Calculations Biogas production

The composition of the substrate used in biogas processes will have a substantial impact on the volume of biogas produced. Fats/lipids generate more biogas and methane per kg than e.g. carbohydrates. In addition, the concentration of methane and carbon dioxide in the produced biogas will also depend on the composition of the substrate.

Some definitions

TS = Total solids: % of substrate wet weight
VS = Volatile solids (same as organic matter, OM): % of TS or % of substrate wet weight
COD = Chemical Oxygen Demand: kg COD/m^3 wastewater

HRT = Hydraulic Retention Time: d (the theoretical average residence time of a liquid volume in a digester). **HRT= V/Q_o**, where V = active digester volume (m^3_r) and Q_0= volume flow out of the digester (m^3/d). $Q_0 \approx Q_i$
Typical values: 20-50 d for CSTR (slurries and solid waste) and 2-12 h for UASB (wastewater).

OLR = Organic Loading Rate: the daily mass of organic matter applied to a given digester volume.
For CSTR (slurries and solid waste): kg VS/m^3_r/d, i.e. kg VS/m^3 digester volume/d.
For UASB (wastewater): kg COD/m^3_r/d, i.e. kg COD/m^3 digester volume/d
OLR = S_0/HRT, where S_0 = influent organic matter concentration (kg VS/m^3 slurry or kg COD/m^3 wastewater) and HRT = Hydraulic Retention Time
Typical values: 3-6 kg VS/m^3_r/d for CSTR, and 1-10 kg COD/m^3_r/d for UASB

Gas volumes should be expressed at a defined temperature and pressure! In the biogas sector gas volumes are **normalised** to 0 °C and 1 atm → Normal cubic metre (Nm^3)

Biogas yield = Nm^3 biogas/kg VS in substrate or Nm^3 biogas/kg wet weight
Methane yield = Nm^3 methane/kg VS in substrate or Nm^3 methane/kg wet weight

1 Nm^3 CH_4 = 9.97 kWh

Theoretical calculations Buswell equation

Theoretical calculations on the volume of biogas and the concentration of methane and carbon dioxide can be done using the following general equation (the Buswell equation) based on the content of C, H, O, N and S:

$$C_cH_hO_oN_nS_s + \{(4c - h - 2o + 3n + 2s)/4\}\ H_2O \rightarrow$$
$$\{(4c - h + 2o + 3n + 2s)/8\}\ CO_2 + \{(4c + h - 2o - 3n - 2s)/8\}\ CH_4 + nNH_3 + sH_2S$$

Example: Protein ($C_5H_7O_2N$)

Determine theoretically:
a) the gas composition (% carbon dioxide and % methane) when digesting protein
b) the normal volume biogas and methane produced from 1 kg of protein

From the Buswell equation:
c=5, h=7, o=2, n=1 (s=0)

Note that in practice all ammonia (NH_3) dissolves in the slurry. Therefore we only calculate CO_2 and CH_4

$C_5H_7O_2N$ + {(4x5-7-2x2+3x1)/4} H_2O →
{(4x5-7+2x2+3x1)/8} CO_2+ {(4x5+7-2x2-3x1)/8} CH_4

$C_5H_7O_2N$ + 3 H_2O → 2.5 CO_2+ 2.5 CH_4

a) The molar ratio for CO_2 and CH_4 is 2.5 : 2.5, thus the gas composition is 50% CO_2 and 50% CH_4

What is the normal volume produced biogas from 1 kg of protein?

Note: The normal volume is here defined as the volume at 0 °C and 1 atm

1 mol protein ⇔ 2.5 moles CH_4

Ideal gas law:
pV=nRT

where

p = absolute pressure of the gas (atm); 1 atm
V = volume (L)
n = amount of substance (mol); 2.5 mol
R = gas constant (L atm K^{-1} mol^{-1}); 0.08205747 L atm K^{-1} mol^{-1}
T = absolute temperature (K); 273.15 K

V = nRT/p = 2.5x0.08205747x273.15/1 = 56.03 L

Molar mass of $C_5H_7O_2N$ = 5x12 + 7x1 + 2x16 + 1x14 = 113 g/mol

The methane yield is 56.03/113 = 0.496 dm^3/g VS = 0.496 m^3/kg protein

Calculating the CO_2 yield → 0.496 Nm^3/kg protein

b) The theoretically biogas yield is 0.496 + 0.496 = 0.992 Nm^3/kg protein = 1.0 Nm^3/kg protein

The same calculations can be made for fat/lipid and carbohydrates giving biogas yields and gas composition presented in table 1.

