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Designing biogas units for cleaner energy production from different wastewater effluents

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ABSTRACT

Organic wastewater flows from different industrial sectors and categories represent substantial resources of biomass. An appropriate recovery of this biomass can ensure a renewable energy development and a sustainable process for waste management. In this work, different aspects related to biogas production and energy valorization were explored and presented. The governing fluxes involved in biogas plants were estimated based on their mass and energy balances and using substrate characteristics under different operating conditions. The produced net energy was directly related to process constraints including temperature, hydraulic parameters, and feedstock characteristics. The overall process performances were presented compared and discussed in order to assist design, dimensioning and control of several biogas plants.

Keywords: Biogas; Anaerobic digestion; Wastewater substrates; Mass and heat balance; Energy yield

1. Introduction

Bioenergy development opens up several ways for energy recovery as alcoholic fermentation for the production of ethanol, methanisation through anaerobic digestion for biogas production and transesterification reaction (including edible and non-edible oils, used oils, microalgae oils, etc.) for biodiesel production. Anaerobic digestion or methanisation has proven to be a promising technology for clean energy production and waste treatment management [1,2]. Organic wastes such as wastewater, food effluents, sludge, agricultural, and municipal wastes can be valorized and codigested in order to produce a valuable energy [3–5]. Actually, the produced biogas can be transformed into combined heat and power within cogeneration units. Furthermore, after a very high level of purification, the resulted biomethane can be used in specific applications as biofuels (in fuel cell, transport, etc.) or injected into natural gas network [2,5,6].

Methanisation technology involves multiphase and heterogeneous phenomena to be controlled as they significantly affect the selectivity and the yield of methane produced in biogas units. Actually, quality and quantity of produced biogas depend critically on biomass feedstocks and process operation [7,8]. Mesophilic or thermophilic temperatures are usually ensured for various organic substrates degradation and most of digesters need energy for bioreactor

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heating. In addition, the hydrodynamic parameters such as, the mean residence time of solids and liquids, the reactor size and the reactor type, impact significantly the process performances [9–11].

Various biodigester systems, including volumes ranged from some L to several m^3, are investigated in the open literature, and most of them are continuously stirred with individual or series tanks. Actually, the reactor configuration is responsible of reaction yield and can directly affect the heat and mass transfer within the entire process [10,12].

Organic wastes and effluents have a low economic cost, and the process yield depends mainly on investment and operation costs. However, before any economical investment, the net energy balance must be considered [13,14]. Thus, biogas utilizations and process flux management strategies also have to be evaluated to ensure energy efficiency.

The present work focuses on organic waste treatment by anaerobic digestion for clean and renewable energy production. The biological process includes complex metabolisms with a variety of possible transformation mechanisms. The species are in continuous competition, implying complex growth kinetics with several activation and inhibition biological steps. To simplify the calculation methodology, those phenomena are not considered in methane yield estimation. Only the overall fluxes governing the process unit are considered to establish mass and heat balances. Thus, different aspects related to the design and optimization of biogas units under different operating conditions are presented and discussed with an emphasis on the net energy production.

2. Modeling biogas production

2.1. Biogas unit

Fig. 1 presents a classic process pattern for anaerobic digestion operation. The unit is composed of tanks for storing and hydrolyzing organic loads, digester to conduct the biological reactions, a gas-meter, and a system for biogas conversion into other forms of useful energy like, heat and electricity.

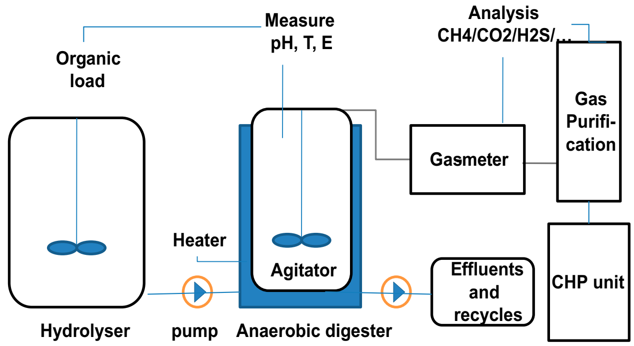

Fig. 1. Process unit for biogas production and energy valorization.

It would be also necessary to integrate other devices for biogas and effluent purification according to methane purity required for the final application.

It is worth noting that bioreactor designed for organic load biodegradation could have several configurations (batch reactor, continuously stirred reactor, fixed bed reactor, fluidized bed reactor, etc.) [10–12].

