the sample having ratio of M: S=9:1. The maximum methane yield of about 150 mLCH4/g TCOD added was observed for the manure and SSO ratio of 9:1. The maximum percentage of increase in the cumulative methane production was about 15% for the sample having mixing ratio of M:S=5:5.

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Glossary

AD	Anaerobic Digestion
AcoD	Anaerobic Co-digestion
SSO	Source Separated Organics
TCOD	Total Chemical Oxygen Demand
VSS	Volatile Suspended Solid
BMP	Biochemical Methane Potential
COD	Chemical Oxygen Demand
K	Potassium
N	Nitrogen
P	Phosphorus
pH	Power of Hydrogen