Chapter III

BIODIGESTERS

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Introduction

The central point of an anaerobic treatment system is the biodigester model. Thus, projects adapted to the type of substrate to be treated, level of investment, and environmental conditions must be sought. Table 1 shows the key points for establishing the process.

Table 1. Important points for choosing the biodigestion system.

Technology	Key points	Options
Feeding system	Type of biodigester and raw material for feeding	Discontinuous feeding for batch biodigesters Continuous or semi-continuous feeding for plug-flow/CSTR biodigesters Solid or liquid feeding system, depending on the dry matter content of the substrate
Reactor temperature	Risk for pathogens*	Mesophilic temperatures when there is no risk of pathogens Thermophilic temperatures when there is a risk of pathogens (e.g., domestic organic waste)
Number of phases	Substrate composition, risk of acidification	One-phase systems when there is no risk of acidification Two-phase system for substrates with a high content of sugar, starch, and proteins, or substrates difficult to degrade
Stirring system	Dry raw material for feeding	Mechanical stirrers for high solids concentration in the biodigester Mechanical, hydraulic, or pneumatic stirrer systems for low solids concentration in the biodigester

*An alternative is the use of the heat treatment process (e.g., pasteurization).

Biodigester types

Biodigesters are characterized by the feeding regime (batch or continuous), feeding form (upward or laminar), solids concentration in the reactor (solid digestion >20%, semi-solid digestion from 10% to 15%, and wet digestion <10%), and stirring system (complete mixing, partial mixing, or no mixing). The most common models found in Brazil and the details will be discussed in this chapter.

Covered lagoon biodigester (CLB)

The covered lagoon biodigester is a tank dug into the ground, waterproofed, and covered with geosynthetic material (e.g., PVC and HDPE) characterized by low permeability to fluids and gases, and flexible enough to accumulate biogas. It has a rectangular base, with a trapezoidal section and variable slope inclination, according to the ground characteristics (Figure 1).

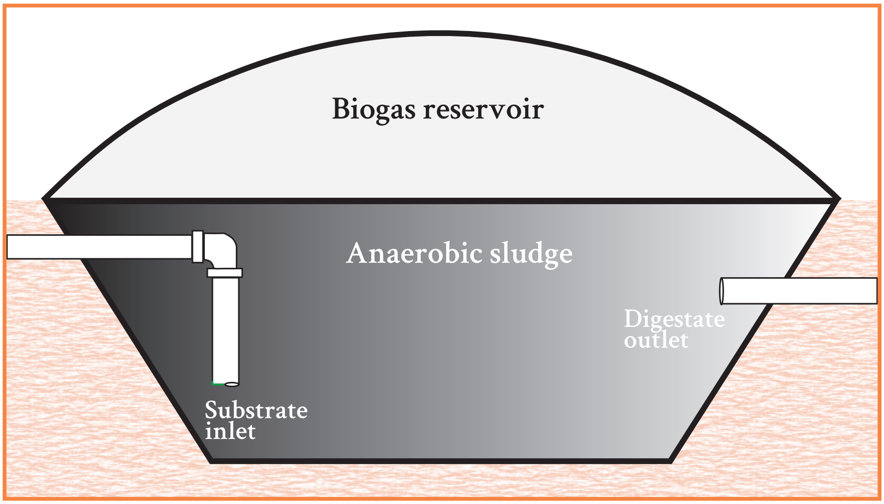


Illustration: Airton Kunz

Figure 1. Representation of the internal view of the covered lagoon reactor.

CLB has been widely used in rural areas to manage effluents from animal production. It is considered of low technological level, with ease of construction and operation. We usually find references to this model as "Canadian" or "canvas biodigester". In general, it does not have heating or stirring systems. Thus, in some cases, we also find reference to this model as "tubular", in which the constructive dimensions and the semi-continuous feeding regime end up generating flow configurations that vary between laminar and plugged (Figure 2). Another aspect of this model is the need for high hydraulic retention time (HRT), which increases the area required for installation. Example 1 presents the design of a CLB.

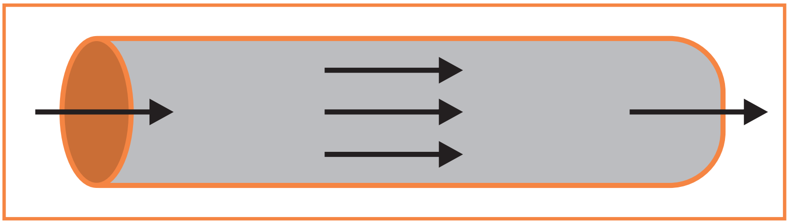


Illustration: Ricardo Steinmentz

Figure 2. Representation of a plug-flow reactor.

The absence of a heating system implies a variation in the biomass temperature of the CLB as a function of the ambient temperature, with direct implications for the capacity of biogas generation, being significantly affected in regions with a more severe winter (e.g., South of Brazil). There is a trend for sludge accumulation at the tank bottom (Example 2) due to the reactor hydraulic regime and the non-use of a solids removal system previously installed at the CLB, creating the need for disposal (Figure 3). It is often hampered by the biodigester dimensioning, preventing the efficient disposal of solids.

