EVALUATION OF THE PERFORMANCE OF DIFFERENT ANAEROBIC DIGESTION TECHNOLOGIES FOR SOLID WASTE TREATMENT

Mariana Chavez-Vazquez[1] and David M. Bagley[1]

[1]Department of Civil Engineering, University of Toronto
35 St. George St., Toronto, Ontario M5S 1A4

ABSTRACT

The anaerobic digestion of solid wastes is now a widely-used technology in Europe with more than 50 full-scale plants operating. However, anaerobic solid waste digestion is still used to only a limited extent in North America with only three facilities in Canada. Because of the expected importance of anaerobic digestion in the future for energy recovery, reliable tools are required to evaluate the different available technologies, as well as the feed stocks that are suitable for treatment. Therefore, this paper presents a framework that has been developed for evaluating anaerobic solid waste digestion. To develop the framework, a review of the performance of digestion processes was first conducted. Because the data presented were for very different operational parameters (retention time, temperature, configuration set up, mixing, etc.) as well as substrates used for digestion, a standard method of comparison was developed. Gas production per Mg input, organic loading rate and percent volatile solids removal were identified as useful standard parameters for evaluating the performance of different technologies. This framework was constructed as a spread sheet and can be used for different set ups (configuration, organic loading rate, etc.) and with different substrates. It can predict, based on the input and using mass balances, the mass of products of the digester including biogas, treated solids and water. This framework provides a useful tool for evaluating the technical capabilities of different technologies, predicting the quantity of the products, and ultimately, making decisions as to which technologies best meet local needs.

Keywords: Anaerobic digestion; municipal solid waste; biogas production; decision making.

INTRODUCTION

The growth of population and urbanization has aggravated the problem of the management of municipal solid wastes. Many methods of disposal present some disadvantages. In many places landfills are approaching their design capacity and due to their environmental impact, like groundwater contamination through leachate migration and the release of the landfill's methane production to the atmosphere, many are facing closure. Incineration and pyrolysis present problems of air pollution and high initial investments. One of the most accepted alternatives to reduce the amount of solid wastes that need final disposal is the use of massive recycling programs. However, even when the quantity of wastes is reduced after recycling there is still an organic fraction that remains in the waste stream to be disposed. This organic fraction presents special challenges for disposal when trying to use conventional methods.

Anaerobic digestion emerges as an another alternative for treating the organic fraction of solid wastes. Anaerobic microbial processes occur in environments that are devoid of oxygen including the bottom of lakes, in swamps and in landfills. Anaerobic processes are recreated at the industrial scale by controlling parameters such as temperature, humidity, microbial activity and the waste used as feedstock. Anaerobic processes can convert the organic biodegradable fraction of the municipal solid waste into a high methane content biogas and an stable residue that can be upgraded to compost quality. Anaerobic digestion does not release green house gases (GHG) to the atmosphere, but captures them for energy generation purposes. Another aspect that can be enhanced is that the use of biogas as an energy source helps to offset the GHG emission associated with energy production using fossil fuels.

Anaerobic digestion is widely used in Europe, and is expanding to the rest of the world including North America. The treatment capacity for organic solid wastes evolved from 122,000 Mg/year in 1990 to 1,037,000 Mg/year in 2000 (De Baere, 2000). During this time, 30 plants were constructed in Germany (total of 33), nine in Switzerland (total of 11), three in Belgium, one in France (total of 2) and four in the Netherlands (IEA, 2002). Additionally anaerobic digestion of organic wastes occurs in Austria (4 plants), Finland (1 plant), Italy (3 plants), Spain (2 plants) and Sweden (4 plants). Denmark also anaerobically digests organic material but primarily animal manures. While France, Belgium and the Netherlands have few plants the average capacity is 50,000 Mg/plant/year. In Switzerland, the plants have capacities in the range of 5,000 to 13,000 Mg/year. All the plants working in Europe use patented European technologies.

In North America, there are only three plants that use anaerobic digestion for processing solid wastes. All of these plants are located in Ontario, Canada. Two of these plants use BTA technology (German patent) one is located in Newmarket and the other in the Dufferin Transfer Station in Toronto. The other facility is located in Guelph, and uses SUBBOR, a Canadian technology. In the case of the US, there are around 95 farms using anaerobic digestion to treat animal waste (Lusk, 1999), but there are no reports of facilities treating residential waste.

Many designs have been tested for anaerobic digestion of municipal solid waste (MSW). All these designs have different key issues, such as reactor solids concentration, organic loading rate, mixing process, retention time, number of phases, etc. Because of the diverse characteristics of all the designs, it is very difficult to evaluate their performance in a systematic way. Therefore, this paper presents a framework that has been developed for evaluating anaerobic solid waste digestion. This framework can be used to predict the mass of products of the digester including biogas, treated solids and water for existing digestion processes. These predictions should assist decision makers that must choose a technology that best meets their local needs.

