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Course:

Biological treatment of waste and effluent

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Chapter 1: Methanogenic Wastes and Effluents

1.1 Introduction

Waste is defined at European Union level as ‘any substance or object which the holder discards or intends or is required to discard.

Waste production has increased in line with rising living standards. The consequences of this are:

- An increase in the cost of treating and disposing of waste so that the burden on the environment remains or becomes acceptable;

- A growing awareness that raw materials and energy resources are finite.

Waste sorting policies at source, currently being implemented by the public authorities, have been advocated with the aim of extracting as many recoverable fractions as possible in order to reduce problematic landfill or undesirable incineration.

For local authorities' finances, these new practices mean that fewer quantities have to be transported to and treated in MSWIs; on the other hand, these same local authorities are faced with the need to find new outlets for sorted materials, particularly for organic matter collected in “green bins”.

Poor waste management - ranging from non-existing collection systems to ineffective disposal -causes air pollution, water and soil contamination. Open and unsanitary landfills contribute to contamination of drinking water and can cause infection and transmit diseases. The dispersal of debris pollutes ecosystems and dangerous substances from electronic waste or industrial garbage puts a strain on the health of urban dwellers and the environment.

1.2. Types of waste

There is a wide variety of types of waste. They can be classified according to different criteria: waste producer, waste properties, sector in which the waste is produced. This classification makes it possible to distinguish the rules applicable by those involved in waste management and to modulate these rules according to the capabilities of the producer and the risks associated with handling the waste.

➢ **Classification according to waste producer**

Waste can be divided into two classes:

- **Household waste:** where the initial producer is a household;
- **Waste from economic activities (WEA):** where the initial producer is not a household.

➢ **Classification according to waste properties**

Waste can be divided into three categories:

- **Dangerous waste (DW):** this is waste that has one or more of the 15 dangerous properties defined at European level: flammable, toxic, dangerous for the environment, explosive, radioactive, emits harmful substances, etc. Dangerous waste is subject to special management rules because of the particular environmental and health risks associated with its handling.
- **Non-dangerous waste (NDW):** this is waste that does not have any of the 15 dangerous properties defined at European level. Management rules are more flexible than for dangerous waste. Examples include bio-waste, glass or plastic waste, wood, etc.
- **Inert non-dangerous waste:** non-dangerous waste is waste that does not undergo any significant physical, chemical or biological change, does not decompose, does not burn, does not produce any physical or chemical reaction, is not biodegradable and does not damage the materials with which it comes into contact in a way that could harm the environment or human health. Most of this waste comes from the building and public works sector (waste concrete, bricks, tiles, etc.).

❖ **Waste classification in accordance with Algerian regulations** (Ministry of Regional Planning and the Environment)

Executive Decree 06-104 of 28 February 2006 sets out the waste nomenclature in 04 classes (table 1):

- **Household and similar waste (HSW).**
- **Inert waste (IW).**
- **Special waste (SW).**
- **Dangerous special waste (DSW) :** substances that are oxidising, excremental or easily flammable, irritating, harmful, toxic, carcinogenic, corrosive, infectious, toxic to reproduction, mutagenic or dangerous to the environment....

Table 1: Examples of wastes in Algerian classification

HSW	IW	SW	DSW
- Plant tissue waste - Wood processing waste - Paper and cardboard production and processing waste - Packaging and packaging waste (paper, cardboard, glass, wood, textile, plastic, metal) - Biodegradable garden and park waste	- Gravel waste, - Stone debris - Drilling muds - Waste from the manufacture of ceramic products, bricks, tiles and building materials, - Gypsum-based building materials	- Waste from the extraction of metallic minerals, - Sludge from alumina production, - Animal tissue waste, - Forestry wastes (forest trees), - Waste from the preparation and processing of meat, fish and other foods of animal origin	- Mud and waste from hydrocarbon drilling, - dangerous agrochemical waste, - Wood protection waste, - Degreasing waste from the baking industry

1.3 Treatment processes

Waste treatment refers to the physical, thermal, chemical or biological processes that modify the characteristics of waste in order to reduce its volume or dangerous nature, facilitate its handling or promote its recovery.

Waste treatment, must respect the hierarchy of waste treatment methods: prioritising re-use, then recycling, and avoiding disposal, saves resources as part of the transition to a circular economy. Waste valorisation consists of reuse, recycling or any other action aimed at obtaining reusable materials or energy from waste.

- **Recycling** is the direct reintroduction of waste into the production cycle from which it came, in total or partial replacement of a new raw material. For example, taking broken bottles, remelting them and making new bottles.

- **Reuse:** this is the re-employment of waste for a use similar to that for which it was first used. In a way, it means extending the life of the product before it becomes waste. An example is the return of bottles, which are refilled after cleaning.

- **Re-usability** involves using waste for a purpose other than its original use, or using waste to make a product other than the one that gave rise to it. For example, using car tyres to protect the hulls of boats or trawlers.

- **Regeneration** consists of a physical or chemical process that restores the characteristics of a waste product so that it can be used to replace a new raw material. This is the case, for example, with the regeneration of used oils or solvents, or paper, which is both recycled and regenerated by de-inking.

- **Energy valorisation** consists of using the calories contained in waste by burning it and recovering the energy produced to heat buildings or produce electricity, for example. It is the exploitation of the energy contained in waste.

- **Composting** is a process of aerobic biological degradation of organic waste (matter) to produce composts.

- **Spreading:** is an agricultural practice that consists of spreading organic waste on fields (is the action of spreading materials of organic interest on fields) is a way of returning organic waste to the soil (' livestock effluents and sludge from waste water treatment plants).

- **Incineration:** destruction of waste by burning (used for contaminated waste), which recovers metals and energy from solid waste and reduces the volume of waste.

Note: Whatever the type of treatment, the waste must be as pure as possible, and free from heavy metals and organic micropollutants (pesticides, medicines, etc.).

1.3.1 Biological processes

All organic waste of animal and plant origin can be degraded by aerobic or anaerobic processes.

- **Aerobic treatment**' is a process that involves using bacterial populations to degrade fats, lactose, and proteins in dairy waste by exposing them to oxygen.

- **Anaerobic waste treatment** is a biological process where microorganisms degrade organic contaminants in the absence of oxygen.

Depending on the characteristics of the waste or effluent to be treated, one or other of these processes may be considered, allowing optimisation of the process and the desired results.

1.3.2 Comparison between aerobic and anaerobic processes

Depending on the characteristics of the waste or effluent to be treated, one or other of these processes may be considered, allowing optimisation of the process and the desired results. Each approach has its advantages and disadvantages, but there are four key differences between the two mechanisms:

a- Energy balance

Aerobic treatment requires prolonged aeration, which results in a high energy expenditure to pulse the air and a loss of non-recoverable thermal energy from the degradation of fermentable matter.

Anaerobic treatment not only dispenses with energy-intensive aeration, but also produces biogas that can be used to balance the energy balance of the process itself and as a back-up resource for industrial applications.

b- Reduction in the volume of material to be treated

Aerobic treatment converts organic matter essentially into biomass and CO_2, whereas anaerobic treatment converts organic matter essentially into combustible gas and CO_2.

c- Plant infrastructure

In most cases, aerobic treatment involves relatively simple technical means, whereas anaerobic treatment requires more complex facilities, which can entail comparatively greater investment. However, the land required for aerobic treatment is larger than that required for anaerobic

treatment.

d- Phases involved in degradation

From the point of view of substrate degradation, aerobic treatment involves three phases: gaseous (oxygen required), liquid (medium in which the micro-organisms live) and solid (the micro-organisms themselves and often also the particles to be degraded), whereas anaerobic treatment is a two-phase process: liquid (habitat of the bacteria) and solid. Biogas is a product whose concentration has little influence on the degradation of substrates. Aerobic degradation is a difficult system to optimise, particularly for solid waste.

1.3 Areas of application of anaerobic digestion

Methanisation (also known as Anaerobic digestion): is a microbial degradation process during which complex organic matter is transformed into a biogas composed of combustible gas methane and carbon dioxide and a solid or liquid residue (called digestate).

This advantage may lead people to opt for systems for the anaerobic treatment and purification of waste or effluents, as they ensure that the processes used are at least energy self-sufficient

The table 2 shows the main sectors in which certain wastes and effluents can be treated anaerobically.

Table 2: Methanogenic Wastes and Effluents by Sector of Activity

Sector of activity	**Methanogenic waste**	**Methanogenic effluent**
Urban sanitation	Organic fraction of household waste	Sewage sludge
	Landscaping waste (lawns, grass cuttings, dead leaves, aquatic plants)	
	Heavily soiled paper	
	Waste from catering, markets and supermarkets	
Food industry		
Milk industry		Whey, process water

Sugar industry	Beet pressing cakes, molasses	Wastewater (washing, pressing, processing)
Distilleries		Stillage, yeasts
Slaughterhouses	Rumen contents, excrement and miscellaneous debris	Effluents from slaughter areas, stables and gut-processing facilities
Fruit juice industry	Fruit residues, suspended matter and sludge	Washing and transport water
Breweries	Draff and hop residues, albumin haze, yeast	Washing, cleaning and cooling water
Potato industry	Peeling pulp, settling sludge from wash water, flour, fried, raw and frozen products	Washing, transport and cooling water, pulp pressing water, starch washing water
Fruit and vegetable production and canning	Production and manufacturing waste	Washing and blanching water
Wine industry	Grape marc	Stillage
Margarine, fat and oil factories	Sieving debris	Cleaning, extraction water, distillate
Coffee and tea processing	Coffee grounds, extraction residues	
Other industries		
Pharmaceutical and cosmetic Industry		Spent culture broths (antibiotic production), mycelium sludge, washing water
Paper industry		Process water from pulp manufacturing, chip cooking, cardboard mills and paper production

1.4 Assessment criteria

The parameters taken into account to assess the applicability of anaerobic digestion depend essentially on the objectives of treatment, as is the case for effluents, or recovery, as is the case for waste.

1.4.1 Common criteria to effluents and waste

- **Temperature**

Most industrial anaerobic digestion plants operate at mesophilic temperatures (30-40°C), which often correspond to the discharge temperatures of industrial waste and effluent. At higher temperatures, or when the waste needs to be hygienised for agricultural use, thermophilic digesters (50-60°C) can be used. When the liquid or solid residues are at too low a temperature, they need to be heated using an auxiliary energy source or the biogas itself. Fresh material can be heated by heat exchange with the digested product.

- **Nutrient composition**

Methanogenic bacteria require certain nutrients for their metabolism, the lack of which is a limiting factor. These requirements can be met by combining certain types of waste (e.g. codigestion of household waste, low in nitrogen and sulphur, with sewage sludge rich in these nutrients). Overall, the culture medium should have C, N and P levels of around 100-4-1. Other elements, such as Na, K and Ca, as well as trace elements such as Zn, Cu and Mg, influence gas production.

1.4.2 Criteria for effluent

- **Organic load expressed as COD**

Effluents with a high (> 15,000 mg COD/l) or medium (> 2,000 mg COD/l) organic load can be effectively treated by anaerobic digestion. The commonly accepted areas of application for aerobic and anaerobic treatment are summarised in the diagram below. Aerobic processes are predominant for effluents with biodegradable BOD or COD of less than 2000 mg/l. Between 2000 and 30,000 mg/l, anaerobic treatment systems, whether conventional or high performance, are applicable. Highly concentrated effluents containing more than 20,000-30,000 mg COD/l, or with high levels of suspended solids, are commonly treated by anaerobic digestion.

- **Suspension matter**

When, for a given effluent, the ratio of total COD to soluble COD is greater than 1, complete reduction of the pollutant load can only be achieved by eliminating both soluble and suspended matter during treatment. Limits for suspended matter are empirically set at 10% of total COD for high-performance systems. For wastewater containing more than 50% of the total COD in particulate form, it may make economic sense to use anaerobic treatment with a low organic load rate (1- 4 kg COD/m3.day) rather than carrying out a pre-treatment stage. It is also important to know whether the suspended matter is biodegradable; if this is the case, it will also undergo anaerobic degradation, albeit more slowly.

- **Toxic and inhibiting substances**

Industrial effluents are likely to contain toxic or inhibiting substances that can, in certain cases, disrupt the operation of anaerobic reactors. This toxicity will depend on the nature of the toxic compounds, their concentration and the degree to which the microorganisms adapt to them.

1.4.3 Criteria for waste

- **Origin and nature**

The solid substrates available for anaerobic digestion are essentially urban and industrial residues of varying chemical composition. Carbohydrates predominate, represented by cellulose and hemicelluloses. Lignocellulosic plant residues are particularly resistant to bacterial action and are less suitable for anaerobic digestion. The water content of the waste is also a determining factor in the choice of recovery method. If the dry matter content is around 30-35%, anaerobic digestion is the most attractive option.

Chapter 2 : Digestion technology

2.1 Biological parameters

The degradation of organic matter by anaerobic digestion, i.e. in the absence of oxygen, leads to the production of a gas composed essentially of methane and carbon dioxide.

This process involves various populations of micro-organisms. The substrates used by these bacteria and the products they produce make it possible to distinguish different phases in the biosynthesis of methane (figure 1).

The bacterial populations involved in anaerobic digestion have very different growth rates, which determines the limiting stages in the process.

- **Hydrolysis and fermentation**

In the first phase, the polymers and complex molecules making up the organic matter are transformed by the hydrolytic and fermentative bacteria (i.e. *Clostridium spp. ; Ruminococcus spp. And Fibrobacter succinogenes*) into a wide range of organic acids, alcohols and gaseous products. The composition of the intermediate products is influenced by the partial pressure of hydrogen.

- **Acetogenesis**

The formation of acetate is favoured in the presence of low hydrogen pressures, while that of propionate, butyrate, ethanol and lactate is favoured in the presence of high partial pressures. Most of the organic acids and alcohols produced in the first stage will then be broken down into acetate, hydrogen and carbon dioxide, which are the precursors of methane; this is the second stage in the process, which avoids an accumulation of volatile fatty acids other than acetic acid. As example of microorganisms involved in this phase: *Escherichia coli; Streptococcus spp.; Clostridium spp.; Syntrophobacter; Desulfovibrio.*

- **Methanogenesis**

The final stage in the process is the formation of biogas. Around 70% of the methane produced comes from the decarboxylation of acetate, with the remaining 30% resulting from the reduction of carbon dioxide by hydrogen. Microorganisms involved are the Archaea as: *Methanobacterium* spp. *; Methanosarcina* spp. and *Methanospirillum hungatei.*

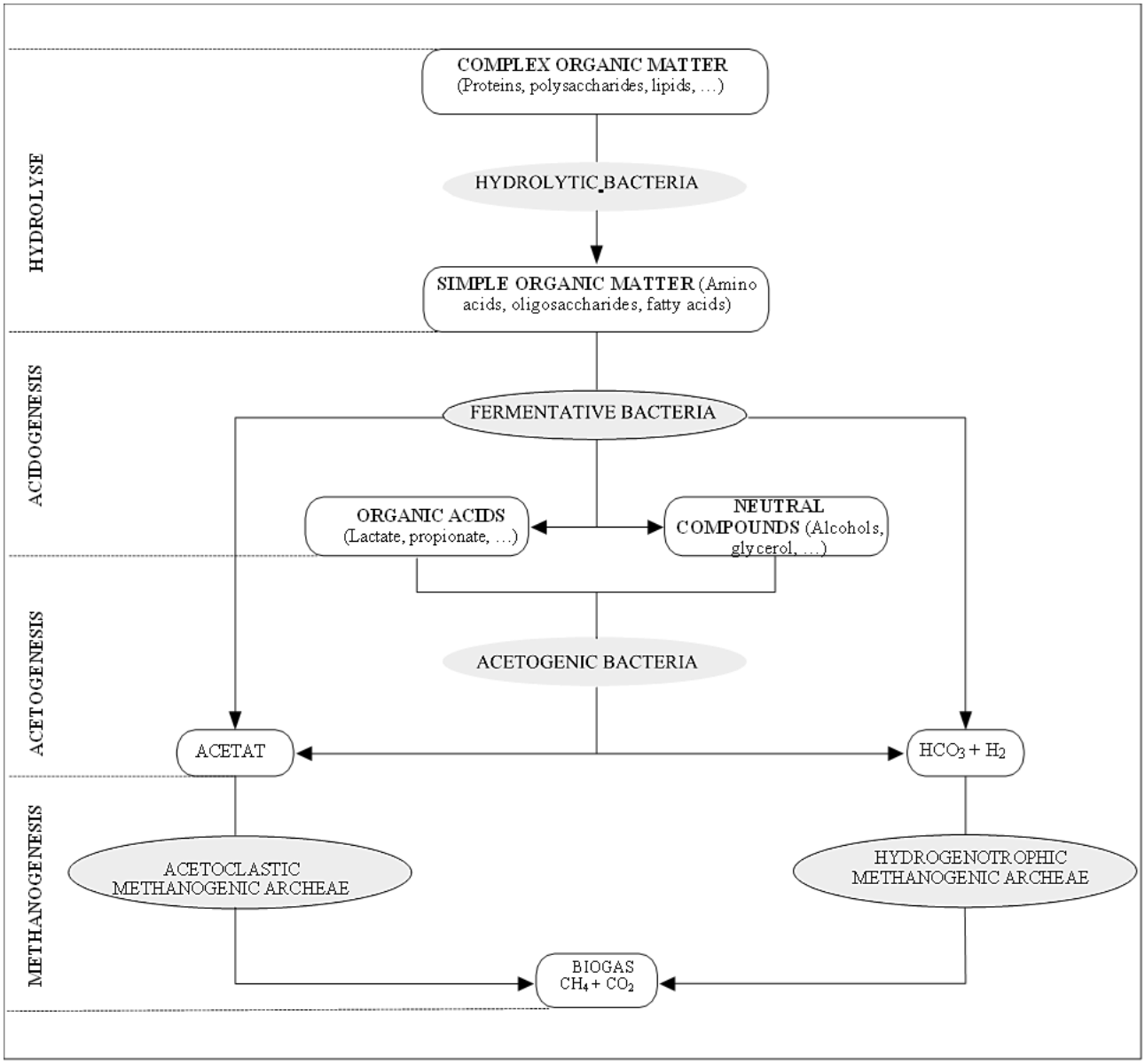


Figure 1: Stages of the biological anaerobic digestion process

2.1.1 Physico-chemical conditions affecting the methanisation process

- **Temperature**

This factor has a direct influence on the reaction rate of the anaerobic digestion process. Depending on their optimum temperature of activity, bacteria are classified into three groups: psychrophilic (less than 20°C), mesophilic (between 20°C and 45°C, with an optimum around 35°C) and thermophilic (from 45°C, with an optimum around 55°C). Gaseous productivity increases in parallel with the rise in temperature, up to around 45°C, a temperature that is not favourable to any of the mesophilic or thermophilic bacteria. Below 10°C, production decreases drastically. The mesophilic temperature range found in most digesters is the most

interesting in terms of the energy balance, as it leaves the largest proportion of net recoverable energy. The thermophilic temperature range can be interesting for household waste, for example, as it helps to inactivate pathogens.

