Biogas calculation tool for theoretical biomethane production

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Abstract

Purpose

The purpose of this work is to present an easy and quick tool to calculate biogas production of a specific feedstock or a mixture of different feedstocks. The aim is to benefit small to medium scale biowaste producers and provide a tool to estimate potential revenues for turning biowaste into valuable biogas.

Methods

The developed tool is based on the Buswell-Boyle equation and database development. Five case studies on small-scale farming are used to demonstrate to tool.

Results

Biogas produced from manures and agricultural waste produces biogas, of which the methane content is approximately 55 mol-% and even in small scale the annual biomethane production rates range from 1 to 4 tons cows being most productive and maize being least productive source. The degradation factors found in literature do not accurately predict region specific case studies.

Conclusions

There is need for geographical adaptation and local database to give realistic results of the local biogas production potential. Encouraging small-scale biowaste producer for investing in biogas production plants would provide more options for replacing natural gas.

(4 to 6) Keywords: Anaerobic digestion, biogas, biomethane, modelling, waste to value.

Introduction

Large amounts of biowaste are generated every year. In the European Union, the amount of biowaste produced is between 118-138 million tons annually [1]. When biowaste is left unattended in landfills, methane emissions to the atmosphere can occur. At the same time, our planet suffers from the extensive use of fossil fuels, which unbalance the CO_2 balance in the atmosphere and lead to climate change. The use of renewable bio-based fuels could reduce both the CO_2 emissions and cut the fossil fuel consumption. Through proper handling and treatment of biowaste, significant value can be recovered in the form of biomethane and biofertilizer, which can be used in energy production and agriculture, respectively. All stakeholders are needed for a global challenge. In this work, a simple, adjustable, and tested biogas calculation tool for biogas production is developed. The tool can solve the two problems simultaneously.

However, the varying quality of biowaste produced makes it difficult to easily process all biowaste by using the same process. Therefore, it is necessary to easily evaluate the yield of the process to convince biowaste producers, who are often farmers or municipal waste collectors, that the waste they currently dispose of in a landfill could be a valuable source of revenue. In addition, transportation costs could be reduced if local biowaste producers were encouraged to refine their biowaste into valuable products. Therefore, a tool is needed to provide a solid and reliable basis for new biogas producers to enter the field. The more producers there are that convert waste into valuable materials, the less waste will end up in landfills and the less fossil fuel will be needed.

In this paper, we present a calculation tool that helps in the planning phase to determine potential biogas production based on our extensive database development. The calculation is based on chemical degradation and tested with experimental data for various feedstocks.

Theory

The primary goal for the biogas calculation tool development is to provide a tool by using which estimates of biogas production rates can be obtained quickly and easily. Therefore, the model is kept as simple as possible to ensure its ease of use. Feedstock is considered on a mass basis and biogas on a volumetric basis at normal temperature and pressure (NTP), which are tangible quantities for all farmers. To apply the model to a specific feedstock, the composition needs to be known. Only the main elements carbon, hydrogen, oxygen, nitrogen, and sulphur are considered.

The elemental composition can be easily determined by the ultimate analysis, so it was chosen as the starting point for the model. Optionally, the model can base the calculations on the fractions of lipids, proteins, and carbohydrates, which is another type of commonly used analysis for bio-based feedstocks. The biogas production potentials of these fractions are stored in the model database. The model database also includes several typical feedstocks such as animal manure, sewage sludge, kitchen waste, and agricultural waste.

In all calculation cases, also the moisture content and inert fraction need to be known in addition to the elemental composition. These are not involved in the biogas production so only the biodegradable fraction of the feedstock is converted to biogas. There are also many other factors that affect the biogas production, such as the animal diet (in case of manure), the storage time and temperature of the feedstock but these are not explicitly considered in the model. However, there are additional parameters that can be used to adjust the feedstock biogas production to better correspond local data.