The biological process includes complex metabolisms with a variety of possible transformation mechanisms. The main steps of anaerobic digestion are substrates hydrolyzing, acidification, acetates production, and transformation to methane.

2.2. Biogas yield

The choice of the organic substrate characteristic and the operation conditions directly impacts the process stability.

The theoretical biogas composition can be estimated from Buswell equation [4,15] considering the elemental substrate composition [16].

$$C_cH_hO_oN_nS_s + a\,H_2O \rightarrow b\,CO_2 + c\,CH_4 + d\,NH_3 + e\,H_2S$$

where:

$$a = \frac{4c - h - 2o + 3n + 2s}{4} \quad (1)$$

$$b = \frac{4c - h + 2o + 3n + 2s}{8} \quad (2)$$

$$c = \frac{4c + h - 2o - 3n - 2s}{8} \quad (3)$$

$$d = n; \quad e = s \quad (4)$$

2.2.1. Mass balance

In the open literature, biogas yield for several organic substrates is usually expressed as Eq. (5):

$$Y_{\mathrm{bg}} = \frac{V_{\mathrm{bg}}}{m_{\mathrm{ds}}} \quad (5)$$

where V_{bg} and m_{ds} indicate, respectively, volume of biogas and mass of biodegradable solid. The mass of biodegradable solid can be represented, depending on the available data, by the mass of biodegradable carbon or the mass of volatile solid [1,8,13,17].

Assuming that biogas behaves like perfect gas under normal temperature and pressure, it can be written that:

$$Y_{\mathrm{bg}} = \frac{\frac{m_{\mathrm{bg}}}{M_{\mathrm{bg}}} RT^{\circ}}{m_{\mathrm{ds}} P^{\circ}} \tag{6}$$

where m_{bg} indicates mass of biogas, R gas constant, T° standard temperature, and P° standard pressure.

The mass of biogas that lives the digester will be expressed as:

$$m_{\mathrm{bg}} = \frac{m_{\mathrm{ds}} M_{\mathrm{bg}} P^{\circ}}{RT^{\circ}} Y_{\mathrm{bg}} \tag{7}$$

Thus, it is possible to estimate the mass of water vapor exiting via biogas using Eq. (8) and considering that at the equilibrium stage, water is at it saturation pressure P^s [Eq. (9)] corresponding to reactor temperature T_r:

$$P^s = y_w P^{\circ} = (1 - y_{\mathrm{bg}}) P^{\circ} = \left(1 - \frac{n_{\mathrm{bg}}}{n_{\mathrm{bg}} + n_w}\right) P^{\circ} \tag{8}$$

$$m_w = \frac{m_{\mathrm{ds}} M_{\mathrm{H_2O}} P^{\circ} P^s(T_r)}{RT^{\circ}(P^{\circ} - P^s(T_r))} Y_{\mathrm{bg}} \tag{9}$$

Mass of residual effluents was then estimated using mass balance between initial and final states. However, it is necessary to keep in mind that a small part of water will be condensed out when leaving the digester at ambient temperature. Nevertheless, the biogas is still considered saturated with water at saturation pressure corresponding to ambient temperature.

$$n_t = n_w + n_{\mathrm{bg}} = n_{\mathrm{bg}} \frac{P^{\circ}}{P^{\circ} - P^s(T_a)} \tag{10}$$

The overall volume of wet biogas at ambient temperature is then expressed as:

$$V(T_a) = \frac{m_{\mathrm{ds}} T a P^{\circ}}{T^{\circ}[P^{\circ} - P^s(T_a)]} Y_{\mathrm{bg}} \tag{11}$$

Those equations allow the dimensioning of purifications units when biogas dehumidification is needed before electric conversion or before any other specific application [2,13].

2.2.2. Heat balance

The net energy produced will be the difference between the overall energy produced by digesting organic substrates and the energy needed to the process.

The energy required to heat the organic effluent is modeled by assuming the heat is similar to that of water and is temperature independent in the operating temperature range. It is stated as:

$$Q_{\mathrm{th}} = m_i C_p (T_r - T_a) \tag{12}$$

m_i is the feedstock load, and Q_{th} is thermal energy needed to heat the feedstock to reactor temperature.

The heat capacity C_p of the organic feedstock was assumed to equal that of water.

The overall energy P_t equivalent to the produced methane is calculated in kWh using the superior calorific value of methane (SCV = 10 kWh/m^3):

$$P_t = \mathrm{SCV} \cdot V_{\mathrm{CH4}} \tag{13}$$

Hence, based on the given set of equations, it will be possible to calculate the different mass and heat fluxes governing a typical biogas plant.