Photo: Pedro Colombari/Granja São Pedro

Figure 3. Sludge accumulation in a covered lagoon biodigester.

This biodigester model is generally used for treating effluents with low solids concentration, with up to about 3% (m v^{-1}) of total solids, and a low organic loading rate (OLR), between 0.3 $kg_{VS.}m^{-3}{}_{reactor}.d^{-1}$ to 0.5 $kg_{VS.}m^{-3}{}_{reactor}.d^{-1}$. Biogas productivity per reactor volume is between 0.03 $m^3.m^{-3}{}_{reactor}.d^{-1}$ and 0.15 $m^3.m^{-3}{}_{reactor}.d^{-1}$ (Catrell et al., 2008), varying according to the substrate type, OLR, operating temperature, and HRT.

Example 1

Dimensioning of a covered lagoon biodigester in a swine farm (weaning production unit) with 500 swine females (sows). The swine manure from this unit has a volatile solids concentration of 18 $kg_{VS}.m^{-3}$. The environmental agency of the State of Santa Catarina, where this farm is located, considers a waste production of 16.2 $L.sow^{-1}.d^{-1}$ (IN11 – IMA, SC).

$$\boldsymbol{Q = WPS \times NS} \qquad \textit{Equation 1}$$

Where:

Q = Waste produced daily ($m^3.d^{-1}$)

WPS = Waste production per sow ($m^3.sow^{-1}.d^{-1}$)

NS = Number of sows

Therefore:

$$\mathrm{Q} = 0.0162 \times 500 = \mathbf{8.10\ m^3.d^{-1}}$$

The biodigester volume can be calculated considering a organic loading rate of 0.5 $kg_{VS}.m^{-3}.d^{-1}$, as follows:

$$\boldsymbol{V = \frac{Q \times S_o}{OLR}} \qquad \textit{Equation 2}$$

Where:

V = Biodigester volume (m^3)

Q = Substrate flow rate ($m^3.d^{-1}$)

S_o = Concentration of volatile solids in the substrate ($kg_{VS}.m^{-3}$)

OLR = Organic loading rate ($kg_{VS}.m^{-3}.d^{-1}$)

Therefore:

$$\mathrm{V} = \frac{8.10 \times 18.0}{0.5} = \mathbf{291.60\ m^3}$$

HRT can be calculated by the equation below:

$$\boldsymbol{HRT = \frac{V}{Q}} \qquad \textit{Equation 3}$$

Where:

HRT = Hydraulic retention time (d)

V = Biodigester volume (m^3)

Q = Substrate flow rate ($m^3.d^{-1}$)

Therefore:

$$\mathrm{HRT} = \frac{291.6}{8.10} = \mathbf{36\ d}$$

The CLB model has some particularities that must be respected in its construction: a) minimum length x width ratio of 2x1; b) depth of 3 m to 4.5 m; and c) slope inclination of about 45°, which may vary depending on the ground.

Besides organic matter, which is the substrate for biogas production, many effluents are also composed of inorganic materials, characterized as fixed solids (FS). These solids, as a rule, do not contribute to biogas production and can lead to the biodigester aggradation, decreasing HRT (Figure 3). Therefore, the sludge needs to be correctly managed in the biodigester.

Example 2

A CLB has 3,000 m3, a feeding flow rate of 100 $m^3.d^{-1}$, and an FS concentration in the substrate of 12 $kg.m^{-3}$. The FS concentration in the effluent (digestate) is 9 $kg.m^{-1}$. The estimate of FS accumulation in the CLB will be:

$$\boldsymbol{AcFS = \left(FS_{substrate} - FS_{digestate}\right) \times Q} \qquad \textit{Equation 4}$$

Where:

AcFS = Fixed solids accumulation ($kg.d^{-1}$)

FS$_{substrate}$ = Fixed solids concentration in the substrate ($kg.m^{-3}$)

FS$_{digestate}$ = Fixed solids concentration in the substrate ($kg.m^{-3}$)

Q = Flow rate ($m^3.d^{-1}$)

Therefore:

$$\text{AcFS} = (12 - 9) \times 100$$
$$\text{AcFS} = \mathbf{300\ kg_{SF}.\,d^{-1}}$$

There is an FS accumulation in the reactor of 300 $kg_{FS}.d^{-1}$. Thus, 108,000 kg of FS accumulates after one year of operation.

A sand density of 2,000 $kg.m^{-3}$ can be used to estimate the sludge volume to be discarded, as follows:

$$\boldsymbol{D = \frac{m}{v}} \qquad \textit{Equation 5}$$

$$2{,}000 = \frac{108{,}000}{\text{v}}$$
$$\text{v} = \mathbf{54\ m^3.year^{-1}}$$

A total of 54 m^3 of FS will accumulate in the biodigester after one year of operation, which means approximately 2% of the useful volume. It is worth noting that we are considering only FS, but other types of solids may accumulate in the biodigester (e.g., sludge generation by biological processes). Thus, there is a recommendation for periodic disposal of this material. There is also the need to separate solids before the biodigester (e.g., sandbox) to avoid solids accumulation at the CLB bottom and a reduction in the useful volume of the tank. Reducing the useful volume of the biodigester will result in lower HRT and provide overload conditions.