Table 3: Main advantages of anaerobic digestion in a mesophilic or thermophilic setting.

Criteria	Mesophilic Range	Thermophilic Range
Water vapour in gas	Less water vapour in the gas	Higher water vapour in the gas
CO_2 content in gas	Less CO_2 in the gas	Higher CO_2 in the gas
Microbial diversity	More methanogenic microbial species: hence ecosystem stability	Fewer microbial species
Energy balance	More favourable energy balance	Less favourable energy balance
Use of calories	Possibility of using calories at low levels	Not applicable
Microbial activity	Lower activity: longer retention time	Greater activity: shorter retention time
Sludge production	Higher volumes of sludge formed	Lower volumes of sludge formed
Pathogen destruction	Limited destruction of pathogenic micro-organisms	Effective destruction of pathogenic micro-organisms
Anaerobic conditions	More difficult to maintain anaerobic conditions	Easier maintenance of anaerobic conditions, due to lower gas solubility at higher temperatures

- **pH and alkalinity**

The optimum pH for methane production is close to neutral, with an optimum of between 6.5 and 7.5. In single-stage systems (see page 25), the production and consumption of acids during the various biological stages means that the pH can easily be stabilised in a range close to the optimum. In two-stage systems, the pH of the acid-generating stage decreases and must be maintained between 5.0 and 6.5 to ensure that the bacteria function optimally.

Any drop in pH reflects an imbalance resulting from an accumulation of volatile fatty acids; it occurs when the medium's buffer capacity is saturated. A drop in pH inhibits the activity of methanogenic bacteria.

The pH balance is essentially ensured by dissolved bicarbonates, themselves in equilibrium with dissolved carbon dioxide. Concentrations of 2,500 to 5,000 mg/l provide a good buffer effect. If, by accident, methanogenesis is inhibited, the accumulation of volatile fatty acids will lead to a reduction in dissolved bicarbonate ions and a release of carbon dioxide. The drop in alkalinity due to bicarbonates, below 1500 mg/l, precedes a drop in pH.

- **Redox potential**

Microbial processes are always accompanied by oxidation-reduction reactions. It is from this type of reaction that microorganisms draw the chemical energy they need for their maintenance and growth. In pure culture, methanogenic bacteria require low redox potentials (-300 to -330 mV). In a fully active digester, much higher redox potentials are measured (-50 mV to 0 mV). To encourage the activity of methanogenic bacteria, it is important to ensure a favourable redox potential at all points in the digester; to do this, the input of oxidising substances such as nitrates, nitrites and, of course, oxygen is kept to a minimum. Toxicity and inhibition

Industrial effluents are likely to contain toxic or inhibiting substances that can, in certain cases, disrupt the operation of a digester. The extent of the effect depends on the nature of the toxic compounds, their concentration and the degree to which the micro-organisms are adapted to them (see table below). In practice, however, we can only speak of toxicity in rare cases, often linked to questions of concentration.

Several contradictory results have been published concerning the maximum concentrations of different organic or inorganic toxins that can be tolerated in a digester. These discrepancies can be attributed to differences in the sensitivity and adaptation of the bacteria present, the type of digester and its mode of operation, the com- position of the effluent, and also the criteria used to assess toxicity. The table is therefore a synthesis of information from different sources and should not be regarded as an absolute truth establishing once and for all limit concentrations that are valid in all cases. Its purpose is simply to draw attention to a few substances that may cause problems when starting up or operating an anaerobic digester. It is also important to note the following points:

- Like all living organisms, anaerobic bacteria are sensitive to a number of toxic or inhibiting factors. However, most of these have reversible effects, temporarily reducing or blocking the growth and activity of the bacteria. Irreversible or bactericidal effects are only observed for a few substances or for very high concentrations. In addition, the sensitivity of bacteria to an

initially toxic compound can change over time as a result of adaptation or the selection of resistant bacteria. The microbial ecosystems present in two digesters of identical or different types, treating similar or dissimilar effluent, are therefore not necessarily composed of the same bacterial strains. As a result, their reaction to the various toxins will not be the same.

- The addition of a toxicant will not have the same consequences on the operation of a digester, depending on whether it is a one-off, chronic or continuous addition. In the case of a one-off or accidental addition, the toxicity is reversible below a critical concentration and the recovery time depends on the concentration of the toxicant and the duration of exposure. Above this level, no recovery is possible and the only solution is to empty the digester completely. If the presence of the toxicant is chronic or continuous, the bacteria will probably be able to adapt to increasing concentrations (see figure below), even if the performance of the system is temporarily impaired.

- Sensitivity to a toxicant also depends on the type of digester and how it is fed. Generally speaking, immobilised biomass systems such as anaerobic filters or UASBs have higher concentrations of inhibitors than conventional digesters, which have a lower concentration of bio-mass. In an infinitely mixed system, however, the hydraulic residence time is high, which has the effect of diluting the toxic compounds below the critical thresholds and thus limiting their inhibiting effect if their addition is limited in time. In an immobilised biomass process, the short hydraulic residence time minimises the effect of a one-off shock. In addition, the high concentration of biomass and its long residence time mean that it can withstand a period of reduced growth and activity without being eliminated from the digester. This encourages acclimatisation and adaptation to toxic substances in the event of chronic exposure, or recovery in the event of temporary exposure. In addition, the support of a fixed, expanded or fluidised bed can often adsorb toxic compounds and limit their effects. In some cases, it is even possible to play with the possibilities offered by the system configuration and the different effluent loading options to obtain appropriate dilution of the toxic compound or concentration of the biomass.

- The presence of antagonistic or synergistic compounds in the effluent will determine the effect of certain toxins. As a compound only acts on bacteria in free or soluble form, the presence of agents that complex heavy metals or precipitate them can modify their apparent concentration and therefore their toxicity. The inhibitory effect of metals also depends largely on the anion that accompanies them (chloride, sulphide, sulphate, nitrate, carbonate, etc.). In the presence of sulphide, for example, they precipitate and therefore become non-toxic for the

bacteria present in the digester. However, it is difficult to define a course of action or to prescribe a strict methodology for adding the appropriate antagonistic substances in a safe and reproducible way. Finally, the undissociated forms of sulphides (H2S, Na2S) and ammonia (NH3) are toxic at much lower concentrations than the dissociated forms. As the equilibrium between the two forms depends largely on pH and temperature, these two factors can be manipulated to minimise their inhibitory effect.

2.2 Waste and effluent from industry and public authorities

Urban waste and wastewater can be clearly distinguished by the method of disposal: sewage for liquid waste and containers for solid waste. The latter category also includes all fermentable waste from supermarkets, catering establishments, landscaping and river and lake cleaning. Fermentable waste from industry is very often in wet form, as water is either a manufacturing agent or a means of cooling. Industry therefore generates both polluted effluents and wet waste (manufacturing rejects, sludge, separation residues, etc.). The latter is sometimes discharged mixed with the former.

Table 4: Examples wastes from the food industry

Abattoirs	
Activities	**Waste produced**
Transport of animals, Cleaning of lorries	Manure, straw and other bedding, slurry
Stabling before slaughter	Hay, mulched manure, slurry
Slaughter :	
Bleeding, evisceration, splitting Cutting and weighing of animals	Stomach contents (stercorales), blood clots, bone sawdust, dander (pig bristles, hair, hooves, horns, etc.) Cartilage, ears, etc.
	Fragments of fatty, connective and muscular tissue
Tripe - gutting	Fat, tripe and gut contents, connective tissue ... Sawdust and shavings, various sweepings Pre-treatment solid waste : Screening Fine screening Degreasing by flotation
Cleaning of equipment, premises, maintenance Liquid effluent pre-treatment station	Sewage sludge after pre-drying for handling

Most organic waste with more than 15% dry matter has no free water and is considered solid. Residues with between 6% and 15% dry matter contain small amounts of free water or high concentrations of suspended solids, and can be defined as semi-solid.

In the past, anaerobic digestion was reserved for treating waste containing more than 90% water, but it has now been shown that it can also be successfully applied to waste with a dry matter content of close to 30%.

2.3 Digestion systems

Three essential characteristics are used to distinguish digestion systems:

- **Alimentation mode:** how the substrate is fed into the digester;
- **Biomass format:** the route chosen to ensure the maintenance of a large biomass and the longest possible residence time for the micro-organisms, and to improve contact between the biomass and the substrate to be treated (free or immobilized biomass)
- **Number of stage:** separation of the stages of the biological process.

2.3.1 Alimentation mode

There are three feeding modes to consider.

a- **Batch feeding:** The reactor is completely filled with the substrate to be digested in a single operation. Once anaerobiosis has been achieved, gas production evolves regularly, but is limited in time and reaches a maximum, so that to obtain a regular flow of biogas you need several reactors in a battery, filled and emptied at regular intervals. This feeding method, originally used for agricultural waste, has been adopted for applications in the methanisation of household waste.

b- **Fed-batch:** The second feeding method involves progressively filling the reactor during digestion, without removing any substrate before the end of the process. This is known as semi-continuous feeding or fed-batch.

c- **Continuous feeding**: In the third mode, the substrate is introduced and the digested product extracted progressively and continuously, so that the effective volume of biomass in the digester remains constant. In practice, most systems operate in continuous mode.

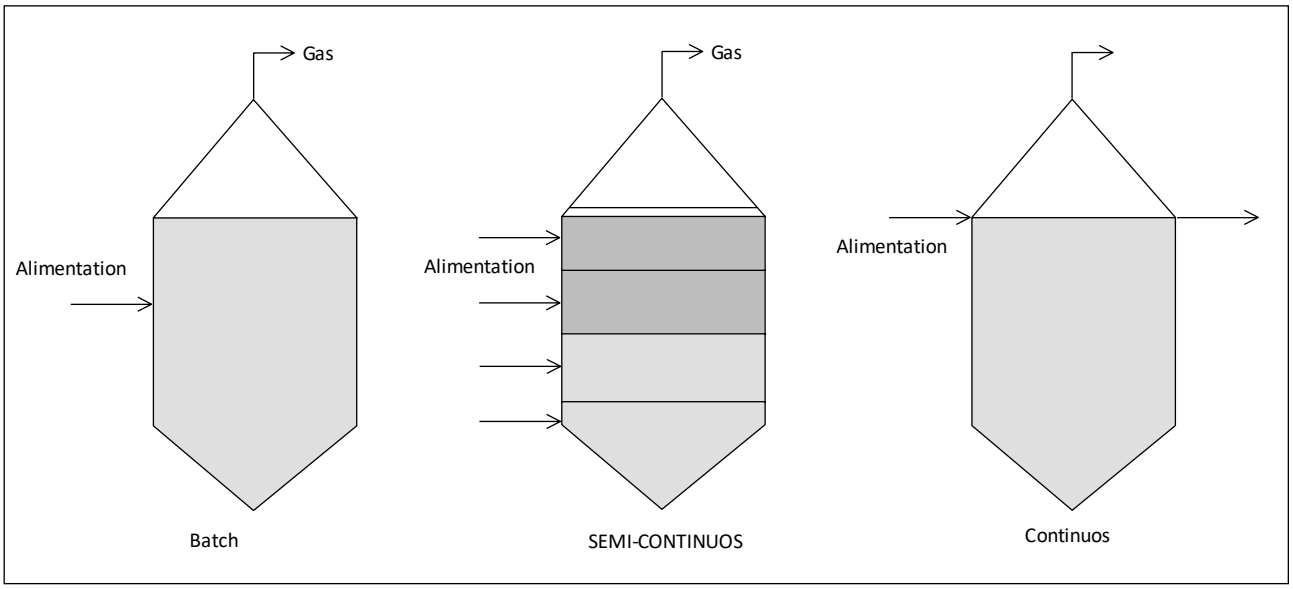


Figure 2: Schematic representation of alimentation modes of anaerobic digestion reactor

2.3.2 Biomass format

The second characteristic relates to the physical arrangement and retention strategy of the microbial biomass within the reactor. The primary objective is to maintain the highest possible concentration of active biomass whilst ensuring the longest achievable residence time for the micro-organisms, and to maximise contact between the biomass and the substrate to be treated. Two broad approaches are distinguished:

a- Free biomass systems: in which micro-organisms are suspended throughout the liquid medium. In this configuration, the hydraulic retention time (HRT) and the sludge retention time (SRT) are directly linked, which may limit process efficiency when fast-growing substrates are used.

b- Immobilised biomass systems: in which micro-organisms are attached to a support medium (biofilm) or form dense aggregates (granules), as seen in technologies such as the Upflow Anaerobic Sludge Blanket (UASB) reactor. This approach effectively decouples the HRT from the SRT, allowing for significantly shorter hydraulic retention times without compromising microbial retention, thereby improving overall reactor performance and stability.

2.3.3 Number of stages

The third characteristic concerns the degree of separation of the successive biological stages of the anaerobic digestion process (hydrolysis, acidogenesis, acetogenesis, and methanogenesis). Two principal configurations are employed:

a- **Single-stage systems**: all four biological phases occur simultaneously within a single reactor. Whilst simpler and less costly to construct and operate, this configuration requires a careful balance of operating conditions to satisfy the often-conflicting requirements of the different microbial populations involved.

b- **Multi-stage systems:** in which the biological process is deliberately separated into two or more reactors, each optimised for a specific phase of digestion. Most commonly, hydrolysis and acidogenesis are carried out in a first reactor, whilst acetogenesis and methanogenesis take place in a second. This separation allows each stage to be operated under its own optimal conditions (pH, temperature, retention time), resulting in greater process stability, improved biogas yields, and enhanced resistance to toxic or inhibitory compounds.

The appropriate combination of these three characteristics determines the design and suitability of a digestion system for a given substrate and operational context.