PROCESSES FOR SOLID WASTE DIGESITON

The commercial options for anaerobic digestion can be classified according to the solids content in the reactor. Systems where the feedstock is diluted to 10-15% solids in the digester are considered wet while systems with a solids content of 20-40% are considered dry. Digestion systems are also classified based on the number of phases that contain the digestion process. This classification recognises one phase and two-phase systems. Finally, the digestion systems can be classified according to the temperature at which the process is conducted. Systems operated near 35°C are considered mesophilic while those operated above 50°C are considered thermophilic.

In wet systems, the organic solid waste is diluted to less than 15% TS in the reactor. Digesters of the CSTR-type (completely stirred tank reactor) are primarily used (Lissens et al, 2001). These designs have been used for sewage sludges, animal slurries, and industrial wastes. The major disadvantages include washout of unreacted solids and microorganisms, mixing problems, and liquid heating and disposal requirements (Chynoweth and Pullammanappallil, 1996). These processes can be run under mesophilic or thermophilic temperatures. One-phase wet technologies are sold by Waasa and BTA.

In dry systems, the solid content in the reactor is kept in the range of 20-40 %TS. All the designs recycle part of the digested residues which are mixed with the feed for inoculation (Chynoweth and Pullammanappallil, 1996). Due to their high viscosity, the fermenting wastes move via plug low inside the reactors, which offers the advantage of technical simplicity as no mechanical devices need to be installed within the reactor (Lissens et al., 2001). These processes can be run under mesophilic or thermophilic temperatures. One-phase dry technologies are sold by Valorga (mesophilic), Dranco (thermophilic) and Kompogas (thermophilic).

The two-phase systems physically separate the phases that occur during anaerobic digestion. Usually, the first reactor is a liquefaction-acidification compartment and the second is the acetogenic and methanogenic compartment. When separating the phases, it is possible to enhance the rate of methanogenesis by designing the second reactor with a biomass retention scheme or other method (Weiland, 1993). The main advantage of two-phase systems is that they are very stable for highly degradable wastes such as fruits and vegetables (Pavan et al., 2000). However, one-phase systems can be as reliable as two-phase systems for the same kind of wastes if the operational parameters are carefully adjusted. The major disadvantage of two-phase systems is that they are more complex and do not present higher biogas yields than those achieved by one-phase systems. These processes can be run under mesophilic or thermophilic temperatures. Two-phase technologies are sold by BTA (mesophilic), PACQUES (mesophilic) and BRV (thermophilic). A novel two-phase system where both phases are methanogenic and are separated by a steam disruption step is solid by SUBBOR.

In batch systems, the digesters are filled with wastes mixed with an inoculation material, usually taken from the previous run. Once the digester is filled, it is closed and the reaction is allowed to go to completion. The reactors using this system have chambers under them that allow the collection of leachate that is sprayed on top of the wastes that are being digested. This system is similar to a landfill cell, but it controls the leachate re-circulation and is conducted at a higher temperature than in a landfill. This process is conducted at mesophilic temperature. Batch systems are sold by Biocel.

Leaching bed systems are sequential batch reactors that recycle leachate between new and mature reactors to inoculate and provide humidity to new cells. Organic acids produced during start-up of a new reactor are re-circulated via leachate to an older reactor for methanogenesis. The leachate of the older reactor, acid free and full with bicarbonates that act as pH buffer is then recirculated to the new reactor (O'Keefe et al., 1993). This technology (SEBAC) was developed at the University of Florida and has not yet been used at commercial scale.

Almost 60% of the plants currently working in Europe, are working under the one-phase dry scheme. The use of two-phase systems is limited due to the complexity of the operation and the higher investment needed. Only 10.6% of the facilities operate under this scheme (De Baere, 2000).

DEVELOPMENT OF THE FRAMEWORK

To develop the framework, a review of the performance of digestion processes was first conducted. This review examined the results reported for both lab and full-scale systems. Once information about the operational parameters for each technology and the biodegradability of different available substrates was collected, the framework was developed as an spread sheet. One spread sheet was constructed for each one of the technologies chosen for evaluation. This spread sheet can predict, based on the input and using mass balances, the mass of the products of the digester including biogas, treated solids and water. In the next sub-sections a description of each one of the technologies chosen is presented. Then descriptions of how the mass balances were conducted and the process that was used to develop the framework are presented and discussed.

Selection and Description of Technologies

The technologies selected for evaluation in this paper are the Dranco, Kompogas, Valorga, BTA, Biocel, and SUBBOR processes. Dranco, Kompogas and Valorga are one-phase dry technologies, which are the most common configuration used at industrial scale. The BTA technology represents the one-phase wet configuration and the Biocel is the only technology that works as a batch reactor. These five technologies were developed in Europe and have full-scale operating facilities. SUBBOR was developed in North America and currently has one facility in Canada.