UASB biodigester

The upflow anaerobic sludge blanket (UASB) biodigester is characterized by the upward flow of wastewater through a sludge blanket to the top of the reactor, where there is a three-phase separator (Figure 4).

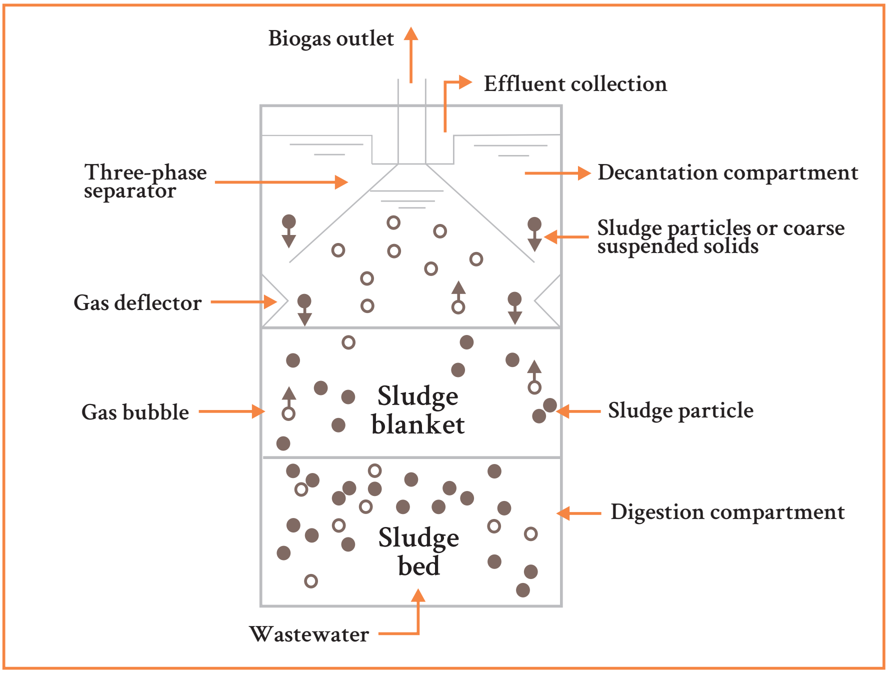


Illustration: Marcos Lins

Figure 4. Operating scheme of a UASB biodigester.

These reactors are characterized by their high biomass retention capacity, which allows them to work with a low hydraulic retention time (4 to 72 hours). In addition, UASB reactors are stable in situations of variations in the wastewater characteristics and support for high organic loading rates (0.5 $kg_{VS}.m^{-3}.d^{-1}$ to 8.0 $kg_{VS}.m^{-3}.d^{-1}$ or 2 $kg_{CODsoluble}.m^{-3}.d^{-1}$ to 32 $kg_{CODsoluble}.m^{-3}.d^{-1}$), especially under conditions in which the organic matter is solubilized.

The wastewater of the UASB reactor must have a low concentration of total solids (<2%) due to hydrodynamic reasons. It indicates that a pre-treatment of effluents from animal production is often necessary.

UASB reactor dimensioning

The organic loading rate, surface velocity, and effective treatment volume should be considered to determine the dimensions and required volume of a UASB biodigester. The effective treatment volume is the volume occupied by the sludge blanket (active biomass). There is an additional volume between the sludge blanket and the three-phase separator. The biodigester nominal volume is calculated based on the organic loading rate, as shown:

$$\boldsymbol{Vn = \frac{(Q \times S_o)}{OLR}} \qquad \textit{Equation 6}$$

Where:

Vn = Nominal volume (m^3)

Q = Wastewater flow rate ($m^3.d^{-1}$)

S_o = Wastewater concentration ($kg_{VS}.m^{-3}$)

OLR = Organic loading rate ($kg_{VS}.m^{-3}.d^{-1}$)

A correction factor is used to determine the total corrected liquid volume below the gas collection, indicating the fraction occupied by the sludge blanket. The total reactor volume can be calculated considering the correction factor, which can range from 0.8 to 0.9:

$$Vc = \frac{Vn}{E} \qquad \textit{Equation 7}$$

Where:

Vc = Corrected volume (m^3)

Vn = Nominal volume (m^3)

E = Correction factor (0,8 to 0,9)

The upward velocity is another important variable to avoid biomass carryover, being found by relating the wastewater flow rate with the cross-sectional area of the UASB biodigester:

$$v = \frac{Q}{A} \qquad \textit{Equation 8}$$

Where:

v = Upward velocity ($m.h^{-1}$)

A = UASB cross-sectional area (m^2)

Q = Wastewater flow rate ($m^3.h^{-1}$)

The upward velocity depends on the availability of organic matter present in the substrate. This relationship is shown in Table 2.

Table 2. Upward velocity and recommended height for UASB biodigesters treating different effluents.