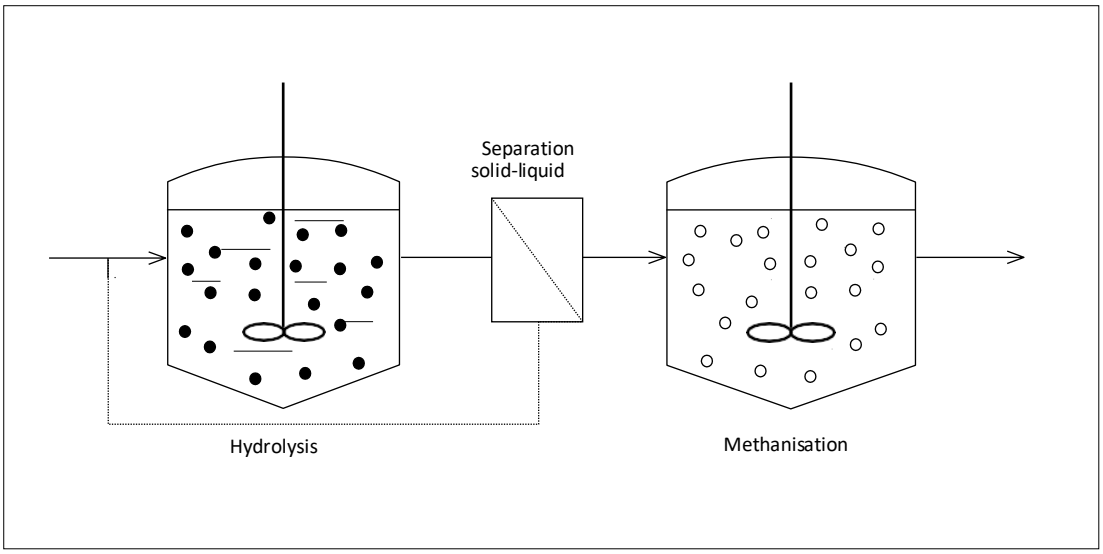


Figure 3: Schematic representation of Bi-stage process reactor

2.4 Digestion system technology

2.4.1 Effluent digestion processes

- **Infinitely Mixed Digesters (Continuously Stirred Tank Reactors – CSTRs)**

Infinitely mixed digesters, commonly referred to as Continuously Stirred Tank Reactors (CSTRs) (figure 4), are amongst the most widely used anaerobic digestion technologies worldwide. They are considered particularly well-suited for the treatment of agricultural slurries and for the stabilisation of urban wastewater sludge, owing to their relatively simple design, ease of operation, and robust performance under varying organic loading conditions.

In these reactors, mechanical or hydraulic mixing devices are employed to maintain the homogeneity of the liquid medium throughout the digestion vessel. This continuous agitation ensures a uniform distribution of substrates, micro-organisms, nutrients, and temperature across the entire reactor volume, thereby promoting consistent biological activity and preventing the formation of dead zones or floating scum layers that could otherwise impair process efficiency.

However, this thorough mixing characteristic also gives rise to a fundamental operational limitation. Since the digested effluent within the reactor is maintained at a uniform concentration, the liquid leaving the digester carries with it the same concentration of micro-organisms as that found within the reactor itself. Consequently, at high hydraulic loading rates -large volumes of influent are processed within short hydraulic retention times (HRTs)) a significant proportion of active biomass is lost through entrainment in the outgoing effluent. This progressive washout of micro-organisms can critically undermine the biological stability of the digestion process, as the replenishment of slow-growing anaerobic bacteria, particularly acetogenic and methanogenic populations, cannot keep pace with the rate of biomass loss.

Furthermore, the use of infinitely mixed systems presents notable limitations when applied to effluents characterised by a high concentration of soluble organic matter or containing readily and rapidly degradable substrates. In such cases, the rapid consumption of available substrates by fermentative bacteria can lead to the transient accumulation of volatile fatty acids (VFAs), causing a drop in pH and potentially inhibiting methanogenic archaea, which are highly sensitive to acidic conditions. The lack of spatial separation between the acidogenic and methanogenic phases within a single-stage CSTR further exacerbates this

risk, making process control more challenging and potentially leading to digester instability or failure.

For these reasons, whilst CSTRs remain a reliable and cost-effective solution for treating complex solid-rich effluents with moderate organic loading, their application to high-strength soluble wastewaters or rapidly biodegradable substrates may require supplementary process adaptations, such as two-stage digestion configurations or biomass retention strategies, in order to ensure stable and efficient long-term operation.

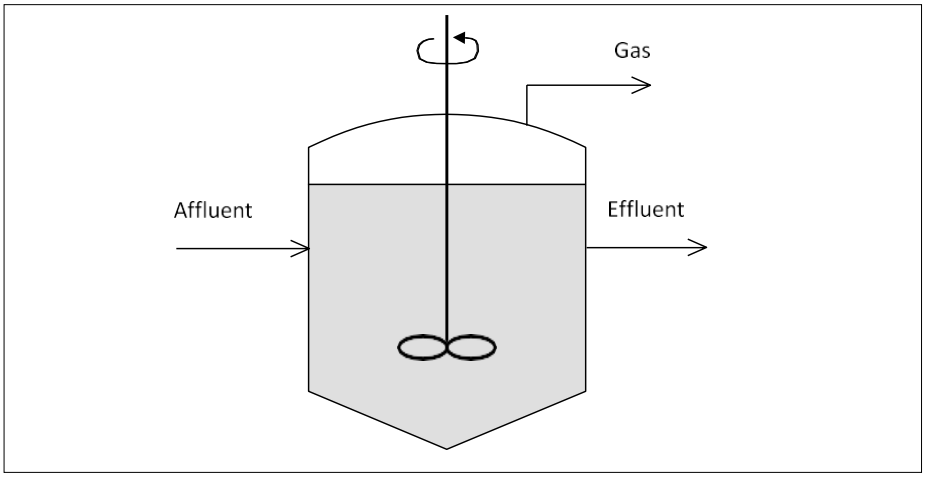


Figure 4: Schematic representation of infinitely mixed digester

- **Anaerobic contact**

The anaerobic contact process represents one of the earliest and most fundamental advances in anaerobic effluent treatment technology. Derived directly from conventional aerobic treatment processes — most notably the activated sludge system — the anaerobic contact process adapts the same core principle of biomass recycling to suit the specific conditions of an oxygen-free environment.

The system consists of two principal components: a continuously and infinitely mixed digester, in which the incoming effluent is brought into thorough contact with the active microbial biomass, followed by a dedicated decanter (or settling tank), where the active organic matter suspended in the treated effluent is allowed to settle and separate. The settled biomass is then recycled back to the digester, thereby maintaining a sufficiently high concentration of active microorganisms to ensure efficient degradation of the organic load.

This recycling mechanism is what fundamentally distinguishes the anaerobic contact system from a simple infinitely mixed digester. By retaining and returning the biomass rather than allowing it to be washed out with the treated effluent, the system effectively decouples the hydraulic retention time (HRT) from the sludge retention time (SRT). This allows the digester to operate at shorter hydraulic retention times without compromising the biological activity within the reactor. In practice, digesters operating on this principle have been shown to perform approximately twice as efficiently as a conventional simple infinitely mixed digester operating under comparable conditions.

However, a notable limitation of the anaerobic contact process lies in the external decantation stage. Unlike aerobic sludge, anaerobic biomass does not always exhibit favourable settling characteristics. The presence of fine colloidal particles, biogas bubbles adhering to the sludge flocs, and the generally lower density of anaerobic biomass can render external settling tanks less reliable and less effective than their aerobic counterparts. This inherent drawback has driven considerable research and development efforts towards alternative configurations.

As a direct response to this limitation, digesters incorporating integrated decanters were subsequently developed. By internalising the separation stage within the digester vessel itself, these systems offer greater control over the settling environment and reduce the risk of biomass washout. As illustrated in figure 5, this configuration enables the maintenance of a high sludge concentration within the reactor, even when treating effluents where the organic load is predominantly in dissolved rather than suspended form a condition that would otherwise prove particularly challenging for conventional external settling systems.

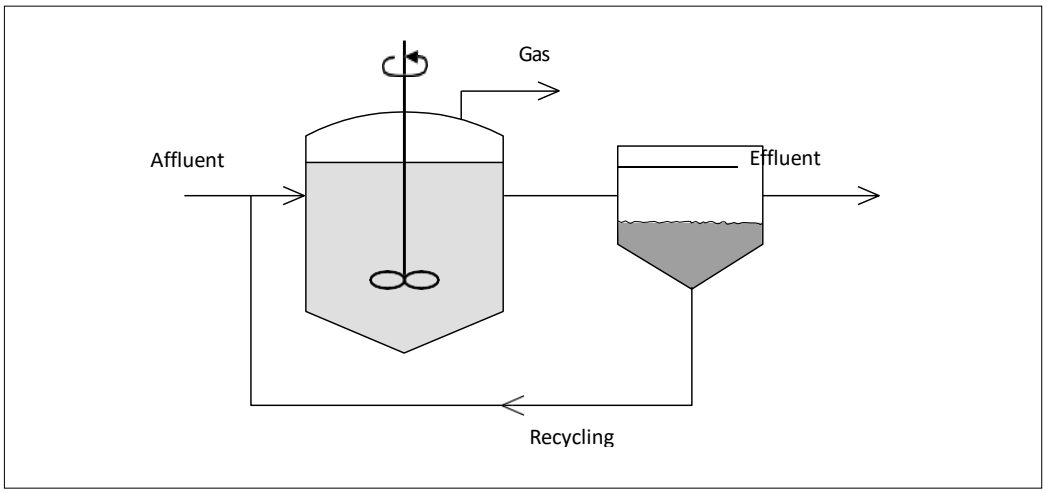


Figure 5: Schematic representation of anaerobic contact digester

- **Anaerobic sludge bed**

Unlike conventional continuously stirred tank reactors (CSTRs) or plug-flow digesters, which rely on mechanical or hydraulic mixing to maintain contact between the substrate and the active biomass, the anaerobic sludge bed technology is founded on a fundamentally different operating principle. It was discovered that, under quiescent conditions (in the absence of agitation) highly dense and structured granules of anaerobic biomass can spontaneously form and self-organise. This key observation led to the development of one of the most widely adopted anaerobic treatment technologies in the world: the Upflow Anaerobic Sludge Blanket (UASB) reactor, pioneered by Professor Gatze Lettinga in the Netherlands during the 1970s.

Operating Principle

In a UASB reactor, the raw effluent (influent) is introduced through a series of inlet points distributed uniformly across the base of the reactor. The wastewater then flows upward through a dense blanket of granular anaerobic sludge. As the effluent percolates through this sludge bed, the organic matter it contains is degraded by the microbial communities present within the granules, producing biogas (primarily methane and carbon dioxide) as a metabolic by-product.

The upward flow velocity is a critical operational parameter. It must be maintained within a relatively narrow range — typically 0.5 to 1.0 metres per hour — in order to:

- Ensure adequate and uniform distribution of the influent across the sludge bed;
- Promote optimal contact time between the wastewater and the active biomass;
- Prevent excessive turbulence that could disrupt or wash out the granular sludge;
- Maintain the structural integrity and settlement characteristics of the granules.

Granule Formation and Characteristics

The granules that form within a UASB reactor are compact, roughly spherical aggregates of mixed anaerobic microbial communities, typically ranging from 2 to 5 mm in diameter. Their internal structure is highly organised, with different microbial species stratified in layers according to their metabolic function — hydrolytic, fermentative, acetogenic, and methanogenic bacteria each occupying distinct ecological niches within the granule.

The rate at which granulation occurs is highly dependent on the nature of the substrate:

- Granules form more rapidly and reliably when treating sweet effluents (e.g., from sugar processing or fruit industries) or effluents rich in volatile fatty acids (VFAs), as these substrates provide readily available carbon sources that favour the selective enrichment of syntrophic and methanogenic consortia.
- Conversely, granulation may be slower or more difficult to achieve with complex, heterogeneous substrates or effluents containing significant quantities of suspended solids, fats, or inhibitory compounds.

The quality and density of the granular sludge bed are directly linked to the overall performance and stability of the reactor.

Gas-Liquid-Solid Separation

At the upper section of the UASB reactor, a three-phase separator (also known as a gas–liquid–solid separator or GLS separator) is installed. This device serves a dual function:

- Biogas collection: The methane-rich biogas produced during anaerobic digestion rises through the sludge bed and is captured beneath the inclined baffles of the separator, from where it is directed into a gas collection hood and extracted for energy recovery.
- Effluent clarification and sludge retention: The treated effluent overflows into launder troughs located at the top of the reactor. The design of the separator ensures that any floating or suspended granules are deflected back into the sludge bed rather than being carried out with the effluent, thereby preserving the biomass inventory within the reactor.

Application and Limitations

The UASB system is particularly well suited to the treatment of effluents with a high concentration of soluble organic matter, such as those generated by the food and beverage industry (distilleries, breweries, dairy processing, starch production, etc.). Its principal advantages include:

- High organic loading rate capacity;
- Low energy consumption due to the absence of mechanical mixing;

- Compact reactor footprint;
- Production of energy-rich biogas for on-site recovery.

However, the technology does present certain limitations:

- Well suited to effluents with high suspended solids content, as particulate matter can clog the sludge bed, impair granule formation, and reduce treatment efficiency;
- Start-up periods can be lengthy if suitable granular seed sludge is not available;
- Requires careful hydraulic management to avoid sludge washout or bed expansion beyond operational limits;
- Pre-treatment (e.g., screening, settling) may be required to remove coarse solids prior to UASB treatment.

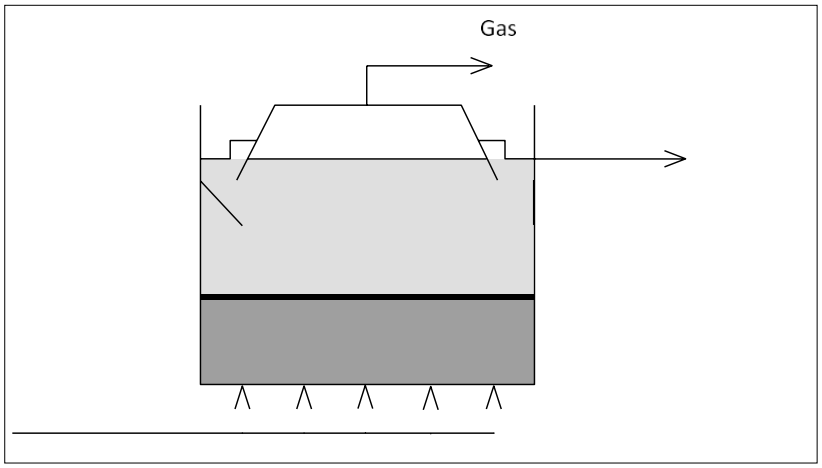


Figure 6: Schematic representation of UASB digester

• **Anaerobic filter**

The anaerobic filter is one of the most widely used fixed-film biological treatment technologies in anaerobic digestion systems. Its operating principle is based on the formation and adhesion of a biological film, also referred to as a biofilm, composed of anaerobic micro-organisms, which colonise and attach themselves to an inert support medium contained within the digester vessel.

Structure and Support Media

The inert support constitutes the core element of this type of digester. It is made up of a static, fixed structure that does not move during operation, thereby providing a stable surface upon which the microbial community can develop and maintain itself over time. The support materials used may vary considerably depending on the application and the design of the installation. Commonly used materials include:

- **Granular materials** such as gravel, crushed stone, or activated carbon, which offer a large specific surface area for biofilm development;
- **Modular plastic matrices**, such as structured packing or random plastic media, which provide a high void ratio, thereby reducing the risk of clogging whilst maximising the contact surface between the biofilm and the incoming effluent;
- **Coal or mineral-based supports**, chosen for their chemical inertness and mechanical durability.

The choice of support material has a direct influence on the overall performance of the digester, particularly in terms of organic load removal efficiency, hydraulic retention time, and long-term operational stability.

Flow Configuration

Anaerobic filters can operate in two distinct flow configurations, depending on the design requirements and the nature of the effluent to be treated:

- **Ascending flow (upflow):** In this configuration, the effluent enters the digester from the bottom and flows upward through the fixed support medium. This is the most commonly adopted arrangement, as the upward flow promotes better contact between the incoming substrate and the biofilm, whilst also facilitating the natural separation of biogas produced during the digestion process.
- **Descending flow (downflow):** In this configuration, the effluent is introduced from the top of the digester and percolates downward through the support medium. Whilst this arrangement can offer certain advantages in terms of hydraulic distribution, it is less frequently used due to a higher susceptibility to short-circuiting and uneven distribution of the organic load.

Applicability and Limitations

The anaerobic filter is particularly well suited to the treatment of effluents characterised by a predominantly dissolved organic load, meaning that the majority of the biodegradable matter is present in soluble form rather than as suspended solids. This is a critical consideration, as the presence of significant quantities of suspended solids or excess matter, such as fibrous materials, fats, or coarse particulates, within the influent can lead to progressive clogging of the filter medium. Such clogging would reduce hydraulic conductivity, create preferential flow pathways, and ultimately compromise the biological performance of the system.

For this reason, anaerobic filters are commonly employed in the treatment of:

- Industrial wastewater from the food and beverage sector (breweries, dairies, sugar refineries, etc.);
- Municipal wastewater with a low suspended solids content;
- Effluents from the pharmaceutical or chemical industries.

Where the incoming effluent contains elevated levels of suspended solids, pre-treatment steps, such as screening, settling, or flotation, are generally required upstream of the anaerobic filter in order to protect the integrity of the support medium and ensure the long-term reliability of the treatment process.