The Dranco (Dry Anaerobic Composting) process is a one-phase dry process that was developed in Gent, Belgium. Feed is introduced daily into the top of the reactor and the digested waste is removed from the bottom at the same time. Part of the digested waste is used as inoculum while the rest is dewatered to obtain an organic compost material. There are no mixing devices in the reactor other than the natural downward movement of the waste (Soton 2002). This process focuses on the conversion of the organic fraction of the municipal solid wastes to energy and a humus-like final product, called Humotex (Six and De Baere, 1992). The operating temperature is 55 ^{o}C, the total solids concentration is 32% and the residence time is aroud 18 days. The process produces approximately 100 m^3 biogas/Mg input (Six and De Baere, 1992). This system has seven facilities working in Germany, Belgium, Switzerland and Austria.

The Valorga System is a one-phase dry process that was developed in France. The reactor has a cylindrical shape with an horizontal plug flow. The mixing of the waste occurs through high pressure biogas injection every 15 min. Process water is re-circulated to achieve a solids content of 30%. The Valorga process is ill suited for relatively wet wastes because sedimentation of heavy particles inside the reactor takes place when the total solids content is less than 20% (Lissens et al., 2001). The residence time is between 18-25 days at 37^{o} C. Some of the biogas is pressurised and pumped back into the reactor to improve mixing. The rest of the biogas is transported to an upgrading plant, where it is refined to natural gas quality.

The Kompogas system is a one-phase dry process that was developed in Switzerland. The reactor is also an horizontal cylinder which is fed daily. After the impurities are removed.

the organic wastes are shredded mechanically and press-water from the dewatering unit is added to adjust the water content. The movement is in a horizontal plug flow manner, with the digested material being removed from the far end of the reactor after approximately 20 days. This flow is aided by rotating impellers inside the reactors. This process is run at 55^{o} C and the system requires a careful adjustment of the solids content in the reactor to 23%.

The BTA system was developed in Germany for the digestion of the organic fraction of municipal solid waste. The process consists of two major steps: mechanical wet pre-treatment and the biological conversion. During the mechanical pre-treatment the contaminants are removed, and the solids are diluted in pulpers to a 10% content. The pasteurisation of food waste (70 ^{o}C, 30 min) is an integrated function of the pulpers. The biological process can be a single or multiple phase depending on the size of the plant. In the one-phase process, the pulp is processed in one mixed fermentation reactor where it is digested for around 15 days. In the multi-phase process the pulp is separated into solid and liquid. The liquid components are fed into a methane reactor and the solid content into a hydrolysis reactor. Both options are at 35 ^{o}C (BTA, 2002). The digester is completely mixed by biogas injection. The digested solids are dewatered by a decanter centrifuge. A part of the centrate is directly used in the waste pulper as process water. The remaining centrate is cleaned by an aerobic biological wastewater treatment system. The effluent is either used for the treatment of the waste or transferred to a municipal sewage plant (Kubler et al., 2000).

The Biocel process is a high solids batch process operated at mesophilic temperatures. The wastes are kept within the digestion vessel until biogas production ceases. In the plant located in Lelystand, the Netherlands this is achieved in 21 days. Temperature control is done by re-circulation of the leachate heated to 40^{o}C (Ten Brummeler, 2000). The solids content in the digester is 35%. One limitation of the process is the plugging of the perforated floor, resulting in the blockage of the leaching process.

The SUBBOR (Super Blue Box Recycling Corp.) process was developed in Canada. The process introduces the wastes previously mixed with inoculum to a thermophilic digester for around 35 days with a solids concentration of 25%. After this primary digestion, the wastes are steam disrupted at 240^{o}C for five minutes. This steam disruption involves the heating of the material to a temperature above the boiling point of water under pressure, followed by a rapid depressurization. This treatment at very high temperature improves the hydrolysis of cellulose and hemi-cellulose compounds and facilitates the anaerobic digestion of solid wastes. After this, the wastes are sent through a 15 day secondary digestion which yields a biogas production 40% larger than that obtained in the primary digestion (Liu et al., 2002).

Mass Balance

An overall mass balance can be constructed to examine the products from the anaerobic digestion of solid wastes (Figure 1).

Solid wastes entering the digester consist of organic material, inorganic constituents and water. During digestion a fraction of the volatile solids are converted into biogas. The biogas consists primarily of methane and carbon dioxide. Other compounds that are present in the biogas such as hydrogen sulfide are practically important but due to their low fraction will not be considered in the framework when calculating the volumetric weight of the biogas. Also leaving the digester are the digested residue, waste waster and non-recyclables. The digested residue consists of the volatile solids that were not converted into gas, any microbial biomass formed and the fraction of the total solids that was not digestable. The amount of waste water that comes out of the digester will change depending on the technology used.