Type of effluent	Upward velocity ($m.h^{-1}$)		Reactor height (m)	
	Range	Typical	Range	Typical
Totally soluble COD	1.0-3.0	1.5	6-10	8
Partially soluble COD	1.0-1.25	1.0	3-7	6
Domestic effluent	0.8-1.0	0.7	3-5	5

The biodigester liquid height can be determined using the following relationship:

$$H_L = \frac{V_C}{A} \qquad \textit{Equation 9}$$

Where:

H_L = Biodigester height based on the liquid volume (m)

V_C = Corrected volume (m^3)

A = UASB cross-sectional area (m^2)

The gas collector height is additional to the UASB biodigester height, approximately 25% more. Therefore, the total UASB biodigester height is defined as:

$$H_T = H_L + H_G \qquad \textit{Equation 10}$$

Where:

H_T = Total biodigester height (m)

H_L = Biodigester height based on the liquid volume (m)

H_G = Biodigester height based on the liquid volume (m)

Example 3

Many agro-industrial effluents have considerable concentrations of readily available organic matter, followed by a low concentration of volatile solids. It allows the use of UASB reactors for biogas recovery and waste stabilization. Dimension and determine the HRT for a UASB reactor treating agro-industrial effluent with the characteristics described in Table 3.

Table 3. Characteristics of an agro-industrial effluent.

Item	Unit	Value
Flow rate	$m^3.h^{-1}$	41.67
TS	$g.m^{-3}$	2,000
VS	$g.m^{-3}$	1,700
Alkalinity	$g.m^{-3}$ as $CaCO_3$	500
Temperature	°C	30

Answer:

Determine the UASB reactor volume based on a OLR of 8 kg_{VS}.m-$^{-3}$.d^{-1}:

$$\boldsymbol{Vn = \frac{(Q \times S_o)}{OLR}} \qquad \textit{Equation 6}$$

In which:

$$\mathrm{Q} = 41.67 \times 24\ \mathrm{h} = \mathbf{1,000\ m^3.d^{-1}}$$

$$\mathrm{Vn} = \frac{1{,}000\ \mathrm{m^3.d^{-1}} \times 1.7\ \mathrm{kg.m^{-3}}}{8\ \mathrm{kg_{VS}.m^3.d^{-1}}}$$

$$\mathbf{Vn = 212.5\ m^3}$$

Determine the corrected reactor volume:

$$\boldsymbol{Vc = \frac{Vn}{E}} \qquad \textit{Equation 7}$$

$$\mathrm{Vc} = \frac{212.5\ \mathrm{m^3}}{0.85} = \mathbf{250\ m^3}$$

Determination of the UASB reactor dimensions:

First, the cross-sectional area is determined based on the surface velocity (Table 2). A value of 1.5 m.h^{-1} was used because the VS/TS ratio in the effluent is 85%.

$$\boldsymbol{v = \frac{Q}{A}} \qquad \textit{Equation 8}$$

$$\mathrm{A} = \frac{1{,}000\ \mathrm{m^3.d^{-1}}}{(1.5\ \mathrm{m.h^{-1}}) \cdot (24\ \mathrm{h.d^{-1}})} = \mathbf{27.8\ m^2}$$

From this, the diameter is calculated:

$$\boldsymbol{A = \frac{\pi \cdot D^2}{4}}$$

$$27.8 = \frac{\pi \cdot D^2}{4} = \mathbf{6\ m}$$

The next step consists in determining the UASB biodigester liquid height:

$$\boldsymbol{H_L = \frac{V_C}{A}} \qquad \textit{Equation 9}$$

$$H_L = \frac{250\ m^3}{27.8\ m^2} = \mathbf{9\ m}$$

Finally, the total reactor height is determined, as follows:

$$\boldsymbol{H_T = H_L + H_G} \qquad \textit{Equation 10}$$

$$H_T = 9\ m + 2.25\ m = \mathbf{11.25\ m}$$

Note: H_G was calculated as 25% of the H_L height.

In short:

- Diameter: 6 m
- Height: 10 m
- Volume: 235 m^3

The HRT calculation considers the corrected reactor volume and the feeding flow rate:

$$\boldsymbol{HRT = \frac{V}{Q}} \qquad \textit{Equation 3}$$

$$\text{HRT} = \frac{250\ \text{m}^3 \times 24\ \text{h.d}^{-1}}{1{,}000\ \text{m}^3.\text{d}^{-1}} = \mathbf{6\ h}$$

CSTR biodigester

The continuous stirred-tank reactor (CSTR) is a biodigester model that supports high organic loading rates (1 $\text{kg}_{\text{VS}}.\text{m}^{-3}.\text{d}^{-1}$ to 4 $\text{kg}_{\text{VS}}.\text{m}^{-3}.\text{d}^{-1}$) and is characterized by its homogenized content due to the presence of a stirring system. It is the most used biodigester configuration in biogas plants, especially regarding the co-digestion (mixture of substrates) and a higher solid concentration (close to 10% m.v^{-1}). CSTR biodigesters represent approximately 90% of the reactors constructed in Europe.

The hydraulic retention time (HRT) and solids retention time (SRT) are the same for CSTR anaerobic reactors, as it is assumed that there is no sludge accumulation in the reactor. The minimum HRT in the reactor is usually between 15 and 20 days, which can vary greatly depending on the type of substrate to be digested. CSTR biodigesters without sludge recirculation are best suited for effluents with high solids concentrations.

The presence of a stirring system adds implementation and maintenance costs to a CSTR biodigester, but it assists in the heat transfer and keeps the solids in suspension, which improves the contact between organic matter and microorganisms. The temperature maintenance by heating systems ensures higher biogas production capacity, as it helps to stabilize the reactor and maintain the population of microorganisms.