2.2.3. Digester sizing

The digester volume can be estimated according to a mean residence time of the process. Actually, the mean residence time value is most of the time fixed by the operator and is usually ranged between 10 and 30 d for liquid organic load [5].

$$Q_i = \frac{V}{t_s} \tag{14}$$

V, Q_i, and t_s, indicate, respectively, volume of digester, inlet flowrate of feedstock, and the mean hydraulic residence time.

The different volumes required for storing feedstock, biogas, and effluents can be estimated according to the process constraints. The storing periods for feedstock depends on the substrate accessibility. It depends on the considered application for biogas and for effluents. Thus, to allow an appropriate gas-meter sizing, a biogas containing at list, methane, carbon dioxide, and water vapor have to be considered. Eq. (11) gives a first estimation of the gas-meter volume needed for storing the produced biogas.

3. Results and discussion

An anaerobic digester is often started in batch mode before reaching a stable state for a continuous operation. An example of calculation on a set of organic wastes is presented here. The purpose was to help on methane yield prediction for the selection of appropriate organic wastes according to their elemental composition.

3.1. Organic substrate characteristics

Methane potentials of different organic substrates are presented in previous works [4]. Those experimental results can be used as data in the presented methodology. However, for this work, the elemental composition of substrate is used here as the only initial data in order to allow a more generic methodology.

Table 1 gives the elemental composition of some organic substrates extracted from the literature [16]. The rate of inert species is designated by I in Table 1.

To achieve mass and heat balances, a similar fixe organic load was considered for each substrate separately. The rate of total solids and the rate of biodegradable solids in feedstock were considered similar for each case in order to distinguish the effect of substrate composition from the others.

Table 1
Elemental composition of the investigated organic substrates [16]

Substrate composition (%)	C	H	O	N	S	I
Wastewater	45.5	6.8	25.8	2.4	0.5	19
Bovine dejection	42.7	5.5	31.3	2.4	0.3	17.8
Municipal waste	33.9	4.6	22.4	0.7	0.4	38
Paper waste	30.9	7.2	51.2	0.5	0.2	10.2
Sludge	14.2	2.1	10.5	1.1	0.7	71.4

Table 2 presents feedstocks with two examples of degradable carbon rates (Case A and Case B). Mass of biodegradable solid corresponds to mass of carbon that could be converted on biogas products.

Based on Buswell equation and using the set of relation arising from mass balances, the theoretical yields are calculated for each element present in a standard biogas composition (Fig. 2).

Fig. 2 depicts that municipal waste (organic fraction) and wastewater exhibit the highest methane yields on the one hand and the smallest carbon

Table 2
Organic load characteristics

The overall feedstock characteristics	Case A	Case B
Mass of feedstock m_i (kg)	1,000	1,000
Mass of biodegradable solid carbon m_{ds} (kg)	$0.01 \times m_i$	$0.05 \times m_i$
Masse of total solids (kg)	$0.2 \times m_i$	$0.2 \times m_i$

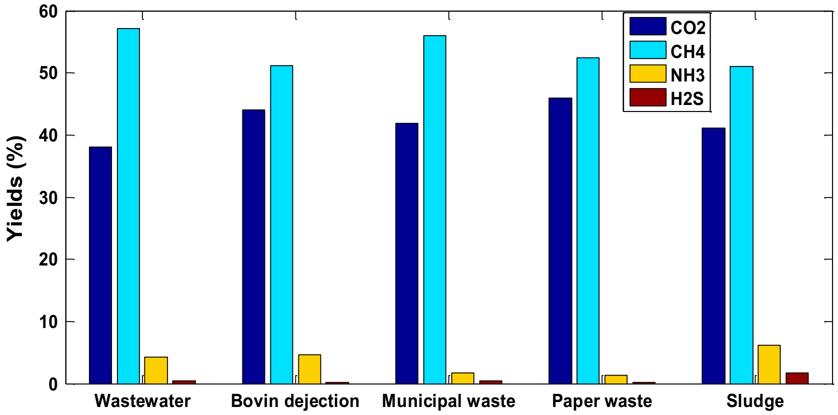

Fig. 2. Biogas composition for the different organic substrates.