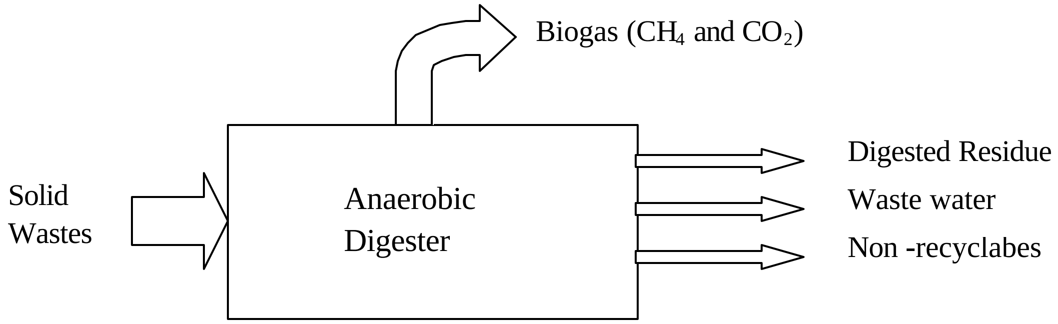

Figure 1. Mass Balance of Anaerobic Digestion

Based on the mass balance shown in Figure 1, a basic model to predict the amount of each product was constructed (Figure 2). The first step (Figure 2-1) is to determine the composition and characteristics of the feedstock used for the anaerobic digestion. For this framework, the composition was take from the basic components of the organic fraction of

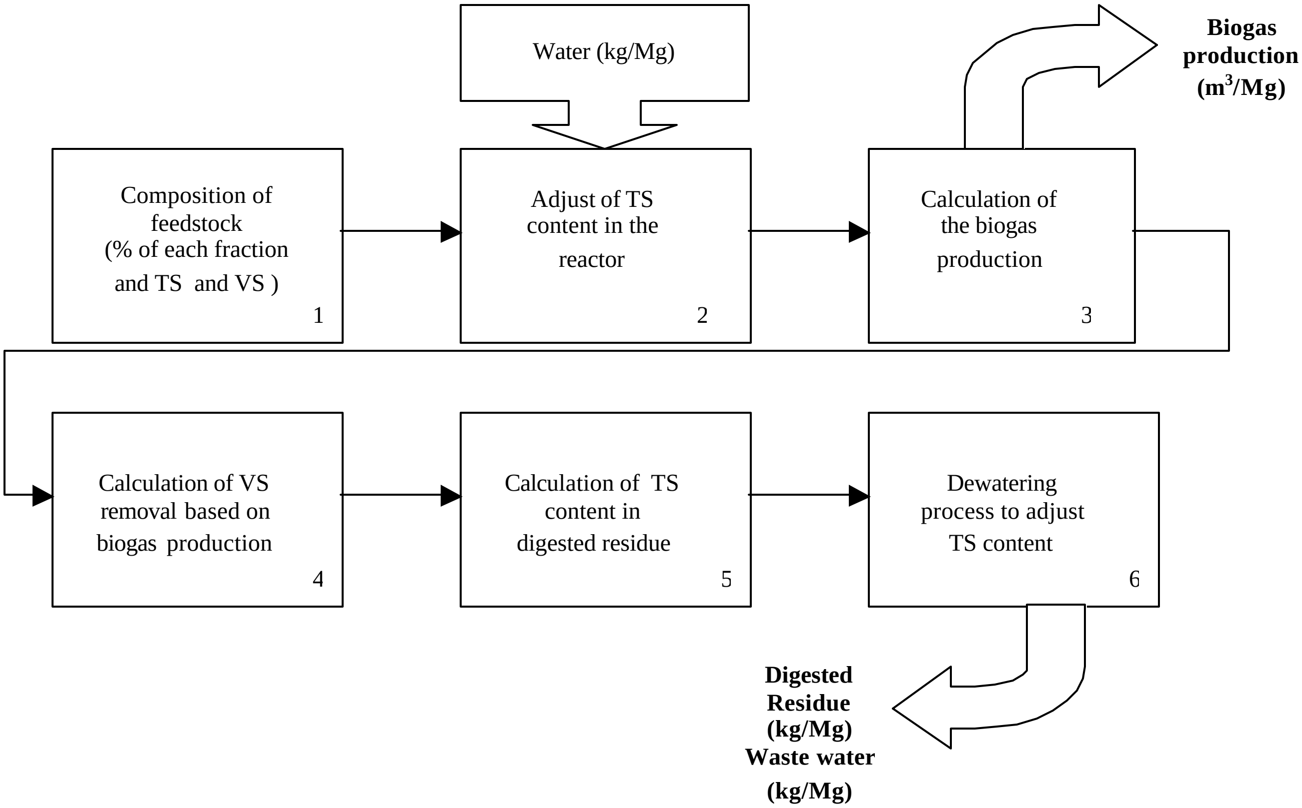

Figure 2. Conceptual map of the framework construction

MSW: kitchen waste, garden waste and paper and cardboard. The total and volatile solids of each fraction is then provided by the user if available, or it is calculated by the framework using average values obtained from the literature.