Feeding system

The feeding system takes the substrate from the storage site to the biodigester. It can consist of simple transport structures, but it can also be complex systems coupled with methods of homogenization, crushing, and flow control. The level of technology applied is dependent on the project's need and budget.

Stirring system

The proper functioning of the stirring system is essential for the process stability in a CSTR biodigester. The use of a stirring system implies a 15% to 30% gain in biogas productivity (Karim et al., 2005). The importance of proper stirring applies is related to an increase in the distribution of substrates, nutrients, enzymes, and microorganisms in the biodigester. Stirring also contributes to the elimination/reduction of crusts and optimizes the release of biogas present in the sludge.

Two important aspects of stirring in a biodigester are intensity and timing. However, the information available in the literature on these aspects is still contradictory. Very intense stirring for long periods can lead to scum formation problems, affecting biogas release from the biodigester. Insufficient stirring leads to phase separation in the biodigester, interfering with inoculum/substrate contact, heat transfer, and biogas release. In summary, the influence of stirring on the biodigester efficiency depends on factors such as solids content, viscosity, fat content, and the presence of surface-active substances, which promote foam.

Stirring technologies are divided into mechanical, hydraulic, or pneumatic. Figure 5 shows schemes that exemplify the types of stirring. Hydraulic stirring (Figure 5a) occurs with recirculation inside the biodigester utilizing hydraulic pumps located inside or outside the CSTR reactor. Pneumatic stirring (Figure 5b) is established as a function of biogas recirculation, causing homogenization in the reaction medium by bubbling in the liquid or a process known as gas lift. Mechanical stirring (Figure 5c) is the most used in biogas plants and can have different intensities and stirrer models, as follows:

a) Submersible propeller motor pumps. It features high-speed ope ration (1,500 RPM) and good efficiency. It usually operates in discontinuous mode, that is, it turns on and off at programmed time intervals.

b) Long-shaft mixer (Figures 6a). It features an operation with speeds in the range of 10 RPM to 50 RPM. It usually operates in continuous mode, with the disadvantage of higher power consumption.

c) Horizontal paddle mixer (Figure 6b). It is characterized by low speed (2 RPM to 4 RPM). The operation of this stirrer is continuous, and its disadvantage is the difficulty in maintenance.

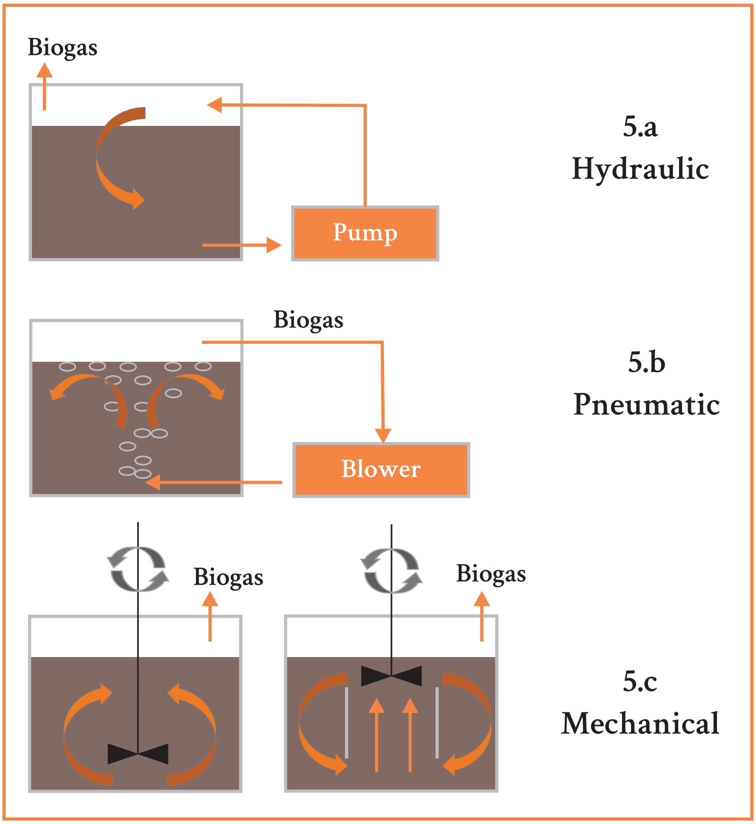


Figure 5. Examples of different stirring modes: a) hydraulic stirring, b) pneumatic stirring, and c) mechanical stirring.

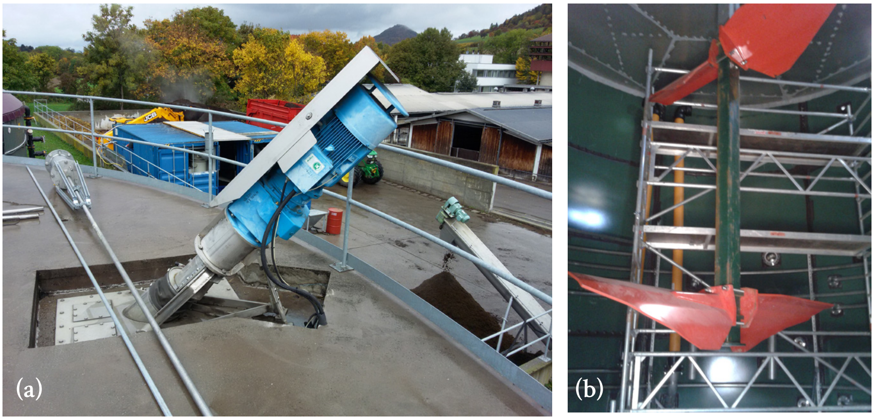


Photo: Ricardo Luis Radis Steinmetz

Figure 6. Examples of mechanical stirrers: (a) long-shaft mixer and (b) vertical paddle mixer.