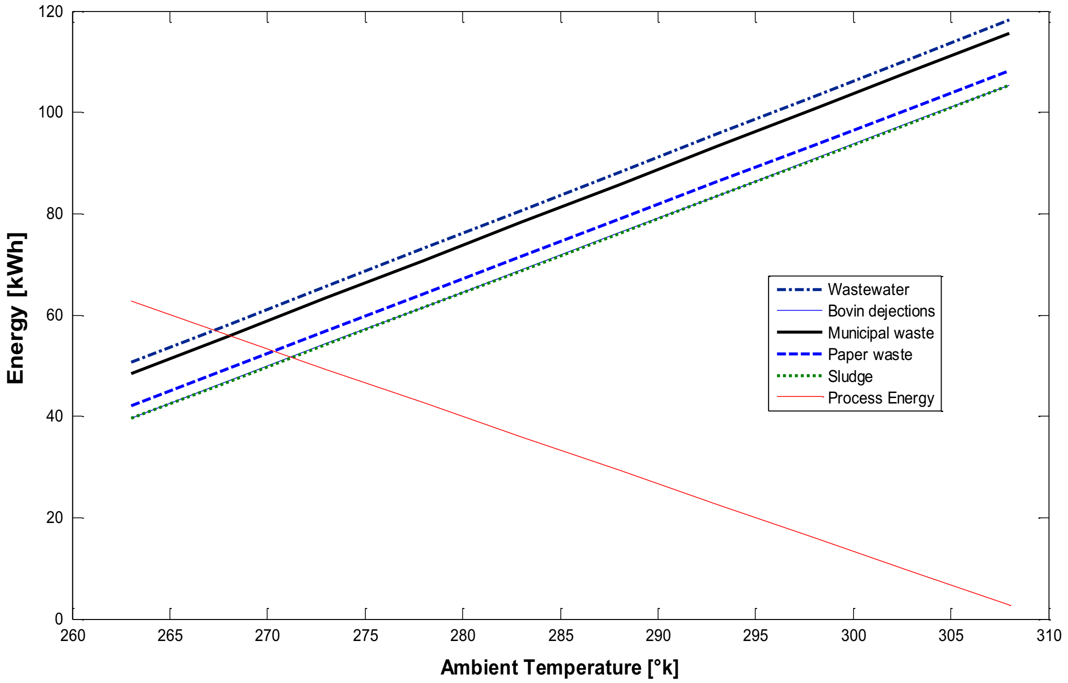

Fig. 3. Power generated from the produced biogas related to the different organic substrates in Case A.

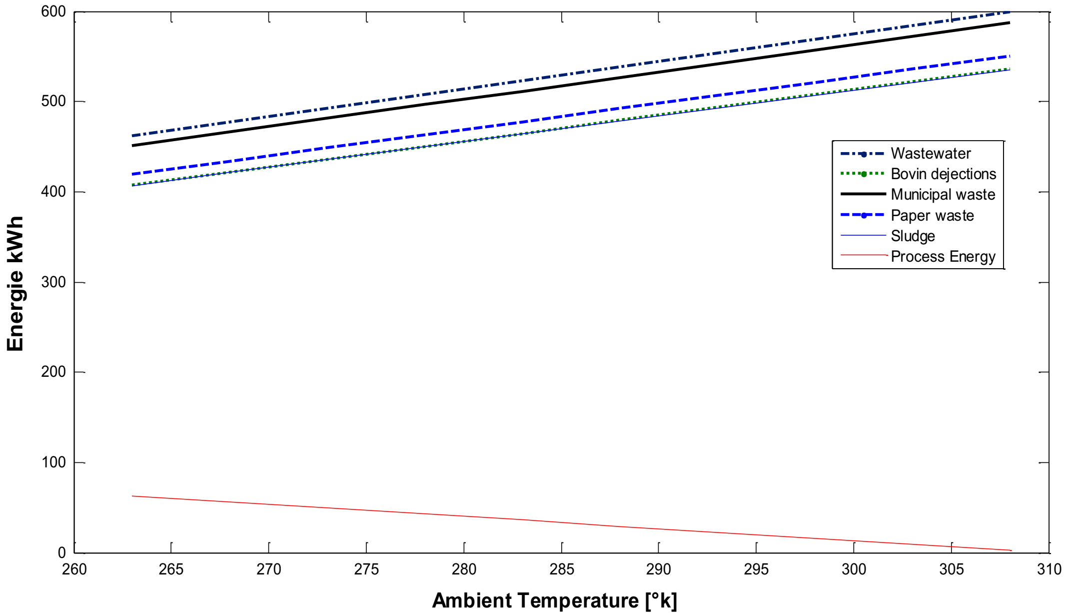

Fig. 4. Power generated from the produced biogas related to the different organic substrates in Case B.

dioxide yields on the other hand, in comparison with the other elements.