The biogas production is calculated theoretically by using the Buswell-Boyle equation (see Eq. 1), originally developed by Buswell and Hatfield [2] and further developed by Buswell and Mueller [3]. This was modified by Boyle to add nitrogen and sulphur to obtain ammonia and hydrogen sulphide [4]. The theory assumes that the biological degradation proceeds through acidogenesis and methanogenesis and produces biogas with only four components: methane, carbon dioxide, ammonia, and hydrogen sulphide.

$$C_aH_bO_cN_dS_e + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4} + \frac{e}{2}\right) H_2O \rightarrow \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4}\right) CH_4 + \left(\frac{a}{2} - \frac{b}{8} + \frac{c}{4} + \frac{3d}{8} + \frac{e}{4}\right) CO_2 + dNH_3 + eH_2S \quad \textbf{(1.)}$$

where *a*, *b*, *c*, *d*, and *e* are average molar composition indexes.

Since the Buswell-Boyle approach assumes 100 % degradation of the feedstock, the Buswell-Boyle equation was adapted to the experimental data by using a degradation factor. This adaptation is done through our extensive database development.

Methods

In this work, the developed biogas calculation tool was used for nine feedstocks of which the characteristics derived from the database are summarised in Table 1. These feedstocks [5-8] were selected for case studies to cover many different types of waste categories and demonstrate the versatility of the chosen modelling approach.

The composition of the feedstock is derived from our database that was developed to provide feedstocks for the biogas calculator. The database was built on feedstocks that have been scientifically studied and validated against experimental data. Since the feedstock composition of animal manure largely depends on the diet of the animals, the different feedstocks were not averaged but included as separate entries in the database.

Mass-based compositions, which are received from ultimate analysis, were scaled to dry content (volatile solids, VS) and converted to molar-based units. This provided a means to compare various feedstocks and their methane production potentials.

Many factors affect the degradation factor of a specific feedstock, such as storage conditions, ageing, and moisture content of the waste. The degradation factor given in the table is a general average value. However, detailed degradation factors can be applied to waste fractions from specific areas.

Chemical composition is used to determine the coefficients in Equation 1. These coefficients are listed for the selected feedstocks in Table 2. Since sludges, food wastes, and fats do not contain sulphur in their elemental analysis, the coefficients for H_2S are zero. In addition, fats do not contain nitrogen, so the coefficient for NH_3 for fats is also zero. Based on these coefficients, the specific composition of the biogas can be calculated by using Equation 1.

Results and discussion

Figure 1 shows the theoretical composition of the biogas produced for each feedstock based on the Buswell-Boyle approach. As can be seen from Figure 1, the average methane content of the produced biogas is 55 mol-%, which is a rather conservative methane concentration of the biogas. Fats have the highest methane production potential, while manure and secondary sludge have the lowest. However, the microbiological process in anaerobic digestion cannot easily use fats as the only carbon source for the process. Secondary sludge is abundantly available, but it has rather low potential for biogas production. Nevertheless, mixing it with different feedstocks can result in much better microbiological methane production.

The second largest fraction of biogas produced contains carbon dioxide. This can additionally be converted into methane if a suitable source of hydrogen is available, which increases the total biomethane yield. This increase in biomethane production is beyond the scope of this paper, as the conversion of carbon dioxide to methane usually requires considerable investment costs and only larger biogas producers benefit from it due to its investment cost and more complex technology requirement. The approach used in this paper is aimed at small to medium sized biowaste producers, which generally do not have freely available hydrogen sources.

Case studies for typical small to medium scale biowaste scenarios for biogas production.

To investigate the potential that small to medium sized farms with livestock or agricultural fields have for biogas production, five domestic case studies were selected for practical review [9]. For poultry farmers, a small hen house with 1000 hens was selected as a case study. For larger animals, such as pigs, cattle, or cows, a small number of 10 animals was selected as a case study. To compare animal manure with agricultural waste fractions, a farm with only one hectare of maize cultivation area was selected as a case study.

The estimated biowaste production of these five case studies is presented in Table 3. The table shows that the selected case studies produce 6 to 11 tons of dry biowaste in the form of VS. The biomethane production potential (BMP) ranges from 255 to 413 m^3 of methane gas under normal conditions for one ton of VS in the feedstock. The BMPs were taken from a Finnish reference to match the Finnish geographical conditions [9].

The calculated biomethane productions are summarised in Table 4. The Buswell-Boyle approach is considered a theoretical biomethane production potential (TBMP) because it assumes 100 % decomposition without adjustments, which is too optimistic. To correct this, a degradation factor f_d was introduced to adjust the TBMP.