Heating system

The biomass heating method is of paramount importance in continuous processes. The heat requirement is a function of the substrate flow, the specific heat capacity of the materials, the temperature difference between the substrate and the operating temperature in the biodigester, and the system heat loss.

There are several possibilities for heating biomass in a CSTR biodigester (Figure 7). Some systems opt for heating the substrate, others for direct biomass heating or even the circulation of heated water through coils inside the reactor.

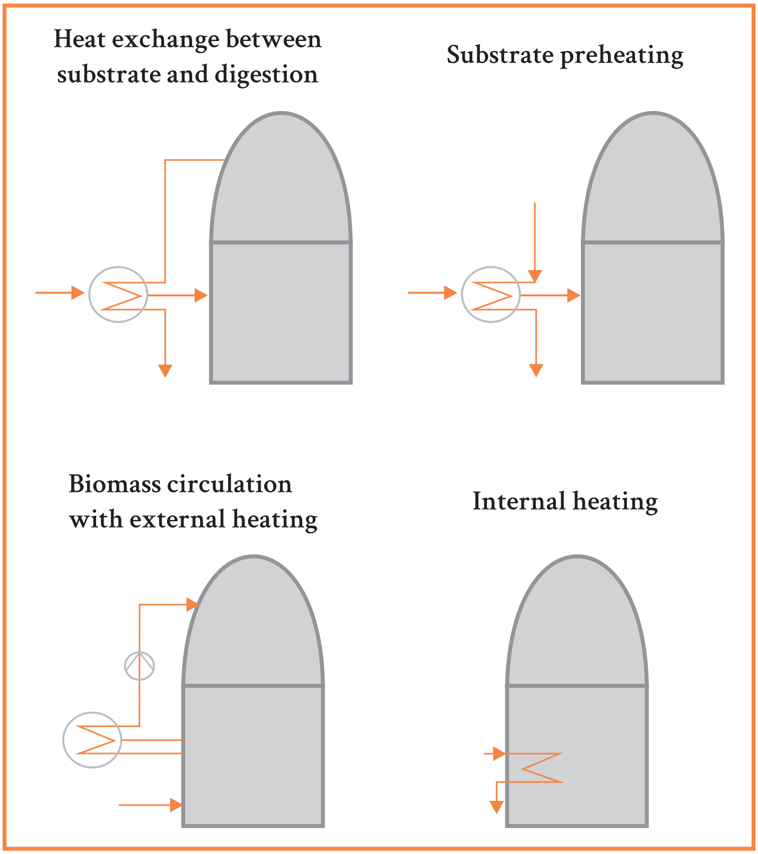


Illustration: Vivian Fracasso

Figure 7. Heating systems most used in anaerobic digestion.

The most adopted practice is the use of coils as a heat exchanger, where heated water circulates through the biomass, maintaining the desired temperature. The substrate is heated to the desired temperature suitable for biogas production through heat transfer processes.

The need for heat to be generated by the heating system can be calculated by the equation:

$$Q_{sa} = m.c_{pa}(T_2 - T_1) \times \eta$$ *Equation 11*

Where:

Qsa = Need for heat (kJ)

m = Vheating fluid flow rate (kg.s^{-1})

c$_{pa}$ = Heating fluid specific heat (kJ.kg^{-1}.ºC^{-1}; for water: 1 kJ.kg^{-1}.ºC^{-1}).

T$_1$ = Substrate initial temperature (ºC)

T$_2$ = Reactor operating temperature (ºC)

η = Process efficiency (%)

The heat needed to heat the substrate to the desired temperature can be obtained by Equation 12:

$$Q = m_s\, c_e(T_2 - T_1)$$ *Equation 12*

Where:

Q = Energy required for wastewater heating (kJ)

c$_e$ = Substrate-specific heat (kJ.kg^{-1}.ºC^{-1})

m$_s$ = Substrate mass (kg)

T$_1$ = Substrate initial temperature (ºC)

T$_2$ = Reactor operating temperature (ºC)

The following equation is used to estimate the substrate-specific heat, considering the total solids concentration:

$$C_e = 4.19 - 0.00275 \times S_{TS}$$ *Equation 13*

Where:

S$_{TS}$ = Total solids concentration in the substrate (g.L^{-1})

The heat needed to keep the temperature inside the biodigester constant is equal to the heat flux through the external surfaces and considers the construction material, which can be calculated by the equation:

$$Q_W = \frac{A(t_i - t_e)}{R}$$ *Equation 14*

$$R = \frac{e_x}{k_x}$$ *Equation 15*

Where:

Q_w = Heat flow through the contact surface ($W.m^{-2}$)

A = Surface area (m^2)

ti = Internal temperature (°C)

te = External temperature (°C)

R = Material thermal resistance ($m^2.°C.W^{-1}$)

ex = Material thickness (m)

kx = Material thermal conductivity ($W.m^{-1}.°C^{-1}$)

Example 4

A water heating system working with two heating elements of 1,800 W each was studied. These heating elements heat 55 L of water externally to a 10 m^3 biodigester, and the heated water is recirculated with a motor pump through coils in contact with the biomass in the biodigester.