Once the solids content of the feedstock is established, it must be adjusted to the design solids content in the reactor (Figure 2-2). The solids content in the reactor is different for each technology and is specified by the manufacturer. The solids content is adjusted by the addition to water to the wastes.

After the solids content is adjusted, the feedstock is treated anaerobically inside the reactor. This anaerobic digestion converts part of the volatile solids to biogas (Figure 2-3). Based on the biogas production, the volatile solids removal is calculated (Figure 2-4). This information is necessary to later calculate the digested residue quantity. Both the biogas production calculation and the volatile solids removal calculation are discussed in subsequent sections.

After the volatile solids removal is calculated, it is possible to calculate the solids content in the digested residue (Figure 2-5). From that the amount of water to be removed by dewatering to achieve the design solids content in the residue can be determined (Figure 2-6).

Biogas Production

The quality of the organic fraction of the municipal solid wastes highly impacts the rate of conversion that might be achieved during the anaerobic digestion. The main components of the organic fraction are kitchen waste, garden waste and paper and cardboard. The biogas production will depend on the percentage of each one of these fractions. The quantity and quality of this organic fraction will change from place to place depending on the type of collection system that is used (source sorted or mixed collection), the geographical area (rural or urban), seasonal and even from one country to another. Cellulose conversion is the rate limiting step in anaerobic digestion of municipal solid waste (Peres et al., 1992) so, the garden wastes (GW) are the hardest to degrade due to their high cellulose content, followed by the paper and cardboard (PC), with kitchen wastes (KW) being the most readily degradable.

To calculate the biogas production for each technology, information about different facilities working with the same technology was compiled. This information included the percentage of each component of the organic fraction that was fed to the digester and how much biogas was produced per Mg of volatile solids. With these data, the biogas production of each component was calculated. When sufficient data were available, Equation 1 was solved for KW_i, GW_i and PC_i.

$$X_iKW_i+Y_iGW_i+Z_iPC_i= G_i \tag{1}$$

Where:

G_i = Total biogas produced for facility i (m^3 biogas/Mg VS influent)
KW_i= Biogas production for kitchen waste fraction for facility i (m^3/Mg VS)
GW_i= Biogas production for garden waste fraction for facility i (m^3/Mg VS)
PC_i = Biogas production for paper and cardboard fraction for facility i (m^3/Mg VS)
$X_{i=}$ Percentage of kitchen waste for facility i
$Y_{i=}$ Percentage of garden waste for facility i
$Z_{i=}$ Percentage of paper and cardboard for facility i

When insufficient information was available to solve Equation 1, a linear approximation approach was used to estimate KW_i, GW_i and PC_i. Ratios relating the value obtained for the biogas production of the organic fraction of the municipal solid wastes (OFMSW) that was provided for all the technologies to the biogas production of the different fractions (e.g. Kitchen Waste biogas production/OFMSW biogas production) were developed. The set of data that was used as the basic standard for comparison was that obtained for the Valorga system. This set was used because it was considered to be the one with the most reliable results (Saint-Joly et al., 2000).

The first step was to compare the values of biogas production for the OFMSW of the Valorga technology and any other and find the ratio between them. Once this relation was established, the ratios of production between the different fractions (kitchen waste, garden waste, paper and cardboard) were adjusted with this relation.

The biogas production numbers that were obtained with these two approaches, were cross-checked with information available from different researchers about the biodegradability of these fractions at lab and pilot scale.

Digested Residue and Waste water

The predicted mass of the digested residue was calculated from the biogas production using Equation 2.

$$DR_i = A_i + \{V_i - [(X_i KW_i V_i + Y_i GW_i V_i + Z_i PC_i V_i) x (1.178 \times 10^{-3} \text{ Mg gas/m}^3 \text{ gas})]\} \qquad (2)$$

Where:

DR_i = Digested residue in facility i, Mg
A_i = Non biodegradable solids (Mg) = total influent solids – volatile influent solids
V_i = Influent volatile solids (Mg)

Mass of volatile solids removed was estimated by converting the cubic meters of biogas produced into Mg of biogas by assuming that the biogas was 55% methane and 45% carbon dioxide. This average composition was assumed to be the same for all the systems for the purpose of this paper, however it might change at full scale depending on the feedstock used. Any other trace compound was neglected. The calculation was done at 23 ^{o}C and provides a gas density of 1.178 kg of biogas per cubic meter. The mass of volatile solids remaining was then taken as the difference between the entering volatiles solids and the volatile solids converted to biogas. This was added to the non-biodegradable influent mass.