However, the calculated TBMP with f_d does not match the empirical results for biomethane production in Finland with the f_d taken from another reference with higher biomethane production. A similar approach is used to obtain a region-specific f_d value for Finland, which appears to be significantly lower. It is well known that Buswell-Boyle makes overly optimistic predictions for biogas production. This work suggests that more realistic results are obtained for the Buswell-Boyle approach if the decomposition factor is adjusted to regional specifics. This new regional $f_{d,FI}$ ranges from 55 % to 74 % of the f_d taken from literature.

For the case studies, the absolute amounts of produced biogas are calculated by using the regional $f_{d,FI}$. The annual biogas production rates are measured in tons as shown in Fig. 2. Ten cows produce over 4 tons of biomethane in a year at Finnish conditions. Beef cattle produce 2 tons of biomethane in a year, which is approximately the same as 1000 hens. Biogas is, however, not purely biomethane. On a mass-basis, anaerobic digestion produces more carbon dioxide than methane, which is also seen in Fig. 2. If carbon dioxide could be converted into methane, biomethane production could be substantially raised. In countries where distances are long, biofuel production has more advantages.

Conclusions

The collected database contains the characteristics of various feedstocks, which serve as input data for biogas production calculation. The developed biogas calculation tool provides results that can be used to estimate the potential biogas yield of a particular feedstock or a mixture of different feedstocks. The tool can be used to optimize the composition of feedstocks to obtain the desired composition of the biogas produced. The database is crucial to adapt the BMP to local geographical conditions.

Five domestic case studies on animal manure and agricultural waste showed that several tons of biomethane can be produced annually with just ten cows. If the by-product CO_2 can also be converted to methane, even higher production rates can be achieved. Encouraging small-scale biowaste producer for investing in biogas production plants would provide more options for replacing natural gas.

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Table 1 Example set of nine feedstocks, their composition (C, H, O, N, S) on molar basis (mol-%) and degradation factor f_d (weight-%) derived from our database [5-8,10]

Feedstock name	Elemental composition *mol-%*					Degradation fraction f_d
	C	H	O	N	S	*weight-%*

Manure, chicken	4.48	6.90	2.03	0.44	0.01	0.80
Manure, swine	5.00	7.43	1.59	0.41	0.04	0.80
Manure, beef feedlot	4.55	6.40	2.33	0.08	0.01	0.80
Manure, cattle/cow	3.79	6.26	2.39	0.16	0.02	0.52
Sludge, secondary	6.60	12.0	2.40	1.00	0.00	0.29
Sludge, primary	17.0	31.0	7.20	1.00	0.00	0.53
Waste, food	17.0	30.0	6.00	1.00	0.00	0.80
Waste, agricultural (maize)	0.04	0.08	0.02	0.004	0.00	0.75
Fats	16.0	32.0	2.00	0.00	0.00	0.90

Table 2 Molar coefficients of the equation 1. for the chemical products using selected feedstocks with known molar composition as starting material [5-8,10]

	H_2O	CH_4	CO_2	NH_3	H_2S
Manure, chicken	2.0793	2.4270	2.0564	0.4377	0.0167
Manure, swine	2.6727	2.8635	2.1334	0.4149	0.0368
Manure, beef feedlot	1.8560	2.4598	2.0949	0.0826	0.0109
Manure, cattle/cow	1.1580	2.0171	1.7744	0.1571	0.0181
Sludge, secondary	3.1500	3.8250	2.7750	1.0000	0.0000
Sludge, primary	6.4000	10.2000	6.8000	1.0000	0.0000
Waste, food	7.2500	10.3750	6.6250	1.0000	0.0000
Waste, agricultural (maize)	0.0141	0.0237	0.0180	0.0043	0.0003
Fats	7.0000	11.5000	4.5000	0.0000	0.0000

Table 3 Case studies of small farms with chicken, swine, beef, cattle/cow or maize cultivation with the estimated annual biowaste production on a dry basis (t_{VS}/a) and experimental biomethane production potential BMP (m^3 of CH_4/t_{VS}) [9]

	Quantity	Biowaste production	BMP
		t_{VS}/a	$m^3 CH_4/t_{VS}$
Manure, chicken	1000 hens	11	263
Manure, swine	10 sows	6.24	413
Manure, beef feedlot	10 animals	11.0	300
Manure, cattle/cow	10 cows	23.9	255
Waste, agricultural (maize)	1 ha of area	6.68	288