The biomass temperature was indirectly controlled by the temperature of the water that recirculates in the coil. A set point could be determined for the coil water using the installed temperature controller.

The amount of energy used to heat the biomass was evaluated through the monitoring of the average time that the heating elements remained on.

The heating had the characteristic of turning on for 8.20 minutes, remaining turned off for an average of 16 minutes. It resulted in 7.50 hours connected per day.

The heating element power was calculated by multiplying current x voltage, resulting in 3.63 kW. Therefore, consumption reached 27.21 kWh d^{-1} or 816.44 kWh in a month.

This energy was enough to keep the water between 45 and 55 °C circulating in the biodigester coil, which allowed an average increase in the waste temperature of 5.6 °C, that is, from 24.70 °C to 30.30 °C in the biodigester.

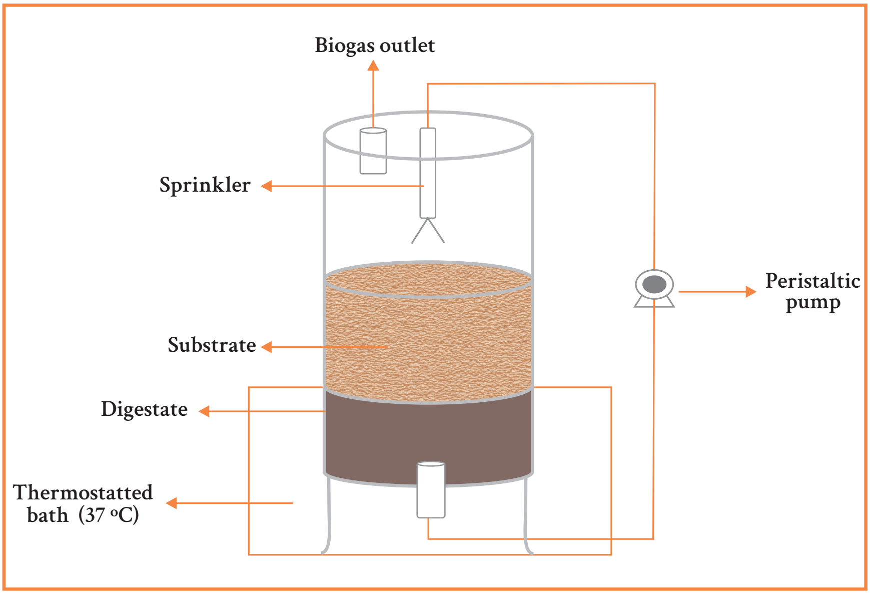
The biodigester operating conditions during this experiment were:

Flow rate = 560 $L.d^{-1}$

HRT = 18 d.

Solid-state biodigester (dry digestion)

Solid-state biodigesters are more common with a batch operation (Figure 8), being fed with waste containing between 20% and 40% solids. The substrate is added to the reactor together with inoculum (50% $m_{substrate}/m_{inoculum}$), with the percolated liquid recirculated over the solid fraction.



Source: Adapted from Marchioro et al. (2018).

Figura 8. Solid-state batch biodigester with inoculum recirculation.

The amount of solids in the biodigester affects its volume and the treatment process. Biodigesters with a smaller volume than the other technologies studied in this book are required due to the low water concentration in solid-state digestion systems. On the other hand, there is a need for pumps to recirculate the leachate.

The digestion time lasts from 2 to 4 weeks, depending on the type of substrate. The methane concentration in the biogas is relatively high, that is, approximately 80%. Solid-state digestion has some characteristics:

- Biogas productivity is 15% to 40% lower than wet digestion.
- Smaller biodigester volume.
- Supports substrates with higher solids concentration as well as larger particle size.
- No large substrate dilutions are required.
- The bioreactor needs to be opened to be filled in and/or emptied.
- The bioreactor feeding is discontinuous.

Safety in the biodigester operation and biogas handling

There is a wide range of hazards that exist in an anaerobic biodigester or biogas and/or biomethane plant. These hazards are related both to occupational and environmental risks and also the effectiveness of the biogas production process.

Biogas itself represents a hazard with chemical and physical risks due to its constituents. The gas mixture that composes the biogas has asphyxiating (suffocation) properties. Other aspects such as corrosivity and toxicity of hydrogen sulfide (H_2S), the toxicity of ammonia (NH_3), and inflammability of methane (CH_4) and hydrogen (H_2) must also be considered.

In the case of methane, the mixture with air in concentrations from 5% ($v.v^{-1}$) to 15% ($v.v^{-1}$) is sufficient for combustion to occur, and the vapors trigger an explosion if restricted in a confined space. Oxygen concentration in H_2S removal systems by injecting air or oxygen in situ in the anaerobic biodigester must never exceed 4.5% (Brasil, 2015a).