The wastewater produced by the process was calculated for each technology. It depended on the TS content to which the final product was adjusted which is different for each technology. Only the difference between the water produced during dewatering and the water needed for initial dilution will be considered wastewater.

EXAMINATION OF SELECTED TECHNOLOGIES

Following the criteria detailed in the previous section, the biogas production was calculated for the different technologies. The results obtained for the different fractions are summarized in Table 1.

Table 1. Biogas production for the different components of the organic fraction of MSW

Biogas Production (m^3/Mg VS)	Valorga	Kompogas	Dranco	BTA	Biocel	SUBBOR
Kitchen waste	634	460	671	695	498	880
Garden waste	211	152	426	230	166	293
Paper and Cardboard	353	256	485	385	277	490

The results obtained for the biogas production of kitchen wastes are in the range of 460 to 695 m^3/Mg VS depending on the technology used. These results can be compared with the results obtained by different researchers to cross-check their reliability. The low range is similar to results obtained at lab scale digesting fruit and vegetable wastes, like apricot, corn, apple, asparagus and pineapple that ranged between 446 and 585 m^3/Mg VS (Lane, 1984). Other studies that can be used to compare these results are Cecchi et al. (1986) and Pavan et al.(2000). Both of these studies used wastes collected from a representative area in Treviso, Italy. The first paper used a single phase mesophilic reactor and obtained a 640 m^3/Mg VS yield while the second paper used a single phase thermophilic reactor and obtained 780 m^3/Mg VS.

In the case of the garden wastes, the biogas production for the different technologies is predicted to be in the range of 152-426 m^3/Mg VS. Results of previous studies using garden waste and woody biomass in batch essays can be compared with the results obtained for the different technologies. In the case of garden waste (grass, leaves and branches) biogas production ranged between 123 and 209 m^3/Mg VS (Owens and Chynoweth, 1993). For woody biomass, the results obtained were higher. In another study conducted by Chynoweth and Jerger (1985), the highest biogas yields (considering a 60% methane content) of 530 m^3/Mg VS were achieved from hybrid poplar and sycamore species, while red and black alder achieved 470 and 400 m^3/Mg VS. The results of both studies are expected to be higher than those for full scale technologies because batch assays were conducted with very long retention times.

For the paper and cardboard fraction, the predicted biogas production ranged between 255 and 485 m^3/Mg VS. These results are in the same range as those obtained by Vermeulen et al. (1993) for different types of paper and cardboard. The type of paper that showed the lowest biogas production was newsprint (139 m^3/Mg VS), while brochure, magazine and packing paper showed higher productions (208, 327 and 381 m^3/Mg VS). The highest production was for computer paper with 710 m^3/Mg VS. In the case of cardboard, the results ranged from 381 to 440 m^3/Mg VS depending on the type.

Testing framework

After construction, the framework was tested by comparing its predicted results to published results. The predicted values and the actual results from full-scale facilities are shown in Table 2.

Table 2. Testing of the model with real data

Parameter	Valorga	Kompogas	Dranco	BTA	Biocel	SUBBOR
Predicted						
Biogas Production (m^3/Mg VS)	372	350	468	335	299	546
Digested residue (kg/Mg)	1333	691	557	623	675	540
Waste water (kg/Mg)	209	201	321	305	245	192
Actual						
Biogas Production (m^3/Mg VS)	372	350	468	464	299	546
Digested residue (kg/Mg)	415	680	500	N/A	580	510
Waste water (kg/Mg)	305	176	320	N/A	230	160
References	(1), (2)	(3), (4)	(5), (6)	(7)	(8), (9)	(10), (11)

(1) Saint Joly et al., 2002 (2) CADDET, 1998 (3) Wellinger et al., 1993 (4) Kranert and Hillebrecht 2000 (5) De Baere, 2000 (6) Sinclair and Kelleher, 1995 (7) Kubler et al., 2000 (8) Brummeler, 2000 (9) Brummeler et al., 1992 (10) Liu et al., 2002 (11) Vogt et al., 2002

When testing the framework with real data, the only parameter that presents no deviation from published results (with the exception of the BTA) is the biogas. This is because the model was constructed based on the biogas production. In the BTA case, the published data, presented different runs with very similar conditions (composition of the feedstock, organic loading rate and retention time) but non-similar biogas production results (Kubler et al., 2000). This situation did not allow an equation system to be constructed and it was necessary to use the ratios of production approach.