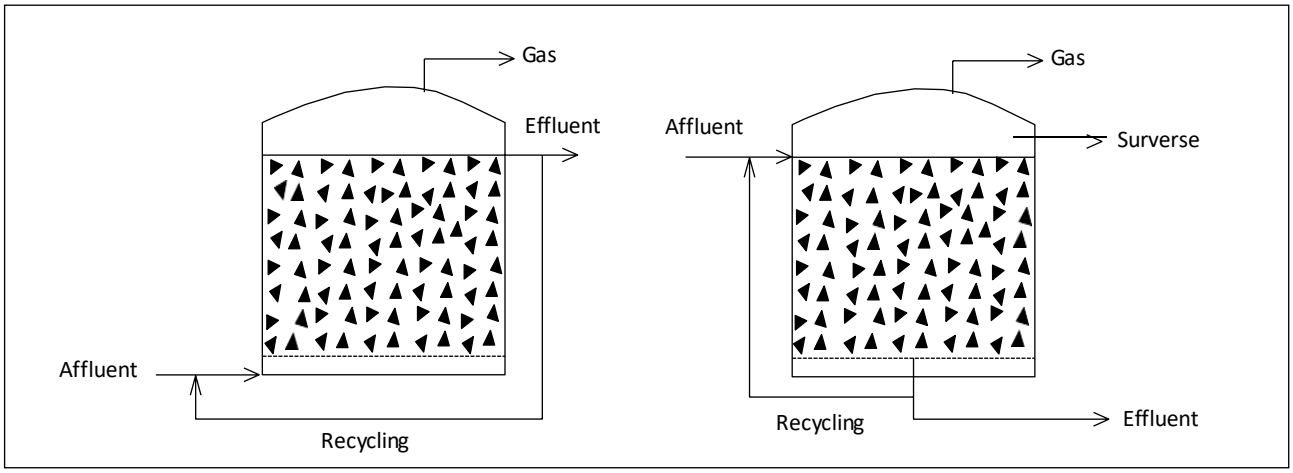


Figure 7: Schematic representation of anaerobic filter digester

- **Fluidised or expanded bed**

The fluidised or expanded bed is an advanced anaerobic digestion technology designed to maximise contact between the active microbial biomass and the effluent to be treated. The fundamental principle relies on immobilising the biological community responsible for methanisation onto small inert carrier particles, typically silica sand, activated carbon, or pumice stone. This colonisation forms what are known as biofilm-coated granules, which concentrate high microbial activity within a compact reactor volume.

Mechanism of operation

The granules formed are maintained in a state of suspension within the reactor through an upward liquid flow, which may be generated by one or more of the following means:

- Direct injection of the influent effluent from the base of the reactor
- Partial recycling of the treated effluent to maintain a sufficient upward velocity
- Recirculation of the biogas produced during anaerobic digestion

The behaviour of the granular bed is directly governed by the upward flow velocity of the liquid. As this velocity increases, the granules progressively separate from one another, increasing the overall volume of the bed:

- **Expanded bed:** At moderate upward velocities, typically between 5 and 8 m/h, the granules are set apart but still exert a degree of mutual influence. The bed expands but retains a relatively structured arrangement. Interparticle interactions remain partially significant.
- **Fluidised bed:** At higher upward velocities, generally between 20 and 30 m/h, each granule behaves as an entirely independent unit, with negligible interaction with neighbouring particles. The bed is said to be fully fluidised. This state ensures optimal mass transfer between the effluent and the biofilm.

Advantages of the technology

This configuration offers several notable benefits:

- High biomass retention within the reactor, even at short hydraulic retention times

(HRT), thanks to the attachment of microorganisms onto carrier particles

- Excellent mass transfer between the substrate and the biofilm due to the turbulence generated by the upward flow
- Compact reactor design, as the high concentration of active biomass allows for significantly reduced reactor volumes compared to conventional systems
- Resistance to hydraulic shocks, since the biomass is physically fixed and less susceptible to washout

Suitable applications

This type of digester is particularly well suited to the treatment of effluents characterised by:

- A high proportion of soluble organic matter (e.g., agri-food industry effluents, distillery stillage, paper mill effluents)
- Easily biodegradable suspended matter that can be rapidly hydrolysed and solubilised within the reactor
- Not recommended for effluents with a high content of coarse suspended solids, fibrous materials, or refractory compounds, as these may clog the bed, inhibit granule formation, or cause uneven fluidisation.

Technical challenges and limitations

Despite its theoretical advantages, the development and industrial scaling of fluidised and expanded bed systems have encountered significant technical obstacles:

- **Hydraulic control complexity**: Maintaining a uniform and stable upward velocity across the entire reactor cross-section is particularly challenging, especially at large scales. Any hydraulic heterogeneity leads to preferential flow channels, dead zones, and uneven distribution of the biomass.
- **Interference between biogas production and fluidisation:** The biogas generated during anaerobic digestion creates ascending gas bubbles that disturb the hydrodynamics of the liquid flow. This interaction can lead to instability in the bed, making it difficult to maintain the precise upward velocity required for either

expanded or fluidised conditions.

- **Granule management:** Controlling the size, density, and integrity of the biofilm-coated granules over time requires careful monitoring. Excessive biomass growth on the particles can alter their buoyancy, leading to bed stratification or granule washout.

- **Start-up period:** The initial colonisation of the carrier particles by the microbial community can be a lengthy process, requiring careful inoculation and gradual loading rate increases.

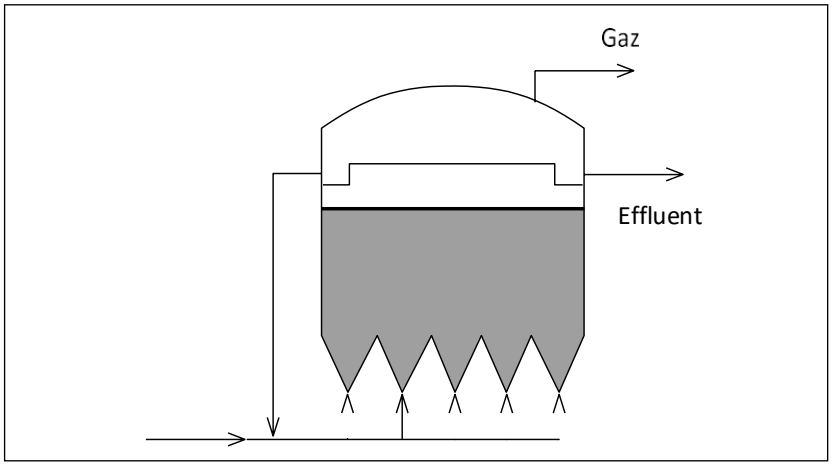


Figure 8: Schematic representation of Fluidised digester

2.4.2 Waste digestion processes

The digestion techniques used to treat solid waste can be distinguished according to whether the various phases of biomethanisation take place in one (single-stage system) or two (two-stage system) reactors. Digester systems can also be classified according to the feeding method and the characteristics of the solid substrate. Three categories can be considered:

- Discontinuous dry phase systems
- Continuous dry-phase systems
- Continuous wet-phase systems.

• Dry phase batch system

Dry phase batch systems represent one of the most widely used approaches in solid waste anaerobic digestion, particularly suited to substrates with a high total solids content (typically

above 20–30% TS), such as the organic fraction of municipal solid waste (OFMSW), agricultural residues, or green waste.

Operating principle

In this configuration (figure 9), each reactor, generally a sealed, gas-tight chamber or tunnel, is loaded in a single operation with the solid substrate to be digested. Once the reactor is filled and hermetically sealed, anaerobic conditions (anaerobiosis) are progressively established, allowing the microbial community to initiate the degradation process. As the organi

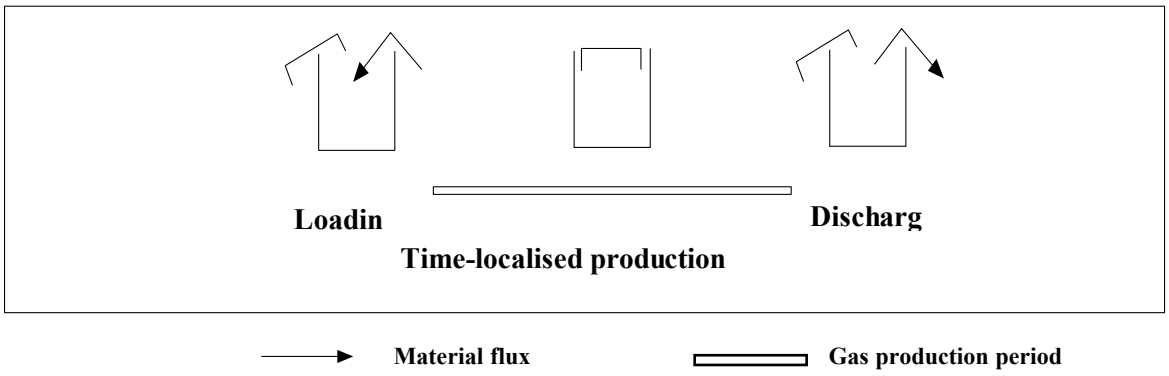


Figure 9: Schematic representation of Batch digestion

Managing biogas continuity

Since a single batch reactor cannot guarantee a continuous and stable flow of biogas, which is essential for energy recovery purposes, industrial installations typically operate several reactors in parallel, filled and emptied at staggered, regular intervals. This sequential scheduling ensures that at any given time, at least one reactor is in its peak production phase, thereby smoothing out the overall biogas output and ensuring a reliable supply to the combined heat and power (CHP) unit or gas upgrading system.

Temperature Regimes

Dry batch systems can operate under two main temperature conditions:

- Thermophilic conditions (50–60°C).
- Mesophilic conditions (35–40°C).

Process water recirculation

A defining feature of all industrial dry batch systems is the continuous or sequential recirculation of process water (also referred to as leachate). This percolate, rich in dissolved organic matter, volatile fatty acids, and active microbial biomass, serves two critical functions:

- **Inoculation:** At the start of each new batch cycle, the recirculated process water introduces a concentrated microbial inoculum into the freshly loaded substrate, significantly shortening the lag phase and accelerating the onset of active methanogenesis.

- **Prevention of acidification inhibition:** During the initial hydrolysis and acidogenesis stages, volatile fatty acids (VFAs) accumulate rapidly and can cause a sharp drop in pH, potentially inhibiting or even halting methanogenic activity. The recirculation of buffered process water helps dilute and neutralise excess acids, maintaining pH within the optimal range for methanogenic archaea (typically 6.8–7.5).

Two-stage Batch configuration

Dry batch systems can also be configured in a bi-stage (or two-stage) arrangement, which physically separates the two main functional phases of anaerobic digestion:

- **Stage 1**: **Hydrolysis and Acidification:** This phase takes place within the batch reactors themselves, where the solid substrate undergoes enzymatic hydrolysis, converting complex polymers (cellulose, proteins, lipids) into soluble monomers, followed by acidogenesis and acetogenesis, producing volatile fatty acids (VFA), hydrogen, and carbon dioxide.

- **Stage 2: Methanisation:** The VFA-rich process water generated in Stage 1 is then transferred to a dedicated high-yield methanogenic reactor, specifically designed to maximise biogas production. Examples of such reactors include:

    - UASB (Upflow Anaerobic Sludge Blanket) reactors, which retain highly active granular sludge and achieve excellent volumetric methane productivity;

    - Anaerobic filters, which use a fixed support medium to retain biofilm-forming methanogens, ensuring high biomass retention and process stability.

This two-stage approach offers several advantages, including optimised conditions for each microbial group, improved process stability, higher overall biogas yields, and greater resilience to fluctuations in feedstock composition.

- **Continuous dry-phase system**

Continuous dry-phase systems represent one of the most widely used technological approaches in industrial anaerobic digestion. The processes classified in this category operate as 'piston-flow digesters' (also referred to as plug-flow digesters), arranged in either vertical or horizontal tanks. These systems function under either thermophilic condition (typically 50–55°C) or mesophilic conditions (typically 35–40°C), depending on the specific installation and desired throughput.

The following diagram shows the operation of a mesophilic process with mixing by pressurised gas injection.

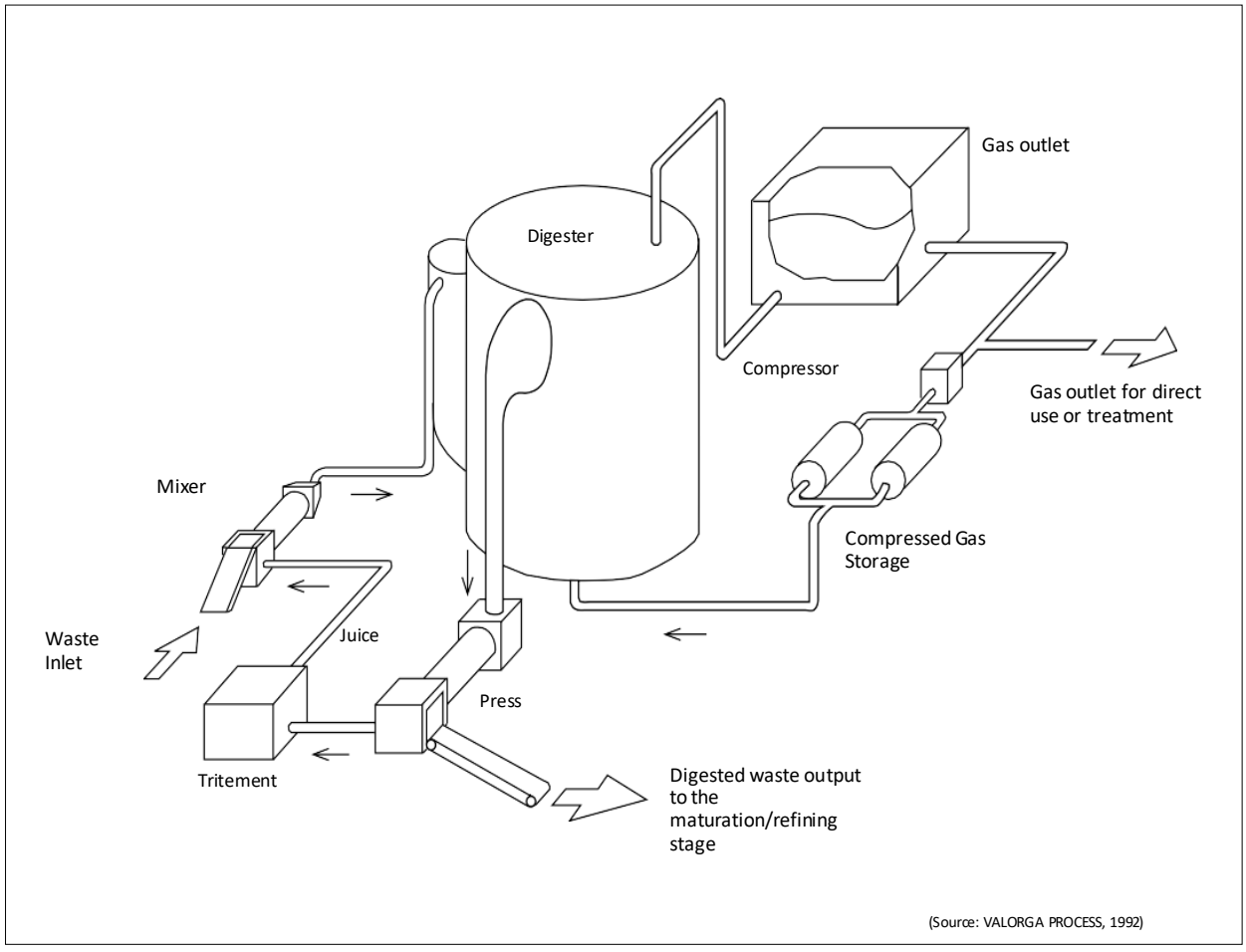


Figure 10: Schematic representation of continuous dry-phase system

Operating principle

The defining characteristic of this system is its continuous plug-flow operation: fresh waste is introduced at one end of the reactor whilst digested material is simultaneously discharged at the opposite end. This configuration ensures a relatively uniform retention time for all substrate particles passing through the digester, which contributes to process stability and consistent biogas yield.

The digester may not have any internal mixing, but a recirculation and inoculation circuit for the fresh substrate.

Before being introduced into the digester, the waste is crushed and mixed with some of the liquid from the pressing of the digested waste; it then reaches a dry matter content of 25-35% in the digester. After pressing the substrate leaving the digester, the dry matter content is around 55-65%, and the material undergoes aerobic stabilisation (refining).

- **Continuous humid-phase systems**

This category is represented by a single industrially developed process comprising six distinct treatment stages, each serving a specific function in the overall treatment chain.

Stage 1: Disaggregation (pulping) organic waste, with a dry matter content of up to 35%, is introduced into a disaggregation reactor, commonly referred to as a pulper. Within this unit, the waste is subjected to intense mechanical shearing forces generated by powerful mixing equipment, combined with the addition of process water. The resulting sludge has a dry matter content of approximately 10%. This initial stage also performs a sorting function, removing undesirable contaminants such as plastics, coarse debris, and dense heavy bodies that could otherwise interfere with downstream processing.