Table 1

	Biogas (Nm^3/kg)*	Methane (%)	Carbon dioxide (%)	Methane (Nm^3/kg)*
Fat/Lipid ($C_{57}H_{104}O_6$)	1.445	70	30	1.014
Protein ($C_5H_7O_2N$)	0.992	50	50	0.496
Carbohydrate ($C_6H_{12}O_6$)	0.748	50	50	0.374

**At 1 atm, 0 °C*

Theoretical calculations COD

Example: Protein ($C_5H_7O_2N$)

Determine theoretically the COD of protein ($C_5H_7O_2N$) based on the content of C, H, O, N as g COD/g protein (g O_2 required for oxidisation of 1 g of protein)

$$C_cH_hO_oN_n + \{(4c+h-2o-3n)/4\}\ O_2 \rightarrow c\ CO_2 + \{(h-3n)/2\}\ H_2O + nNH_3$$

Based on the equation above, the moles of O_2 for oxidation of 1 mole of $C_5H_7O_2N$ can be calculated:

$$C_5H_7O_2N + \{(4x5+7-2x2-3x1)/4\}\ O_2 \rightarrow 5\ CO_2 + \{(7-3x1)/2\}\ H_2O + 1\ NH_3$$

$$C_5H_7O_2N + 5\ O_2 \rightarrow 5\ CO_2 + 2\ H_2O + 1\ NH_3$$

1 mol protein ⇔ 5 moles O_2

Next we have to calculate the mass (g) of 5 moles of O_2 using the molar mass of O (16 g/mole):
5x32 [molar mass of O_2] = 160 g

We also need the mass of the protein using the molar mass of C, H, O and N:
5x12 + 7x1 + 2x16 + 1x14 = 60 + 7 + 32 + 14 = 113 g

Thus, the COD of protein is 160/113 = **1.416 g COD/g protein**

The same calculations can be made for fat/lipid and carbohydrates giving COD presented in table 2.

Table 2

	c	h	o	n	g COD / g $C_cH_hO_oN_n$	dm^3CH_4 / g $C_cH_hO_oN_n$	dm^3CH_4 / g COD
Fat/Lipid ($C_{57}H_{104}O_6$)	57	104	6	0	2.896	1.014	0.35
Protein ($C_5H_7O_2N$)	5	7	2	1	1.416	0.496	0.35
Carbohydrate ($C_6H_{12}O_6$)	6	12	6	0	1.067	0.374	0.35

Task 1: Calculate the theoretical biogas yield (Nm^3/tonne wet weight), methane yield (Nm^3/tonne wet weight) and the composition of the biogas (% methane and % carbon dioxide) for a waste mixture with the composition according to Table 3. Use data in Table 1.

Table 3

Wet weight	1000 kg
TS(total solids)	22 % of wet weight
VS(volatile solids)	86% of TS
Fat/Lipid	34% of VS
Protein	28% of VS
Carbohydrate	38% of VS

Comparison of theory and practice

Task 2: Based on practical experiences from continuous anaerobic digestion of the waste with the same composition as in task 1, the following data is obtained:

150 Nm^3 biogas/tonne wet weight
68 % methane in biogas

Calculate the efficiency (%) in biogas and methane yield compared to the theoretical calculation in task 1. Discuss the results!

Practical calculation

Task 3: Sewage sludge and food waste (CSTR digester)

A municipality is planning for biogas production based on sewage sludge (36 500 tonnes/year). In addition, they like to co-digest food waste (4 000 tonnes/year) from a residential area with source separation. The density for both substrates can be approximated to 1 ton/m^3.

In this case you decide to set the HRT 25 d and to have a 15 % headspace in the digester (i.e. 85% of the total volume is active).

Use the HRT and OLR equations on page 1 and the data in table 4 to calculate:

a) the volume of the CSTR digester (both active and total volume)
b) the OLR
c) the annually volume methane produced
d) the annually volume biogas produced

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Table 4

		Sewage sludge	Source-sorted household waste
Total solids (TS)	% of wet weight	5	30
Volatile solids (VS)	% of TS	75	90
Methane yield	Nm^3/kg VS	0.24	0.42
Methane concentration	%	62	60

Task 4: Wastewater (UASB digester)

The wastewater from a community in India is currently just pumped to an oxidation pond. There is an interest in installing anaerobic digestion using UASB technology. The data available is given in table 5. In this case you decide to set the HRT 10 h.

Calculate:

a) the active volume of the UASB-digester
b) the OLR
c) the annual volume methane produced

Table 5

		Wastewater
COD-concentration	mg COD/dm^3	500
Wastewater flow rate	m^3/d	1 500
Theoretical methane yield	Nm^3/kg COD	0.35
COD conversion to CH_4	%	70