In the case of the digested residues the difference between the predicted and the real data, was only 2-7% for the Kompogas, Dranco and SUBBOR technology. In the BTA case, there was no information available and in the case of the Valorga and Biocel the information presented in different publications was not complete. The best results were obtained for the technologies that have more information available to cross-check the results from the model. In many papers, the mass balance of the process does not show the composition of the feedstock (TS and VS content) so it was not possible to know the conditions that were used to construct the mass balance. This aspect is very important, because in the framework that we are using, the biogas is calculated based on the volatile solids present in the feedstock and the digested residue and waste water quantities depend on this value. Another reason to explain these differences is that the framework was constructed around the biogas production. The digested residue mass was calculated based on reduction of VS due to biogas production. This calculation might be affected by the density of the gas, that was calculated considering a methane content of 55% in the biogas. This assumption is not necessarily true for all the cases.

In the case of the waste water, a similar situation exists. The variation between the predicted and the published results is in the range of 0.5-14% for the Dranco, Kompogas and Biocel technologies. For the BTA process, no information was available. For the Valorga process, the variation was around 30%. Some of the aspects that impact the results are similar to the ones discussed for the digested residue production (incomplete information, dependability on the biogas production, etc.), but there are also another assumptions done that affect the results. In a full scale plant, the operating conditions are adapted to the characteristics of the incoming feedstock. For example, the retention time will change from the peak period to the slack period (Fruteau de Laclos et al., 1997), also some parameters like the TS content in the reactor and in the final product are flexible. However, for this framework we used an average value for these two operational parameters. These two aspects of the digestion rule how much water is added to the process and how much water is obtained at the end after the de-watering process. So, it is expected that the values obtained for the waste water quantity will differ from some of the published results.

Overall the results obtained from the framework are reliable for preliminary decision making because the deviation between the predicted values and the published values was less than 15% in the cases where full information was available for comparison.

Using framework for prediction

To test the usefulness of the framework, two different scenarios were examined. The first scenario considered a feedstock containing kitchen waste (15%), garden waste (75%) and paper and cardboard (10%). In the second scenario, the feedstock contained only kitchen waste (80%) and garden waste (20%). These two configurations were selected because they represent the typical composition of two different full-scale plants. The first composition is used by a Dranco plant in Salzberg, Austria. The second composition represents the Dranco plant working at Brecht, Belgium. Furthermore, the differences in the composition of the wastes can show how the biogas production changes depending on the biodegradability of the substrate used. The predictions are shown in Table 3.

Table 3. Testing of the model for two different waste compositions

Parameter	Valorga	Kompogas	Dranco	BTA	Biocel	SUBBOR
KW (15%), GW(75%), PC (10%)						
Biogas Production (m^3/Mg VS)	289	208	468	315	227	401
Digested residue (kg/Mg)	1121	988	557	910	853	740
Wastewater w/o recycling (kg/Mg)	137	697	464	3009	231	756
Wastewater w/recycling (kg/Mg)	-196	-43	321	9	88	156
KW (80%), GW(20%)						
Biogas Production (m^3/Mg VS)	550	398	622	602	432	763
Digested residue (kg/Mg)	585	595	302	446	499	288
Wastewater w/o recycling (kg/Mg)	308	651	539	2500	391	757
Wastewater w/recycling (kg/Mg)	275	303	539	400	391	517

As can be seen in Table 3, the biogas production is different for each scenario due to the differences in the biodegradability of the substrate used for digestion. From all the products recovered from the digestion process, the biogas is the easiest to evaluate because it will be recovered as energy. The purpose of this paper was only to predict the quantity of the products recovered from the anaerobic digestion process. However, there are other aspects that must be considered when evaluating the biogas production. For example, not all the biogas produced is available to be marketed or fed into the grid. The internal energy requirement of each process and the losses during the energy production process must be considered. The energy consumption, the requirements will be different depending on the characteristics of the process. Thermophilic technologies (like Dranco, Kompogas and SUBBOR) may have higher requirements than mesophilic technologies (Valorga and Biocel). The exception to the rule for mesophilic processes will be the BTA technology due to the pasteurisation step at the beginning of the process. Once the internal energy requirements have been fulfilled, the available energy for each process can be known. This approximation will give a more realistic result for comparison. In any case, the information about energy requirements for each technology should be provided by the suppliers.

The digested residue in Table 3 includes both the solids and the water. This material may be considered a useful product if it can be up-graded to compost quality. As seen in Table 3, the quantities of digested residue are different for each technology. This difference is due to the efficiency achieved by the different processes but also to the design characteristics of each technology (solids content in the reactor, solids content in the digested residue). In the first scenario, for example, the technology that produces the least digested residue is Dranco, while the one that produces the most residue is Valorga. This variation in the quantities of digested residue might be important when evaluating its final purpose. If this product cannot be used as a soil amendment, it will be considered a stable solid waste requiring disposal.