Stage 2: Thermal and alkaline pre-treatment: The lignocellulosic fraction of the waste, comprising materials such as wood fibres, straw, and plant cell wall components, undergoes thermal and alkaline pre-treatment in a dedicated reactor. This stage is essential for breaking down the complex lignocellulosic structures, which are otherwise resistant to biological degradation, thereby improving the overall digestibility of the substrate.

Stage 3: Liquid-Solid Separation (first): Following pre-treatment, the process stream is separated into two distinct fractions:

- The liquid stream, rich in soluble organic compounds, is directly pumped into the anaerobic digestion reactor.
- The solid stream, containing the remaining organic solids, is conveyed with additional process water into a dedicated hydrolysis reactor.

Stage 4: Hydrolysis: The solid stream remains in the hydrolysis reactor for a retention time of 2 to 4 days, during which it is continuously agitated by a mechanical stirrer. This stage promotes the enzymatic breakdown of complex organic polymers, such as proteins, lipids, and carbohydrates, into simpler, soluble molecules that are more readily accessible to anaerobic microorganisms in the digestion stage.

Stage 5: Liquid-Solid Separation (Second) Upon completion of hydrolysis, a second liquid-solid separation is carried out:

- **The liquid stream** is directed to the anaerobic digestion reactor, joining the liquid fraction separated in Stage 3.
- **The solid stream**, now largely stabilised and depleted of readily biodegradable material, is directed towards aerobic treatment.

Stage 6: Aerobic treatment and composting The remaining solid fraction undergoes aerobic biological treatment, during which microorganisms break down residual organic matter in the presence of oxygen. This process produces a stabilised, nutrient-rich compost that can be valorised as a soil amendment in agricultural or horticultural applications.

2.4.3 Co-digestion systems

Co-digestion is an anaerobic digestion process in which two or more different types of organic substrates are treated simultaneously within the same digester. This approach is widely adopted in modern waste management facilities due to the significant operational and biological advantages it offers over single-substrate digestion.

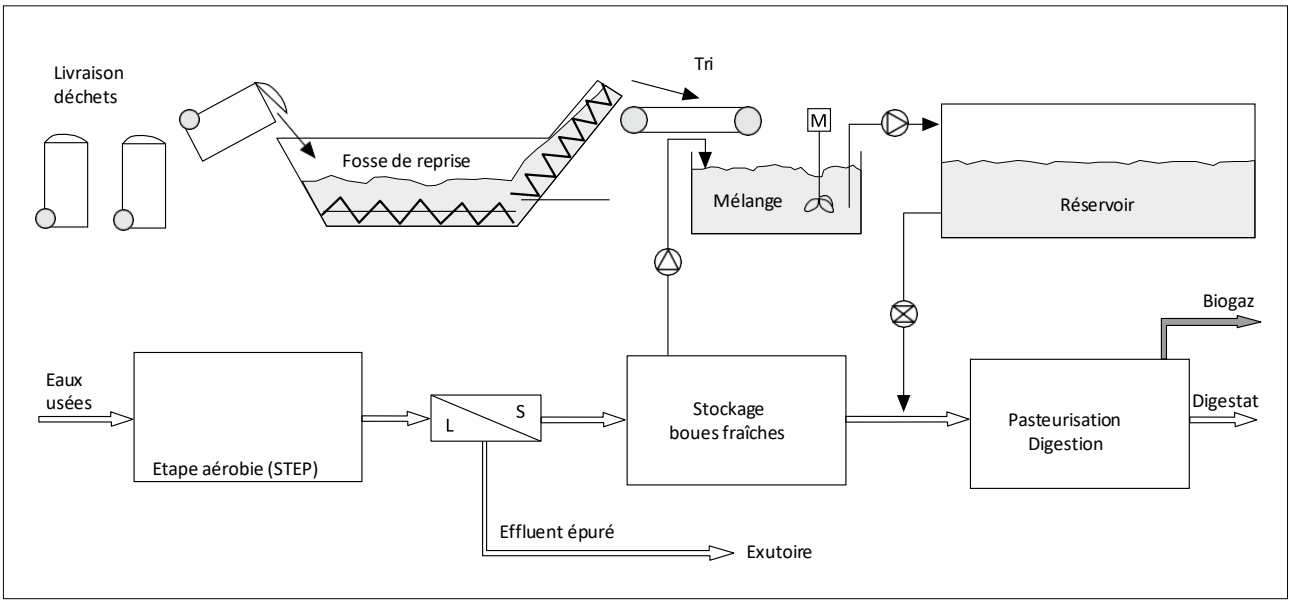


Figure 11: Schematic representation of co-digestion system

Co-digestion occurs under two main configurations (figure 11):

- **Liquid sludge treated in waste digesters:** In this scenario, sewage sludge, a by-product of wastewater treatment, is introduced into digesters that are primarily designed to process solid organic waste. The addition of sludge improves the moisture content and nutrient balance of the feedstock mixture, thereby enhancing microbial activity and overall biogas yield.

- **Waste treated in sewage sludge digesters:** Conversely, organic waste such as food waste, agricultural residues, or industrial organic by-products may be introduced into digesters that are principally designed for sewage sludge treatment. This approach allows existing infrastructure to be utilised more efficiently whilst increasing the volume and calorific value of the biogas produced.

Benefits of co-digestion

Co-digestion offers several notable advantages:

- **Increased biogas production:** The combination of complementary substrates creates a more balanced carbon-to-nitrogen (C/N) ratio, which is essential for optimising methanogenic activity.

- **Improved process stability:** Mixing substrates helps to dilute potentially inhibitory compounds, such as ammonia or volatile fatty acids, that may accumulate when a single substrate is digested alone.

- **Enhanced resource efficiency:** Existing digestion infrastructure can process a greater diversity of waste streams without requiring significant capital investment.

- **Reduced environmental impact:** By diverting organic waste from landfill and converting it into renewable biogas and digestate, co-digestion contributes to both energy recovery and nutrient recycling.

Chapter 3: System technology

3.1 Dimensional parameters

The performance of a digester can be optimised by balancing two key objectives: ensuring the most complete degradation possible of the organic compounds present in the substrate feed, and maximising biogas production. In an industrial context, the extent to which organic matter is broken down is typically the primary dimensioning criterion. However, economic considerations may also make it necessary to factor in methane yield as an additional parameter when sizing the installation.

3.1.1 The methanogenic potential

The methanogenic power or potential known as BMP (Biochemical Methane Potential),

corresponds to the quantity of methane produced by an organic substrate during its biodegradation under anaerobic conditions during the methanisation process.

This indicator is used for sizing anaerobic digestion plants, dosing inputs and monitoring their quality, as well as for assessing the performance of the anaerobic digestion process. but also, to estimate any carbon losses during storage.

Determining this potential, for each input or for mixtures of inputs, is a central and essential element in any consideration of anaerobic digestion processes, from the technical and economic analysis of a project, the sizing of treatment and recovery facilities, to the evaluation of process performance.

$$C_nH_aO_bN_cS_d+\left(n-\frac{a}{4}-\frac{b}{2}+3\frac{c}{4}+\frac{d}{2}\right)H_2O\rightarrow\left(\frac{n}{2}-\frac{a}{8}+\frac{b}{4}+3\frac{c}{8}+\frac{d}{4}\right)CO_2+\left(\frac{n}{2}+\frac{a}{8}-\frac{b}{4}-3\frac{c}{8}-\frac{d}{4}\right)CH_4+cNH_3+dH_2S$$

The equation of Buswell and Müller (1952), completed by Boyle (1976), which includes sulphur and nitrogen, makes it possible to predict the quantity and theoretical composition of the biogas produced during the anaerobic biodegradation of a substrate, the elemental composition of which is known.

The theoretical methanogenic potential of a product can then be calculated using the equation above.

$$PM_{th}=\frac{\frac{n}{2}+\frac{a}{8}-\frac{b}{4}}{12n+a+16b}\times 22{,}4\times[\mathrm{MO}]$$

The result of this theoretical calculation is purely predictive, and cannot take into account a number of factors l associated in particular to:

- **The biodegradability of the substrate and the bioavailability of these elements:** For example, lignocellulosic substrates such as straw or wood chips are poorly biodegradable due to their rigid lignin structure, which limits microbial access to the cellulose and hemicellulose fractions, thereby reducing the actual methane yield compared to the theoretical value.

  Cell growth and multiplication: A portion of the organic carbon present in the substrate is assimilated by microorganisms for their own growth and biosynthesis, rather than being converted into methane. This is particularly significant during the start-up phase of a digester, when microbial populations are actively establishing themselves.

- **The biodegradation rates of the various organic compounds:** Simple sugars and proteins degrade rapidly within a few days, whereas fats and complex carbohydrates such as cellulose may require several weeks to break down fully. If the hydraulic retention time is insufficient, a proportion of these slowly degradable compounds will leave the digester unconverted.

  Solubilisation phenomena (particularly carbon dioxide): Carbon dioxide (CO_2) is partially soluble in the digestate liquid phase, where it may dissolve to form carbonic acid or bicarbonate ions. This means that the CO_2 content measured in the biogas may be lower than theoretically predicted, as a fraction remains dissolved in solution rather than being released as a gas.

- **Substrate precipitation**: Struvite (magnesium ammonium phosphate) can precipitate in digesters processing substrates rich in nitrogen and phosphorus, such as pig slurry or food waste. This precipitation immobilises nutrients and reduces their bioavailability to methanogenic microorganisms, thereby limiting methane production.

- **The presence of inhibitors:** For example, high concentrations of ammonia, resulting from the degradation of nitrogen-rich substrates such as poultry manure, can inhibit methanogenic archaea. Similarly, elevated levels of volatile fatty acids, heavy metals, or antibiotics present in certain agricultural or industrial effluents may significantly impair microbial activity and reduce biogas yields.

- **Nutrient deficiencies:** methanogenic microorganisms require trace elements such as cobalt, nickel, iron, and molybdenum as cofactors for key enzymatic reactions. In digesters processing substrates with an imbalanced nutrient composition, such as maize silage monodigestion, deficiencies in these micronutrients can limit microbial growth and reduce the efficiency of the methanisation process.

3.1.2 Measuring the pollution or load to be treated

The quantity of pollutant in the effluent or the organic load of waste entering the anaerobic digestion reactor is measured in kg of COD or kg of MV respectively.

The BOD (BOD5), commonly used to size aerobic systems (activated sludge, etc.) is only indicative in the case of methanisation, since it is representative of the organic matter that can be biodegraded under aerobic conditions.

Under the anaerobic conditions specific to methanisation, the metabolisms of the microorganisms involved are fundamentally different. Certain compounds that are degradable aerobically are not degradable anaerobically (lignocellulosic compounds, for example). Conversely, a host of compounds that are difficult to degrade aerobically can be broken down

anaerobically. This is demonstrated by the fact that, in some cases, purification yields can exceed 90% for COD, even though BOD represents only half of the incoming COD.

COD and MV are representative of almost all the organic matter present in the effluent to be treated and are therefore good indicators of the pollution or load to be treated.

3.1.3 Main parameter: specific load

The main sizing parameter is the specific load in COD or MV; it is expressed as follows:

kg COD / m^3 - day or kg MV / m^3 - day.

For a given load to be treated, in kg COD/day or kg MV/day, the choice of a given load immediately implies a reactor volume. The load capacity depends mainly on the technical design of the digester and, to a lesser extent, the substrate and its biodegradability.

The fundamental biological parameter is the COD degraded or MV degraded, per unit of biomass and per unit of time, which is expressed as follows

kg COD degraded / kg biomass per day or kg MV degraded / kg biomass per day.

Broadly speaking, this yield is independent of the reactor used and, in general, of the technical conditions under which microbial growth takes place. It depends above all on the biological conditions:

- Type of substrate (temperature, pH, alkalinity, etc.);
- Quality of the organic matter to be degraded (inhibitors, etc.);
- Biomass activity.

The daily degradation yield is linked to the chemical composition of the organic matter, in which not all bonds are equally capable of undergoing complete degradation. For example, fats have a much higher degradability rate than hemicellulose, cellulose or even proteins.

Degradation efficiency is also influenced by the rate at which the various components of the substrate break down. Bacteria will break down fats much more quickly than albumin, cellulose or hemicellulose. For example, effluent from a dairy industry will be purified more quickly and more completely than effluent from a paper or cardboard factory.

However, it is the state of the material that will be decisive in determining the degradation efficiency. Dissolved substances can be metabolised much more quickly by bacteria than particulate substances. Liquefaction, in other words the hydrolysis of solid matter, is the stage in the anaerobic degradation chain that unquestionably determines the speed of degradation.

The table 5 shows the composition of the biogas as a function of the average state of oxidation of the carbon in the substrate. These values should be considered assuming complete mineralisation of the substrate (no biomass formation).

Table 5: specific load of different anaerobic digestion reactor types

Infinitely mixed	2 kg COD/m3. day	Relative volume: 20
Anaerobic contact	5 kg COD/m3. day	Relative volume: 8
Anaerobic sludge bed	10 kg COD/m3. day	Relative volume: 4
Anaerobic filter	10 kg COD/m3. day	Relative volume: 4
Fluidised or expanded bed	40 kg COD/m3. day	Relative volume: 1
Solid waste without substrate recirculation	8 – 13 kg VM/m3. day	
Solid waste with substrate recirculation	18 – 30 kg VM/m3. day	

3.1.4 Retention time (Residence time)

Dimensioning according to a specific charge criterion is often sufficient, but it is incomplete. The organic load parameter assumes that a certain biomass concentration is stabilised in the reactor with a given biological activity.

The retention time is the time taken for the material to pass through the biomethanisation system for treatment.

we distinguish between: the hydraulic retention time HRT (for the substrate) and the biomass retention time BRT.

3.1.5 Treatment of suspended matter (SM)

- **Organic suspended matter**

In practice, we do not simply encounter solid waste or dissolved effluents. As a general rule, they are always intermediate substrates, i.e. wastewater containing a greater or lesser proportion of organic solids. In special cases, it will be necessary to determine whether the residence time should be fixed as a function of the duration of hydrolysis (infinitely mixed or contact reactors), or whether the solids should be separated beforehand and subjected to a separate hydrolysis stage (bi-stage system).

If the influx of solids into the digester exceeds the hydrolysis degradation capacity, the solids will accumulate in the reactor, hindering the activity of the biomass and leading to rapid clogging of the digester.

- **Mineral suspended solids**

As far as possible, mineral suspended solids should be separated during pre-treatment. Screening and grit removal equipment for liquids and mechanical sorting equipment for solid waste enable this separation to be carried out with good efficiency.

Anaerobic contact reactors can accept mineral matter provided that the mixing of the digester prevents it from settling at the bottom of the reactor. However, there is a risk of preferentially separating mineral matter in the clarifier instead of organic matter, leading to a gradual replacement of the active biomass by inert matter. The accumulation of lime in sugar factory digesters is a typical case.

Reactors with fixed biomass (sludge beds, filters) are relatively resistant to mineral or inert matter, which accumulates in the reaction volume and eventually clogs it.

In addition, mineral or inert matter is not necessarily supplied by the effluent to be treated, but can be created by precipitation in the reactor. Beware of water containing high concentrations of carbonates in particular. Examples are known of anaerobic filters with linings clogged by carbonate precipitation after two to three years of operation on dairy water.

3.1.6 Gas productivity

Gas productivity is defined as the quantity of biogas or methane produced per unit of organic substance introduced into the digester. It is expressed in cubic metres of gas per kilogram of organic matter added, using two principal reference parameters: (**m^3/kg COD** or **m^3/kg MV**).

Biogas production depends essentially on three factors: substrate composition, digestion temperature and residence time.

- **Substrate composition** (Not all substances degrade at the same rate or speed)

The more easily and completely degradable a substrate is, the more gas it will form in a given time. In addition, gas yield is influenced by the presence of inhibiting substances. Salts in particular can reduce gas yield. Dry matter content also plays a role. Above around 9-12% DM, the gas yield begins to fall; above 35-40% DM, the degradation process is virtually paralysed, as the critical water content for bacterial growth is exceeded. From an energy point of view, we are really only interested in methane production, and so we define the methane yield (m^3/kg COD, respectively m^3/kg MV). The proportion of methane in the biogas is also dependent on the composition of the substrate (figure 12). In fact, the composition of the biogas depends on the average oxidation stage.