This result can be explained by observing the elemental composition of the investigated substrates. It is seen that substrate containing maximum of carbon and hydrogen and minimum of oxygen correspond to those allowing larger methane production.

Further to the impact of the elemental composition, it is demonstrated experimentally that the municipal waste and wastewater exhibit higher methane yields than bovine wastes. This is due to the fact that urban wastes are fresher and contain a mix of different organic substrates coming from several origins. On the other hand, the cow manures have generally a standard origin (cow foods) and are also predigested by the animal digesting metabolisms which reduce their methane yields [5,17].

However, it is important to remind that the different interactions in organic substrate can affect significantly the methane yield as they can modify the bacteria growth and the reaction kinetics [3,7].

The generated energy corresponding to the methane produced at a reactor temperature of 37˚C is estimated using Eq. (13).

Figs. 3 and 4 illustrate the net power generated using each kind of substrate according to the ambient temperature. Actually, the net power generated is estimated by removing heat power needed to heat the digester [using Eq. (12) converted to kWh] from the power generated considering the methane superior calorific value [Eq. (13)]. It is generally assumed that 20% of the energy needed for feedstock heating can be lost in the top and the base of the digester and those heat loses have to be considered when inappropriate insulation is exhibited.

It appears that for cold seasons and when the ambient temperature is below 273˚C (Fig. 3), the process energy and the possible heat loss are less than the net energy that can be produced. This means that under those operating conditions, the process is not able to generate enough energy for external uses. Nevertheless, heating energy remains low at high temperature (Fig. 4). Thus, it is very important to take into consideration the net energy instead of the overall generated energy in order to justify the biogas plant profitability.

4. Conclusions and perspectives

Methane yield and net energy production were estimated considering mass and energy balances and specific substrate characteristics under chemical and thermodynamic assumptions. This process modeling aims to bring insights and information in order to help on the design and dimensioning of several biogas units while overcoming experimental limitations.

Municipal waste and wastewater behave like appropriate feedstock allowing a high net energy production. The energy balance computation revealed that a part of the produced energy was needed to provide the energy required by the process. As a consequence, the process must be designed in order to allow a net energy production under different operating conditions.

Furthermore, the required sizes for all units constituting a typical biogas plant can be estimated according to the presented methodology and considering several process constraints in order to facilitate biogas unit implementations.

Symbols

C_p — heat capacity of feedstock
m_{bg} — mass of biogas
M_{bg} — molar mass of biogas
m_{ds} — mass of biodegradable solid carbon
m_i — mass of feedstock
M_i — molar mass of element denoted by i
m_w — mass of water vapor
n_{bg} — biogas number of moles
n_t — total number of wet biogas
n_w — water number of moles
P° — standard pressure
P_t — overall Energy
Q_{th} — energy for heating feedstock
Q_i — inlet flowrate of feedstock
R — constant in ideal gas equation
SCV — superior calorific value of methane gas
T° — standard temperature
T_a — ambient temperature
T_r — reactor temperature
t_s — hydraulic residence time
V_t — overall volume of wet biogas
V_{bg} — volume of the produced biogas
V — volume of digester
y_{bg} — molar fraction of dry biogas in saturated biogas
Y_{bg} — biogas yield
y_w — molar fraction of water in saturated biogas

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Appendix

In this section, a brief example of calculations applied to each organic substrate is presented here. The entire calculations are implemented in a code file in order to allow a generic extrapolation of different case studies (Table A1).

From the products composition (%) and the m_{ds}, we can calculate the mass of each product.

For example considering CH_4:$m_{CH_4} = (\%\ \text{products} \times m_{\mathrm{ds}} \times M_{CH_4}/M_C)/100$.

This methodology of calculation can be applied for different products (CH_4, CO_2, H_2S, NH_3, …) within different organic substrates.

Table A1
Example of calculations applied to wastewater substrate

Substrate: wastewater	Calculation results
Elemental composition (% mass):[C; H; O; N; S]	Table 1 [45.5; 6.8; 25.8; 2.4; 0.5]
Molar mass (g/mol): [M_C; M_H; M_O; M_N; M_S]	[12; 1; 16; 14; 32]
Molar composition (% mol): [c; h; o; n; s]	% mass/ Molar mass [3.79; 6.80; 1.61; 0.17; 0.02]
Reaction stoichiometry [a b c d e]	Eqs. (1)–(4) [1.42; 1.52; 2.27; 0.17; 0.02]
% products:[CO_2 CH_4 NH_3 H_2S]	100 × product/∑ products [38.13; 57.17; 4.31; 0.39]