Two different approaches were examined with respect to wastewater. The first was to assume that the water resulting from the de-watering process was not recycled to the process (Table 3 - wastewater w/o recycling). The other approach assumed that the wastewater was recycled to the beginning of the process to achieve the solids content required in the digester (Table 3 - wastewater w/ recycling). In the case of the Valorga and Kompogas technologies, the values shown as wastewater with recycling are negatives. This means that all the wastewater of the process is used, and that new water (196 and 43 kg respectively) must be added. This issue may be important if a municipality does not have the capability to treat excess wastewater. In the case of Valorga and Kompogas (for the first scenario), no excess wastewater is produced. Instead, the added water ends up in the digested residue.

ADDITIONAL ISSUES

The quality of the products obtained by an anaerobic digestion process is important. The purity of the biogas will affect the processing required before it can be readily used, for example. Technology for cleaning biogas is relatively well developed, however, and can be readily added to a facility.

The digested solid residue from an anaerobic treatment facility may be more troublesome. The generally accepted idea is that post-treatment of the residue after anaerobic digestion is needed to obtain a high-quality finished product (Poggi-Varaldo et al., 1999). Indeed, the Valorga, Dranco and Kompogas technologies are often used in conjunction with aerobic post-treatment (composting). Anaerobic solid residues may not be suitable for direct land application if they are too wet or contain significant concentrations of volatile fatty acids which are can be phytotoxic.

Additionally, if digestion does not occur within the thermophilic range of temperatures, the solid residue may not have achieved sufficient pathogen removal. A study showed that *Plasmodiophora brassicae*, a highly heat resistant pathogen chosen as an indicator organism, was not inactivated during anaerobic digestion at 35^oC but was at 55^oC (Engeli et al., 1993). Other experiments have shown that aerobic post-composting at 55^oC provides aerobic composts of better quality than those from mesophilic reactors (Poggi-Varaldo et al., 1999). In the case of weeds, at 35^oC there was not germination observed in two out of three of the runs conducted but at thermophilic conditions there is no weed growth observed at all (Engeli et al., 1993). The results of these studies imply that anaerobic solid residues from mesophilic digesters require thermophilic aerobic post-treatment to obtain a pathogen free compost. Digester residue from thermophilic anaerobic digesters does not require further pasteurization, but aerobic post-treatment may still be required to achieve other characteristics, such as water content, volatile fatty acids, etc.

Predicting the final quality of anaerobically digested solids is a complex issue. Quality depends mainly on the composition of the feedstock and will be highly impacted by parameters such as the collection scheme, recycling policies, reduction of the biomass, etc. Nevertheless, some technologies show results that accomplish the existent legislation in the country where they are being used For example, the Valorga plant in Tilburg the Netherlands achieves the Dutch regulations for heavy metals and macro contaminants (CADDET, 1998).

While the wastewater produced during the anaerobic digestion of solid wastes should also be examined, few studies report the quality of the effluent produces. One study that does was conducted by Kubler et al. (2000) and reports the results obtained in a facility treating the organic fraction of the MSW with a BTA technology. The characteristics of this water are listed in the Table 4. Clearly, this water would require additional treatment prior to discharge. Whether treatment could be accomplished using an existing municipal wastewater treatment plant or would require separate on-site treatment will depend on site-specific factors.

Table 4. Composition of effluent water (taken from Kubler et al., 2000)

COD (mg/L)	993
BOD_5 (mg/L)	89
TKN (mg N/L)	58
Total-Ninorg (mg N/L)	108
NHx-N (mg N/L)	23
Total-P (mg P/L)	12
Salt (mS/cm)	15.3

The principal advantage of anaerobic digestion compared with other disposal technologies is the production of energy. Most of the facilities reviewed during this study fulfill the process energy requirements using the biogas produced on-site and still provide a surplus of energy that can be commercialised. This energy can be commercialised as electricity, or as compressed nature gas (CNG). To upgrade the biogas to CNG quality it is necessary a post-treatment that desulphurises the biogas and clean the carbon dioxide and the chlorofluorocarbons (CFCs). This process is being undertaken by the Valorga facility in Tilburg, the Netherlands and by different Kompogas plants. The viability of this commercialisation will depend on the energy policy of each country. In the case of Belgium, for example, the country has an extensive nuclear power program which makes it difficult to market the energy achieved by anaerobic digestion facilities. This marketability will also depend on the infrastructure existent in each country. For example, it can be considered a valuable option in countries like the Netherlands which has a dense distribution grid for natural gas.

CONCLUSIONS

1. The framework presented in this paper is able to predict the predict the mass of products of the digester including biogas, treated solids and water.
2. The information provided by the framework, such as how much wastewater will need further treatment, how much biogas will be produced and how much solid residue may be available for up-grading to compost can aid decision makers to choose which technologies best meet their local needs.

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