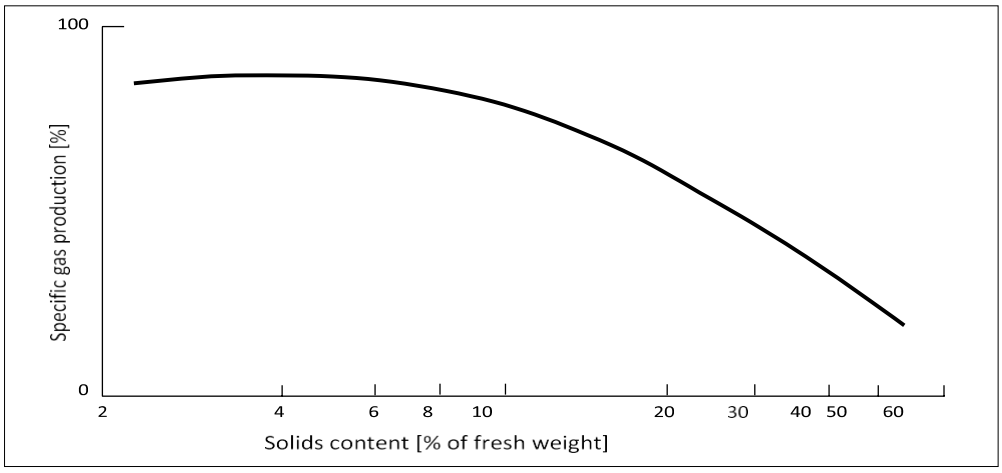


Figure 12: Influence of solids content on gas production.

Digestion temperature

Gas yield also increases with rising temperature (figure 13), so that a clear distinction can be made between mesophilic (25-45°C) and thermophilic (50-65°C) digestion. In all cases, an increase in temperature leads to an increase in gas yield and gross gas production. In the higher temperature ranges, reheating energy requirements increase more rapidly than gas production, so that net energy production tends to decrease.

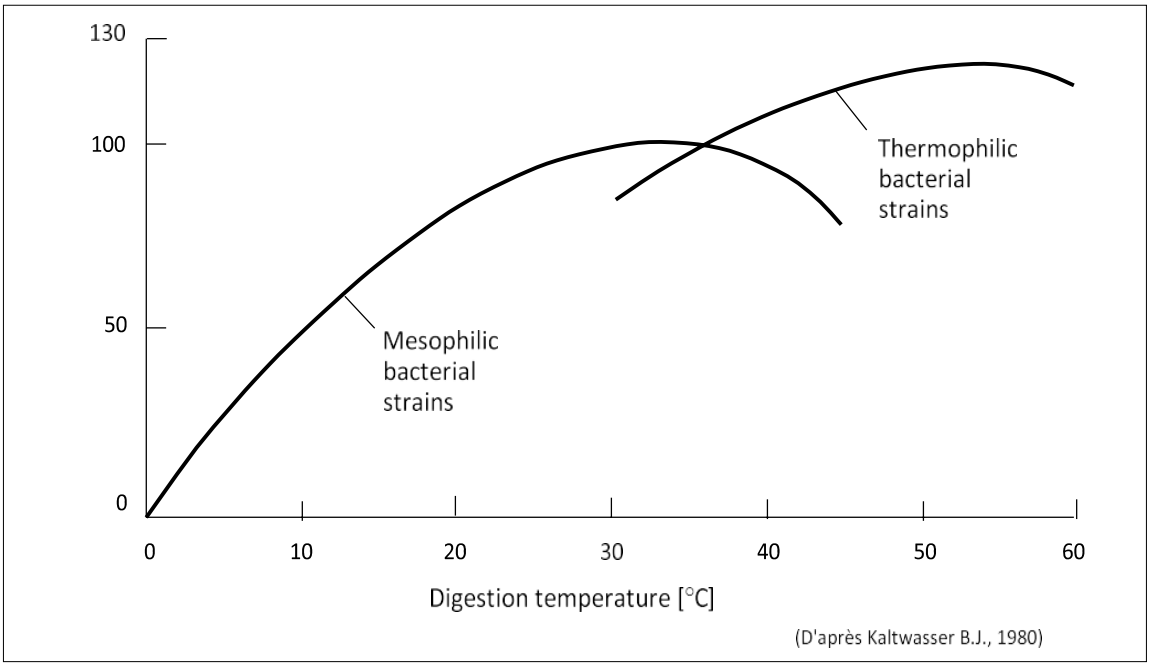


Figure 13: Influence of temperature on the amount of recoverable gas, with reference to optimum temperatures.

3.2 Digester technology

3.2.1 Construction of the cuve

Traditionally, anaerobic digesters were of large capacity and built in reinforced concrete. In addition to the cost of construction for small units, there was the problem of protecting the concrete from corrosion when the substrate-gas phases separated. In this area, there is a high risk that the concrete will be damaged in a very short time. Even metal parts made from 1.4435 stainless steel are not resistant in this environment. The solution is to coat the concrete with an epoxy resin or cover it with polyethylene sheets, and to use only non-metallic equipment.

For economic reasons, most industrial digesters now consist of prefabricated steel tanks. The material used is mainly 1.4435 stainless steel, in thicknesses of around 5 mm, with operating pressures of between -10 and +30 mbar. These prefabricated digesters have capacities of around 100-500 m^3.

3.2.2 Thermal insulation

Maintaining a stable and appropriate operating temperature is one of the most critical aspects of anaerobic digestion, as methanogenic microorganisms are highly sensitive to thermal fluctuations. Effective thermal insulation of the digester is therefore essential to ensure process stability, minimise heat losses, and reduce energy consumption associated with heating the substrate to the required operating temperature (typically 35–38°C for mesophilic digestion, or 50–55°C for thermophilic digestion).

Purpose of thermal insulation

The primary function of thermal insulation is to limit heat transfer between the digester and its surrounding environment, thereby:

- Maintaining a stable internal temperature regardless of external climatic conditions, including seasonal temperature variations and cold spells
- Reducing the energy demand of the heating system, which directly impacts the overall energy balance and economic performance of the installation
- Preventing thermal shock to the microbial communities, which can cause significant disruption to the digestion process and lead to a reduction in biogas yields

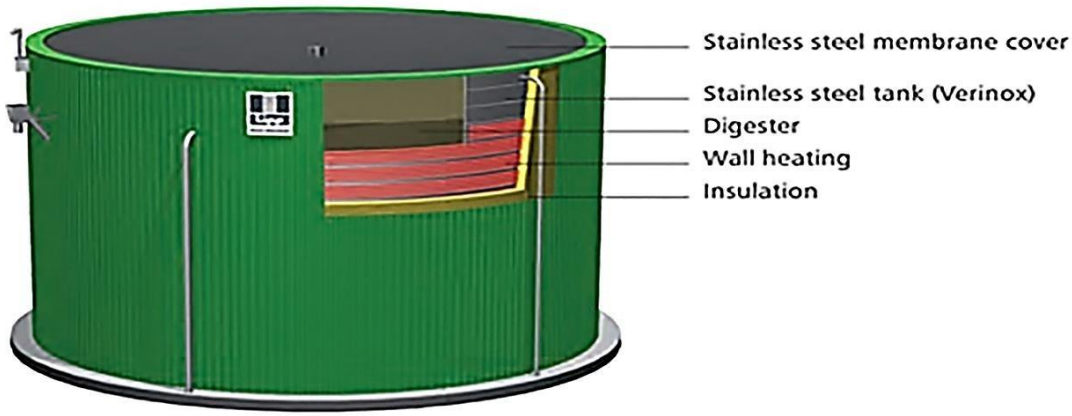


Figure 14: Digester wall composition

Insulation materials and methods

Several insulation systems are commonly employed in the construction of anaerobic digesters (figure 14), each presenting specific technical characteristics, advantages, and limitations:

a) Mineral fibre panels (e.g. glass wool or rock wool)

Mineral fibre panels are among the most widely used insulation solutions for digesters. They are typically fixed to the external surface of the digester walls and protected by a metal cladding or sheet, which shields the insulation from mechanical damage, wind, and moisture ingress.

- Thermal conductivity: typically, 0.030–0.045 W/m·K
- Advantages: good thermal performance, relatively low cost, non-combustible, easy to install in panels or rolls
- Limitations: mineral fibres are susceptible to moisture absorption, which significantly reduces their insulating performance over time. The protective metal cladding is therefore essential to maintain long-term effectiveness. Regular inspection of joints and fixings is recommended to prevent water infiltration.

b) Sprayed polyurethane foam (PUR/PIR)

Polyurethane foam can be sprayed directly onto the outer surface of the digester walls, forming a continuous, seamless insulating layer that adheres closely to the structure and eliminates thermal bridges.

- Thermal conductivity: typically, 0.022–0.028 W/m·K, making it one of the most thermally efficient insulation materials available

- Advantages: excellent thermal performance, seamless application with no joints or fixings, good resistance to moisture when correctly applied, adaptable to complex geometries including curved digester walls and domed roofs

- Limitations: polyurethane foam is combustible and must be protected by an appropriate surface coating or cladding in accordance with fire safety regulations. It may also be susceptible to UV degradation if left unprotected, and its application requires specialist equipment and trained personnel.

c) Other Moisture-Resistant Insulation Materials

Depending on the specific project requirements, site conditions, and budgetary constraints, alternative insulation materials may also be employed, provided they offer adequate moisture resistance and thermal performance. These include:

- Extruded polystyrene (XPS): rigid insulation boards with low moisture absorption and good compressive strength, suitable for below-ground or partially buried digesters

- Expanded polystyrene (EPS): a cost-effective option offering good thermal performance, though with lower moisture resistance than XPS

- Foam glass: a rigid, inorganic insulation material with excellent moisture and chemical resistance, particularly suited to aggressive environments

- Aerogel blankets: a high-performance insulation solution offering very low thermal conductivity (0.013–0.018 W/m·K) in a thin profile, used in space-constrained installations

3.2.3 Mixing

The substrate inside the digester can be mixed by one of the systems shown schematically below. Essentially, these systems are based on mechanical mixing, substrate recirculation or hydraulic mixing with biogas:

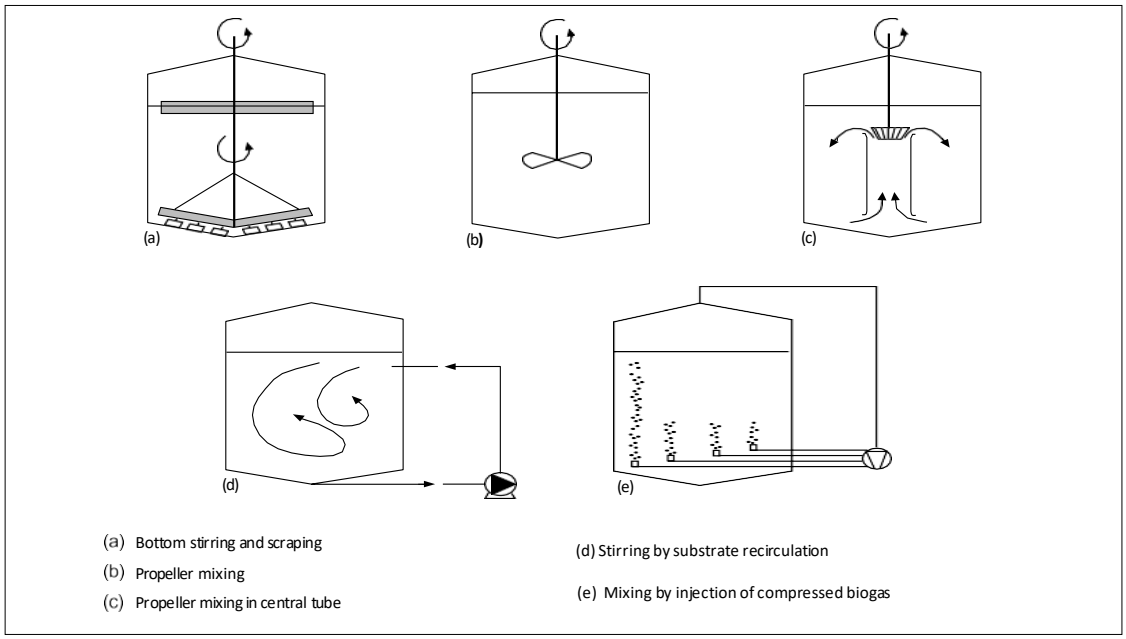


Figure 15: Different internal mixing processes

3.2.4 Feed and discharge

Feeding and extracting the substrate requires reliable, easy-to-maintain systems that avoid creating preferential passages in the digester.

A UASB digester is fed by a sophisticated piping system covering the entire bottom of the digester. The result is uniform distribution of the effluent to be treated, thanks to the multiplicity of injection points. The homogeneity of the feed system is guaranteed by defining the pressure drop across the injection orifices; however, a minimum opening diameter must be ensured to prevent the risk of clogging. In a UASB reactor, the digested effluent is discharged at a considerable height (4.5 m) from the feed network; it can therefore be evacuated by gravity, which simplifies the hydraulic circuit considerably.

Downflow anaerobic filter digesters are equipped with a wastewater distribution system that ensures uniform distribution throughout the right-hand section of the reactor. The treated effluent exits the digester through a weir and a hydraulic seal designed to prevent biogas leaks.

Systems for digesting solid waste in the dry phase operate using a piston effect. Some of these digesters have internal walls to prevent the freshly-introduced substrate from leaving immediately. Depending on the technique, the substrate is fed and extracted using mechanical

devices (suction pump and extraction screw) or hydraulic devices (pressurisation and

depression of the digester using biogas).

3.2.5 Biomass retention

The retention of active biomass within the digester is one of the most critical parameters governing the performance and stability of anaerobic digestion systems. Ensuring that sufficient microbial mass remains within the reactor, regardless of the hydraulic flow rate, allows the biological process to operate efficiently even at reduced hydraulic retention times (HRT). Various strategies have been developed to achieve this, depending on the type of reactor configuration employed.

Sludge bed reactors (UASB Type)

In Upflow Anaerobic Sludge Blanket (UASB) reactors, biomass retention is achieved primarily through sedimentation. In this configuration, the wastewater or substrate is fed upwards through a dense blanket of anaerobic sludge, where the organic matter is broken down by the microbial community. The treated effluent, along with the biogas produced, rises to the top of the reactor, whilst the sludge settles back down under gravity, thereby remaining within the system.

A distinctive and defining feature of the UASB reactor is that granulation occurs without the use of any external support material or carrier medium. Instead, the sludge spontaneously forms dense, compact granules under specific hydrodynamic and physicochemical conditions. These granules are essentially self-organised agglomerations of diverse microbial communities, structured in a way that optimises syntrophic interactions between the various groups of microorganisms involved in the anaerobic digestion process.

Granule formation and structure

The formation of anaerobic granules is a complex and progressive biological process that typically develops over several weeks or months during the start-up phase of the reactor. Granulation is favoured by the following conditions:

- **Upward flow velocity:** A moderate upflow velocity creates a hydraulic selection pressure that washes out poorly settling, dispersed sludge whilst retaining denser, well-structured granules.
- **Organic loading rate:** A sufficient and progressive organic loading rate stimulates

microbial activity and encourages the formation of dense aggregates.

- **Calcium and divalent cations:** The presence of calcium (Ca^{2+}) and other divalent cations promotes the bridging of microbial cells and extracellular polymeric substances (EPS), facilitating initial aggregation.
- **Seed sludge quality:** The characteristics of the inoculum used at start-up significantly influence the speed and quality of granulation.

  A mature anaerobic granule typically exhibits a layered structure:

  - The **outer layer** is predominantly colonised by fermentative and acetogenic bacteria, which are responsible for the initial breakdown of complex organic compounds into acetate, hydrogen, and carbon dioxide.
  - The **inner core** is primarily composed of methanogenic archaea, which convert the intermediate products into methane and carbon dioxide.

This spatial organisation minimises the diffusion distance between syntrophic partners, thereby enhancing the overall efficiency of the anaerobic digestion process.

Support material-based retention: fixed-film and hybrid reactors

An alternative approach to biomass retention involves the use of support materials, onto which microorganisms attach and form biofilms. This strategy is employed in fixed-film reactors (also known as attached-growth reactors) and hybrid systems that combine suspended and attached growth. Support materials significantly increase the effective surface area available for microbial colonisation within the reactor volume, enabling high biomass concentrations to be maintained independently of the hydraulic retention time. Digesters equipped with internal linings use plastic, metal (mesh, mineral, sand, Leca) or synthetic (polyurethane foam, polyamide rings, polyester fibres) supports, some examples of which are given table 6.