Table 4 Produced biomethane (*t/a*) for the case studies by using TBMP 100 %, TBMP with f_d, and experimental BMP methods. New degradation factor for Finland $f_{d,FI}$ is given to match local biomethane production

	TBMP 100 %	TBMP with f_d	BMP	$f_{d,FI}$

	t/a	*t/a*	*t/a*	%
Manure, chicken	4.28	3.43	1.90	44.3
Manure, swine	2.87	2.29	1.69	59.0
Manure, beef feedlot	4.33	3.47	2.16	49.9
Manure, cattle/cow	8.31	4.32	4.00	48.1
Waste, agricultural (maize)	2.53	1.90	1.26	49.8

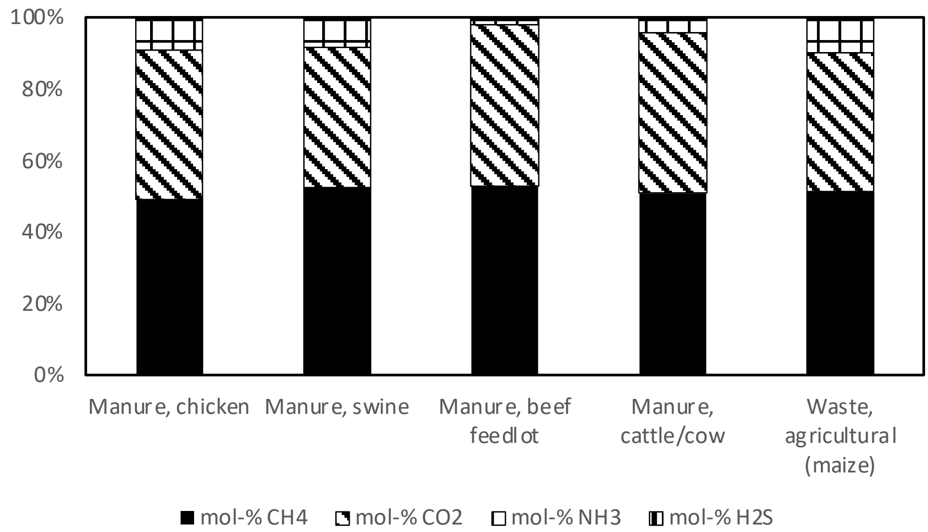

Fig. 1 Composition of the produced biogas in mol-% for the selected feedstock using the Buswell-Boyle approach

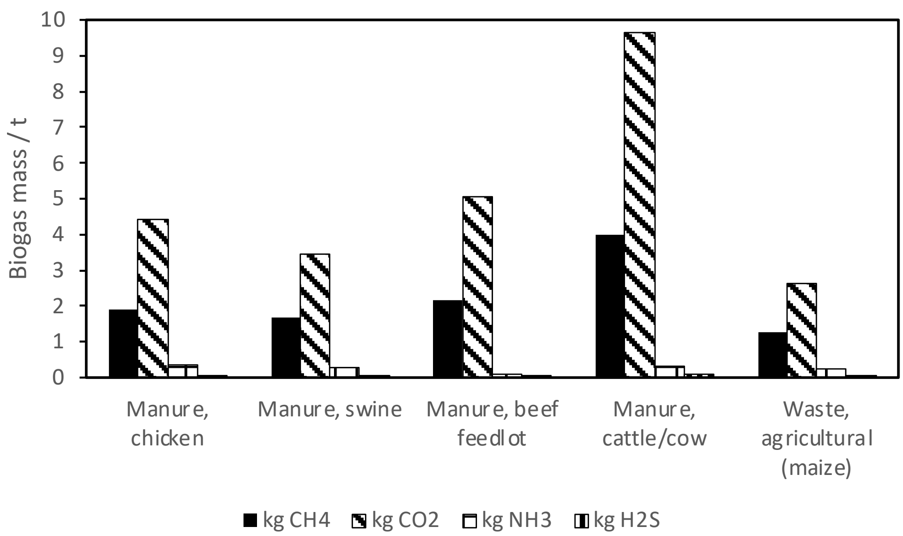

Fig. 2 Produced biogas fractions (CH_4, CO_2, NH_3, H_2S) in tons for each case study