Therefore, periodic monitoring to evaluate whether there are gas leaks in the reactor, pipelines, and reservoirs is of paramount importance. A gas leak can be evaluated in several ways.

A 2% detergent solution can be used in low technological reactors (e.g., CLD in rural properties), being applied to connections, valves, gaskets, and canvas using a brush. The occurrence of bubbles would indicate gas leakage. Leaks in more advanced technological reactors (e.g., industrial-scale plants) can be monitored using special cameras, which generate images in the infrared region, allowing the identification of anomalies in the air.

The use of pressure gauges to monitor gas pressure is recommended to work around problems with excess pressure. Also, the need for valves and the possibility of flame arrester systems in risk areas must be verified. It is desirable to install at least one valve per anaerobic reactor with isolation from its respective gas chamber.

Gate and butterfly valves are the most used. Ball valves are often used in pipes with a nominal diameter of up to DN 50. Butterfly valves must be fitted with a stop. Valves made of nodular cast iron or higher quality steel should be used. Grey cast iron valves should not be used due to the possibility of a chemical attack by H_2S. Thus, valves must be made of materials resistant to the corrosion potential of biogas. Valves must be installed upstream and downstream of the flame arrester valves to allow maintenance activities to be carried out safely and prevent the entry of air into the biogas pipeline.

Alternatively, a very simple system called a water seal is used for pressure control in biodigesters operating at low pressure and small scale, as shown in Figure 9. It is a "U" tube filled with water to act as a hydraulic seal. The height is usually about 10 mm for covered lagoon biodigesters. The importance of internal pressure equalization is shown in Figure 10, in which the biodigester was displaced by excess stored gas, resulting in severe structural problems.

Photo: Ricardo Luis Radis Steinmetz

Figure 9. Gasometer pressure relief valves and simplified water seal system for pressure equalization inside a biodigester.

Photo: André Cestonaro do Amaral

Figure 10. Damaged biodigester in which there was an excessive biogas accumulation, and the water seal did not work properly.

Other risk factors involving electricity and heat should also be considered when designing a biodigester or biogas plant. Concern with the grounding of pipelines and equipment should be considered as a precaution against static electricity, avoiding sparks and electrical discharges.

Therefore, possible sources of ignition must be evaluated and avoided. The use of cell phones, smoking, or any other source of sparks or flames must not be allowed in the risk areas. In addition, the use of lightning rods must also be evaluated and considered.

The installation of burners for the disposal of excess gas is an important safety tool, but it also needs some care. The ABNT NBR 12.209 (1992) standard provided for a safe distance between burner and biodigester and/or gasometer of at least 30 m. Furthermore, the minimum distance to any other building should be 20 m.

These distances were disregarded in the updated version of this standard (2011), only indicating that the burners must be installed so that their flames, gases, and hot components do not pose a risk. In this case, the flame and the gas and smoke outlet must be at a minimum height of 3 m and the area within the 5 m radius of the burner must be free of vegetation (shrubs and trees). The enclosed burner must be installed at least 5 m away from buildings and traffic routes and open flame burners may require longer distances, which must be evaluated for each case. In all cases, the use of windshields and rain shields is recommended to improve the lighting and monitoring of the burner and pilot light, if any (Brasil, 2015a).

Other risks related to the handling of substrates or digestate must also be considered. In addition to the environmental risks, there is a biological occupational risk. Therefore, the requirements in the Regulatory Standards on Safety and Health at Work, especially standards 15 and 32 (Brasil, 2015b), should be considered.

The biological risk will depend on the type of substrate used in the biodigester and, therefore, safety precautions must be proportional. Use of personal protective equipment (e.g., gloves, closed-toe footwear, and safety glasses) should be prioritized when handling substrate and digestate samples.

Substrates with higher risk potential, such as the organic fraction of urban solid waste, domestic effluents, sewage sludge, and dead animals, may receive thermal processes such as pasteurization to reduce and control pathogens. The evaluation of technical and economic feasibility must be considered in all cases.

Inspections of hydraulic pumps and pipelines carrying substrate and digestate must be routinely carried out to avoid clogging and overpressure. Some liquids can form precipitates or deposits on the pipe walls (Figure 11), restricting the flow, causing an increase in pressure, work overload in pumps, leaks, and even a drop in biogas productivity.

In these cases, strategies for inspection of pipelines and leak containment systems must be evaluated. Alternatively, leak containment strategies should be considered. In these cases, the use of physical barriers, channels, and liquid storage tanks should be considered in all risk areas.

Photo: Lucas Scherer Cardoso

Figure 11. Struvite-encrusted digestate pipeline section.

Another basic precaution for accident prevention is the delimitation of areas where the biodigesters, reservoirs, and other facilities are located using fences and orientation notices (Figure 12).

Photo: Lucas Scherer Cardoso

Figure 12. The areas where biodigesters, reservoirs, and other facilities are located must be fenced and signposted.

Other issues such as the control of vegetation around the facilities and the control of rodents, which are largely responsible for damaging plastic membranes and electrical cables, can also avoid simple problems that impact the operation of a biodigester or biogas plant.

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