Support materials used in anaerobic digesters can be classified into three main categories:

1. Plastic supports

Plastic support materials are widely used due to their light weight, chemical inertness, and high specific surface area. Common configurations include:

- **Structured plastic packing** (e.g., corrugated sheets or honeycomb modules): widely used in anaerobic filters, offering specific surface areas of 100–300 m^2/m^3
- **Random plastic packing** (e.g., Pall rings, Hiflow rings, or Raschig rings): loose-fill media providing good biofilm attachment surfaces and favourable hydraulic characteristics
- **Polyamide rings**: offer good mechanical strength and resistance to biological degradation, making them suitable for long-term use in anaerobic environments

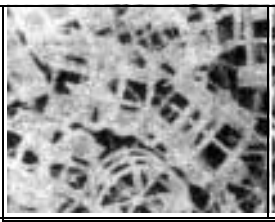
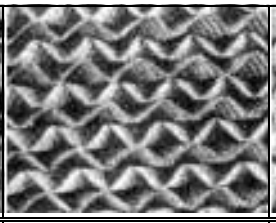
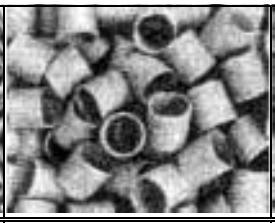
2. Mineral and metallic supports

- **Metal mesh or grids**: provide a rigid, structurally stable support framework within the reactor, suitable for retaining biofilms in high-flow conditions
- **Sand**: one of the simplest and most cost-effective support materials, used in fluidised bed reactors where sand particles serve as carriers for attached biofilms. The fluidisation of sand by the upward flow of liquid ensures intimate contact between the biofilm and the substrate
- **LECA (Lightweight Expanded Clay Aggregate)**: a porous, granular material with a high internal surface area, offering excellent conditions for biofilm colonisation. Its low density makes it suitable for use in expanded bed or fluidised bed configurations. LECA is particularly valued for its mechanical durability and biological inertness

3. Synthetic organic supports

- **Polyurethane foam**: a highly porous material with a very high specific surface area (up to 600–1,000 m^2/m^3 in some formulations), capable of retaining large quantities of biomass within its open-cell structure. Its compressible nature allows it to be used in packed or moving bed configurations
- **Polyester fibres**: used in fibrous-bed or non-woven fibre reactors, providing a large surface area for biofilm attachment whilst allowing relatively free liquid circulation through the fibre matrix.

Table 6: Examples of internal linings supports

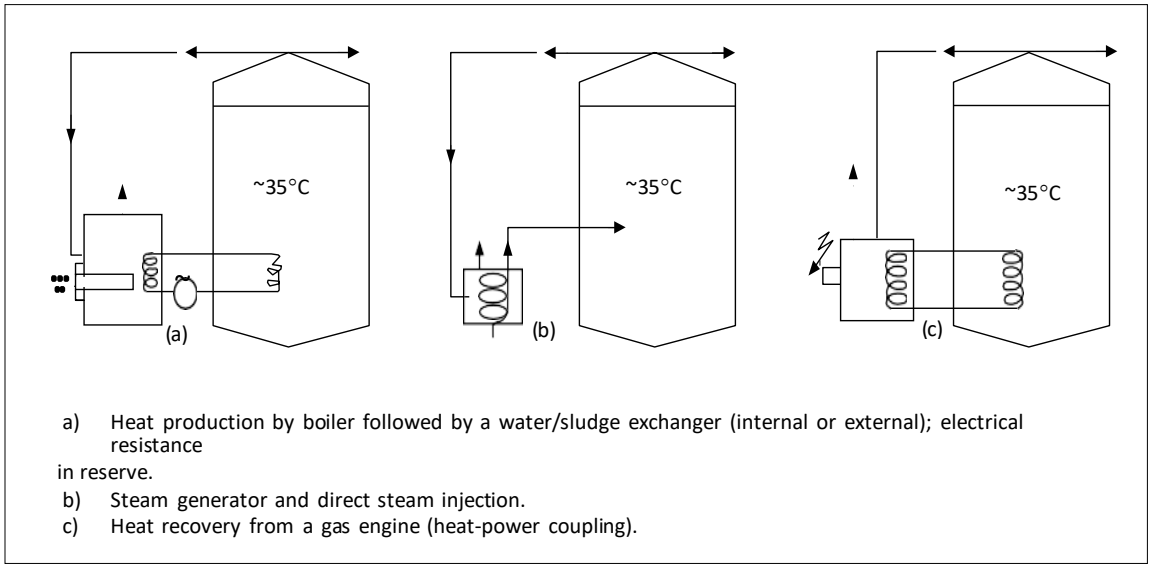
				
Type	**HIFLOW**	**PLASDEK**	**FLOCOR**	**SIRAN**
a: specific surface [m^2 / m^3]	65	148	150	30 000
Ɛ: vacuum volume [%]	96,5	96	97	70

3.2.6 Heating and temperature control

Temperature is one of the most critical operational parameters in anaerobic digestion, as it directly influences the metabolic activity of the microbial communities responsible for biogas production. Maintaining a stable and appropriate temperature within the digester is therefore essential for ensuring process efficiency, microbial stability, and consistent methane yields.

Heating and temperature control methods

Several heating systems are employed in practice to maintain the digester at its target operating temperature (figure 16 and 17). The choice of system depends on the digester design, the available energy sources, and the specific thermal requirements of the installation.



a) Heat production by boiler followed by a water/sludge exchanger (internal or external); electrical resistance
in reserve.
b) Steam generator and direct steam injection.
c) Heat recovery from a gas engine (heat-power coupling).

Figure 16: Different temperature control systems in digester

a) Hot Water circulation via heat exchangers

The most commonly used heating method in wastewater and industrial digesters consists of circulating hot water through a heat exchanger, which transfers thermal energy to the digester contents. Two configurations are generally employed:

- **External heat exchangers:** The digestate is continuously pumped out of the digester, passed through an external water-sludge heat exchanger where it is heated, and then returned to the digester. This configuration allows for easy inspection, maintenance, and cleaning of the exchanger, which is important given the tendency of sludge to foul heat exchange surfaces. External exchangers are typically of the tubular or plate-and-frame type, selected according to the viscosity and solids content of the substrate.

- **Internal heat exchangers:** Heating coils or panels installed directly within the digester vessel circulate hot water, transferring heat directly to the surrounding digestate. This arrangement avoids the need for external pumping circuits and reduces heat losses, but makes maintenance and cleaning more difficult, particularly in the event of fouling or scaling on the coil surfaces.

The hot water circulating through these systems is typically produced by one of the following means:

- **Conventional gas or oil-fired boilers**, which provide reliable and controllable heat output but consume primary energy and generate associated operating costs.

- **Combined Heat and Power (CHP) units**, also referred to as cogeneration engines or heat-power couplings, running on the biogas produced by the digester itself. CHP systems simultaneously generate electricity and recoverable heat. The thermal energy recovered from engine cooling circuits and exhaust gas heat exchangers is used to heat the digester, significantly improving the overall energy balance of the installation. In a well-designed system, the thermal energy recovered from a biogas-fuelled CHP unit can cover the majority of the digester's heating requirements, making the process largely energy self-sufficient.

- **Boilers running on biogas**, where the biogas is combusted directly to produce hot water for the heating circuit, without simultaneous electricity generation. This option is simpler and less costly than CHP but foregoes the economic benefit of electricity production.

b) Direct steam injection

An alternative heating method consists of injecting steam directly into the digester contents. This approach offers several notable advantages:

- **Direct and rapid heat transfer:** Steam condenses immediately upon contact with the cooler digestate, releasing its latent heat very efficiently and achieving rapid temperature elevation without the thermal resistance associated with indirect heat exchangers.
- **Elimination of the heat exchanger:** Direct steam injection removes the need for an external or internal heat exchanger, reducing capital costs, maintenance requirements, and the risk of fouling.
- **Simultaneous mixing effect:** The injection of steam can contribute to agitation of the digester contents, complementing the primary mixing system.

However, direct steam injection also presents certain limitations:

- It introduces additional water into the digester, which dilutes the digestate and may affect the organic loading rate and volatile solids concentration.
- Precise control of steam flow is required to avoid localised overheating, which could inhibit or damage the microbial communities in the vicinity of the injection point.
- Steam generation requires a dedicated boiler system and associated safety equipment, increasing the complexity of the installation.

c) Geothermal and solar thermal systems

In specific contexts, renewable heat sources such as geothermal energy or solar thermal collectors may be used to supplement or replace conventional heating systems. These options are particularly relevant for installations located in regions with favourable geothermal resources or high solar irradiance, and where reducing fossil fuel dependency is a priority. Whilst not yet widely deployed at industrial scale for anaerobic digestion, such systems represent a promising avenue for improving the overall sustainability and energy balance of the process.

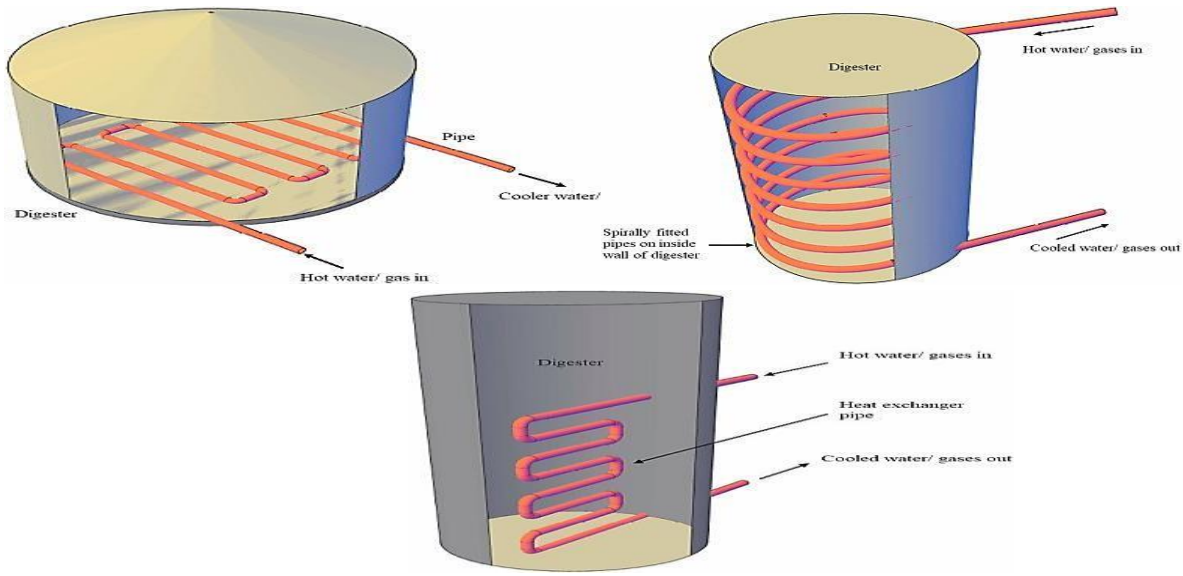


Figure 17: Examples of heat transfer processes using water

3.2.7 Biogas extraction circuit

In addition to the network routing the biogas produced to storage and recovery, various control and safety equipment are directly linked to the digester. These include

- The condensate separator which, in some systems, includes a device to prevent the formation of foam;

- A device to prevent depressurisation of the digester, or 'vacuum breaker';

- An overpressure device to ensure that the biogas is evacuated if it is not used.

Collection takes place in the digester dome or, in UASB-type systems, in standardised separators at the top of the reactor. As a general rule, more than 90% of the theoretical production is recovered. Losses are mainly due to the solubility of the gas in the effluent, under certain pressure and temperature conditions.

3.3 Peripheral treatment

A significant proportion of organic waste may be resistant to anaerobic digestion. Physical, chemical or biological pre-treatment processes will be of prime importance in ensuring the effectiveness of anaerobic digestion treatments. Similarly, the products from the digester must be packaged in such a way as to guarantee their recovery and reduce any nuisance. The various stages of peripheral treatment are summarised in the figure (18).

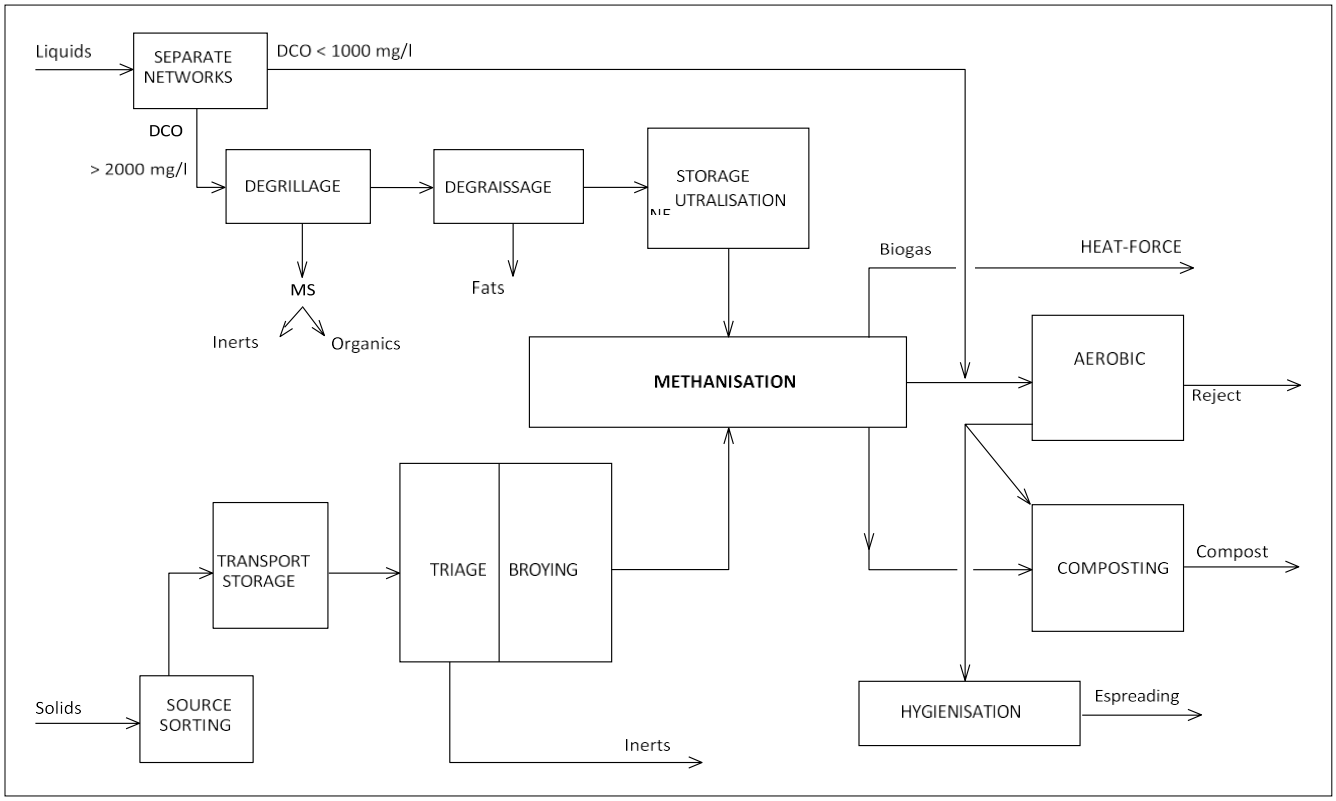


Figure 18: Overview of the integration of anaerobic digestion into solid waste and effluent treatment processes

3.3.1 Before anaerobic digestion a- Effluents

Industrial or urban wastewater very often consists of a mixture of wastewater from different processes. The quality (COD concentration in particular) can vary greatly from one effluent to another, requiring specific treatment.

- **Separation**

Any mineral solids that may accumulate in the digesters must be separated by settling, screening or sieving (rotary sieve).

- **Temporary storage**

In order to supply the digester with a constant flow rate over 24 hours, a buffer volume must be provided to absorb and regulate wastewater flow peaks.

This storage also serves to correct and homogenise the temperature of the effluent to bring it to the optimum temperature conditions for the digester. This can be done by heat exchange between the effluent and the digester influent, by water/affluent exchange (the water being

heated by the biogas produced), or by direct steam injection. Plants operating at a sub-optimal temperature (20-25°) can operate at a reduced volume load.

- **Addition-correction**

The addition of nutrients is sometimes necessary to maintain or achieve a nutritional balance suited to biomass growth. The elements most often used are N, P, S, Fe, Ni and Co.

The optimum pH value for anaerobic digestion is between 6.5 and 7.5. Industrial effluents, particularly those from the food industry, may require pH correction. The pH is corrected using acidic or basic reagents; it must always be possible to correct the pH, although this is not usually necessary.

b-Solid waste

- **Separation**

- **Separating** fermentable waste **at source** and collecting it selectively is the way to eliminate pollutants.

- **Manual sorting** on a slow-moving conveyor belt, after the waste has been received and before it is shredded, helps to remove any undesirable elements that may still be present in the waste.

- **Hydraulic sorting system** using decantation and flotation is used to suspend organic waste in a tank fed by a charge, and equipped at its centre with a powerful mixer-shredder. At the end of the mixing sequence, the floating materials (plastics) are recovered by means of a submerged comb and evacuated. The inert matter (stones, glass, batteries, metal objects, etc.), which settles at the bottom of the tank, is extracted through an interceptor.

- **Fragmentation:** The pre-treatment of sorted waste, as well as selectively collected organic fractions, continues with a view to reducing the granulometry of fermentable elements and homogenising them. Fragmentation includes all the equipment that crushes, grinds, dilates and shreds waste.

- **Other pre-treatments:** Various techniques have been developed to overcome the difficulties associated with digesting certain cellulosic substrates. Most of these

processes aim to obtain saccharification of these substrates (alkaline treatment, sulphur dioxide treatment, solvent delignification, etc.).

3.3.1 After anaerobic digestion

The post-treatment stages that may be carried out after digestion involve:

for **effluent** - aerobic post-purification; nitrification and denitrification;

- treatment of excess sludge;

- odour and exhaust air treatment;

for **solid waste** - hygienisation and aerobic maturation of digestate;

- treatment of excess juice;

- treatment of odours and exhaust air.

a- Effluents

- **Aerobic post-purification; nitrification and denitrification**

1. Discharge of digested effluent into a pipeline or river requires aerobic treatment (activated sludge) to reduce residual COD to the levels prescribed by standards, which for methanised effluent is between 300 and 1000 mg/l COD.

2. In order to guarantee a minimum $_{O2}$ content or to correct the redox potential, it may be necessary to reaerate the effluent.

3. The third phase of effluent treatment consists of eliminating the nitrogen present in organic and ammoniacal form, through **biological nitrification and denitrification**. This process involves four reactions **ammonification,** during which organic nitrogen is transformed into ammoniacal nitrogen; **assimilation**, in which part of the nitrogen is used for bacterial synthesis; **nitrification**, in which micro-organisms oxidise ammoniacal nitrogen into nitrite (NO_2) and then nitrate (NO_3); and finally **denitrification**, during which, in an anoxic reactor (without dissolved oxygen, but with combined oxygen), bacteria reduce nitrate nitrogen to a lower oxidation state.

- **Treatment of excess sludge**

The biological sludge produced by anaerobic digestion (0.10 - 0.15 kg MS/kg COD degraded) is partially separated and accumulated in the reactor as excess sludge.

The sludge can be drawn off at regular intervals for composting or land application.

In practice, some (30-50%) of the excess sludge leaves the anaerobic reactor suspended in the effluent and will be separated in the primary clarifier of the aerobic stage.

- **Treatment of odours and polluted air**

The odours produced by volatile fatty acids are relatively unpleasant. Their release can be limited by taking a few precautions at crucial points (effluent outlet, sludge storage). Several solutions can be envisaged, depending on the size of the installation and the sensitivity of the surrounding area:

- Depressurisation of at-risk areas with discharge through the wastewater storage (buffer tank);

- Discharge and adsorption through activated carbon filters;

- Discharge and absorption in a washing column (velocity: 1 m/s);

- Discharge through a compost filter (biofilter) (surface area approx. 10 times that of the washing column, speed 1 m/s).

Particular attention should be paid to the fact that the exhaust air may contain biogas and thus present a risk of explosion.

b- Solid waste

- **Hygienisation and aerobic maturation of digestate**

In order to degrade the lignocellulosic compounds and hygienise the digestate if the digestion system does not operate at a thermophilic temperature, it is almost essential to subject the digestate to an aerobic maturation stage. This stage is itself preceded by a phase of dehydration of the material leaving the digester (screw presses, centrifuges, etc.). The digestate can represent between 30 and 40% by weight of the input material.

- **Treatment of excess juices**

Excess juice from digestate dehydration can be:

- Discharged into the sewage system for treatment at a WWTP (wastewater treatment plant);

- Spread on agricultural land;

- Treated by centrifugation (figure 19) (legend 18), chemical flocculation (19), digestion (20) in an anaerobic filter and intensive aeration (30) as shown in the process figure below:

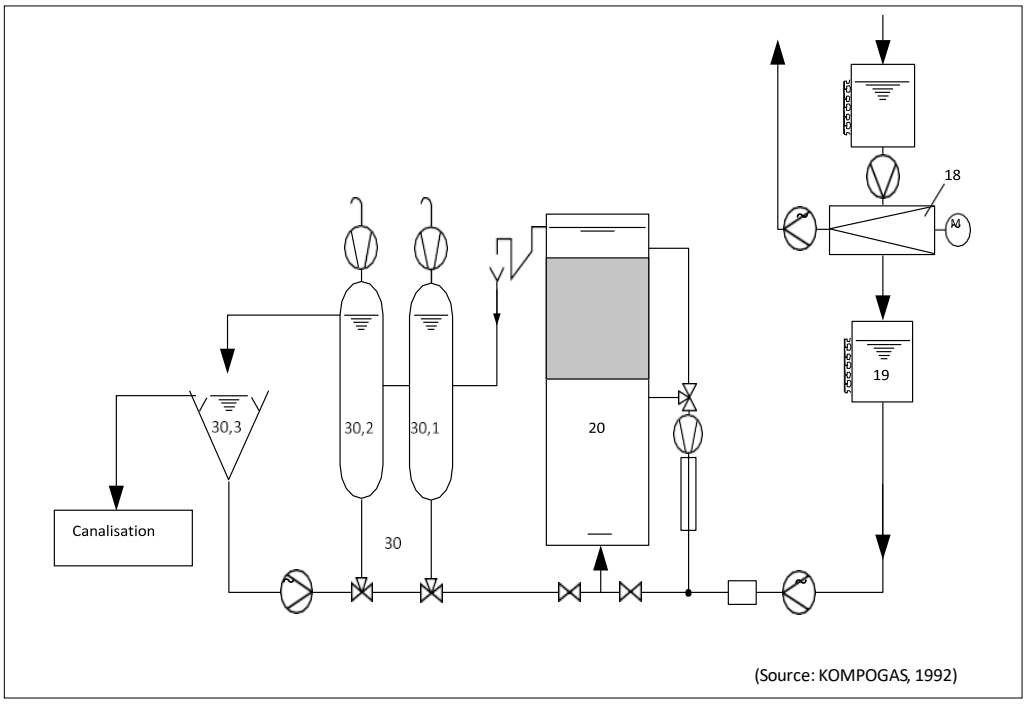


Figure 19: Treatment of excess juices process

- **Treatment of odours and polluted air**

Particularly sensitive areas are the waste reception pit and the digestate maturation room if this stage is carried out by windrow composting.

The equipment and systems recommended are those already mentioned for effluents.

3.3 Commissioning, operation and monitoring

Digestion start-up can be one of the major problems encountered in the application of this technique. It corresponds to the difficulty of developing the culture of micro-organisms best suited to a given substrate. Once the biomass has established itself in the form of granules or

flocs, or attached to an inert support in the form of a biofilter, the digester is generally stable. This initial problem is particularly noticeable in effluent methanisation.

Two phenomena need to be highlighted in order to understand the start-up of a digestion process:

1. Various substances contained in the initial substrate will determine a high redox potential; they will have to be eliminated to allow growth of anaerobic organisms. The

   aerobic organisms will consume the oxygen first, then the reduction of nitrates, trivalent iron and sulphates will complete the lowering of the redox potential.

2. Methanogenic bacteria can be present in the substrate in two ways: either they have developed there and are active and abundant (WWTP sludge, bovine manure), or they are absent or accidentally present (agri-food effluents). Thus, when digestion starts, the methanogenic flora will be sufficiently abundant to allow immediate activity, or it will require a period of development or artificial inoculation.

There are various specific methods for starting up anaerobic digesters, which vary according to the system chosen and the substrate to be treated. Generally speaking, they consist of

1- **Inoculation phase:** this is an initial addition of an inoculum containing the necessary micro-organisms. This phase is followed by an initial feed of substrate, at low organic load rates to ensure stabilisation of the digester's performance.

2- **The charge rate is gradually increased** until the required level is reached.

Successful commissioning requires the use of a viable anaerobic culture containing a broad spectrum of microorganisms, and control of the progressive substrate feed. A digester in normal operation does not normally require a continuous supply of inoculum; the organisms once established in the reactor reproduce and degrade the substrate.

Examples of operation and monitoring

- **Sludge Bed (UASB)**

The process runs optimally if a granular sludge bed from a similar installation can be used for seeding. This sludge activates within a short period of time and adapts fairly easily to new operating conditions. It is ideal, though not essential, to start the reactor with a sludge adapted

to the same substrate; a reactor treating potato processing effluents was seeded with sludge from a cardboard mill digester. The allowable COD loading is initially limited, particularly if the digester has not yet reached its operating temperature. During the start-up phase, the pH of the water to be treated must be strictly neutral. Start-up requires approximately ten days.

- **Anaerobic Filter**

It is preferable to seed with a culture containing a mixture of several sources of organic matter, as is the case with sludge from an urban digester. The substrate feed is regulated according to measurements of soluble COD reduction. Precautions must be taken to reduce the risk of micro- organism washout during substrate injections. Immobilisation depends on several factors such as the chemical composition of the substrate, surface conditions and the nature of the inert support. The immobilisation of micro-organisms is monitored, during the commissioning phase, by continuous measurement of the concentration of suspended organic matter in the recycling circuit. Regular substrate feeding begins when the organic matter concentration decreases significantly in the recycling circuit and gas measurements demonstrate sufficient activity within the digester. Feed increase takes place in successive steps. The determining criterion for moving to the next step is to ensure that volatile acidity remains below 10–20 meq/l. Doubling the feed rate requires a period of at least 10 days. Overall, the duration of the commissioning operation ranges from less than three months for favourable substrates to nine months or more in more challenging cases.

An important aspect of the commissioning procedure for an anaerobic digestion installation is the restart of industrial units with seasonal activities.

The following parameters are usually used to evaluate the stability and performance of the reactor:

- **Biogas production and composition**:

During stable digestion with a substrate that does not vary in composition, relatively stable gas production is observed, with a methane content that can be easily predicted. When biogas production and composition are erratic, this is a sign of instability, with a low methane content being a primary indicator of inhibition of methanogenic bacteria.

- **Reduction of organic matter:**

The organic matter load and reduction efficiency are determined by the OM (organic matter)

content, the COD, or the carbon content in the incoming and outgoing substrate and in the biogas.

- **pH and Alkalinity**

A deviation from optimal pH levels indicates potential toxicity and a digestion incident. Low pH levels are a symptom of digester imbalance. An increase in volatile fatty acid concentrations is accompanied by a drop in pH; at levels below pH 6.0, conditions will become toxic for methanogenic bacteria. The pH of anaerobic digestion is a function of the carbon dioxide content of the gas, as well as the alkalinity.

Alkalinity is a measure of the buffering capacity, or acid neutralisation capacity, of the digester. Total alkalinity is a non-specific measurement frequently used to determine the carbonate, bicarbonate and hydroxide contents of a culture. Maintaining a bicarbonate alkalinity of approximately 1,000 mg/l ensures digester stability. As soon as the alkalinity within the digester is reduced by an increase in volatile acid concentrations, for instance, the pH decreases within the reactor

Measures to promote an increase in alkalinity and pH are therefore necessary, bearing in mind that raising the pH without increasing alkalinity may prove insufficient to restore digester stability. Alkalinity may be increased by adding lime, or alternatively generated through protein degradation into ammonia, forming an ammonium bicarbonate buffer.

Economic considerations determine, on a case-by-case basis, the specific methods chosen to maintain pH and alkalinity within digesters. Wherever possible, operating conditions should be such as to avoid the need for additives.

- **Volatile acids:**

This is a critical parameter in the operation and control of anaerobic digestion. The most important volatile acid for methane formation is acetic acid. The concentration of these volatile acids in an anaerobic digester is determined by their rate of production and their rate of consumption. In a properly functioning digester, there is a balance between the quantity of volatile acids produced and that consumed during conversion by the methane-forming bacteria. When the former exceeds the latter, the concentration of volatile acids increases.

- **Temperature**

This factor can influence the kinetics and stability of the conversion process, the quality of the effluent and the energy balance of the process.

Regarding the effects of temperature on performance, it is considered that higher temperatures increase the destruction efficiency of suspended organic matter, improve the dewaterability of digested solid substrates, and enhance the removal rate of pathogenic organisms. The effects of high temperatures on effluent quality are particularly significant at short retention times; as retention times increase, the difference in effluent quality between mesophilic and thermophilic digesters tends to diminish.

With regard to process stability, temperature fluctuations, even those limited to narrow ranges, can affect the stability of thermophilic digesters in particular.

The effects on the energy balance are primarily due to the fact that thermophilic digesters have greater thermal energy requirements than mesophilic reactors for heating purposes. The significance of this difference on the overall energy balance of the digester depends on the dry matter concentration of the substrate and the methane production rate. It has been demonstrated that the energy output of anaerobic digestion shows a negative balance as soon as the dry matter content falls below 2% for the mesophilic regime, and 4% for the thermophilic regime.

- **Monitoring and Operational Safety**

The monitoring and operational safety of a digester rely on instrumentation (gas analysis and metering, conductivity, temperature, pH, flow rate, etc.), the collection and processing of the data obtained, as well as the control loops enabling intervention in the process. These indicators allow gradual changes to be detected. Load shocks or the presence of toxic substances require rapid corrective responses, particularly when hydraulic retention times are short, as is the case with high-load reactors. Monitoring the metabolic activity of the biomass in these types of reactors can be carried out using elaborate, or even complex, techniques that are time-consuming and not applicable on-line: direct cell counting, measurement of nucleic acid or protein content, enzymatic activities, etc. Regular monitoring of volatile fatty acids is to be preferred over these methods.

The use of ready-to-use enzymatic kits and the forthcoming appearance on the market of management and optimisation systems could increase the reliability of digesters. It should be

noted, however, that preparations containing freeze-dried bacteria have no lasting effects on the digestion process that could justify the cost of purchase.

Chapter 4 : Preliminary Studies

4.1 Technical performance of anaerobic digestion

The performance of an anaerobic treatment process is expressed according to two criteria:

a) In terms of organic load reduction expressed as COD. Within this parameter, a distinction is made between the reduction of COD in particulate form, which is primarily linked to the efficiency of pre-treatment (removal of suspended solids), and the reduction of COD in soluble form.

b) In terms of energy production in the form of biogas.

The efficiencies relating to these criteria depend on the following aspects:

1- **Characteristics of the effluent or waste**: Not all organic compounds are readily degradable by anaerobic metabolic pathways. Ligno-cellulosic materials (wood, wood waste) are, for example, difficult to digest. The occasional or accidental introduction of inhibitors may reduce performance or even halt methanisation activity. A deficiency in nutrients may limit biological activity.

2- **Methanisation system:** Each digestion system offers optimal performance within a specific volumetric loading range. At higher loading rates, efficiencies may decrease, which is a problem that must be taken into account when treating substrates with peak production periods. The following figure illustrates the response of an industrial digester (maize starch production), of the UASB type, designed for a loading of 11 kg COD/m³, which, despite peaks of up to 30 kg COD/m³, maintained a treatment efficiency of approximately 90–95%.

3- **Technical**

Achieving good performance evidently depends on the proper functioning of the installation. Certain technical faults may affect its efficiency, such as:

- Poor temperature control and regulation;
- Lack of airtightness in the digester (oxygen ingress, gas losses);
- Insufficient mixing causing sediment accumulation;
- Clogging by solid matter, grease or precipitated carbonates.

4.1 Treatment and recovery of biogas and process-derived materials

The performance of digesters and the characteristics of the waste and wastewater treated influence the material balance of the methanisation process.

The disposal or utilisation of the various products arising from digestion may be carried out according to the following pathways:

4.1.1 Biogas

4.1.1.1 Recovery

- **Feeding cogeneration units.** The principle of cogeneration units consists in the simultaneous use of the mechanical energy produced by a combustion engine and the heat it generates. This is also referred to as "combined heat and power" (CHP) or "total energy installations". In such cases, the stationary engine drives an electrical generator; this represents the option offering the greatest recovery potential for biogas in industrial installations. Where electrical energy can be fed into an existing grid, the use of an asynchronous generator simplifies implementation; however, in the event of a grid failure, autonomous power supply to the plant is not possible. Connecting a cogeneration unit to a distribution network requires special technical provisions concerning power feedback, metering, electrical protection and the prevention of incidents originating from the connected installation that could propagate across the network.

- **Thermal applications:** Biogas can be used in most industrial heating appliances. Equipment designed at the construction stage to operate on biogas or a gas mixture is specified to function within the extreme limits of the feed gas composition. For equipment operating on heating oil, the adaptation concerns the burner. Only appliances that are sensitive to even minor variations in characteristics (such as blowtorch flames), or whose output is too low to allow for a biogas adaptation device, should be excluded from these applications. The reheating of effluents to be digested and the maintenance of the digester temperature constitute the thermal self-consumption of the system.

- **Injection as a blend into a natural gas pipeline:** If there is a single industrial user, their combustion equipment will be adjusted according to the composition of the natural

gas/biogas blend. If the purpose is to supply a distribution network, prior purification of the biogas is essential in order to bring it to the characteristics of natural gas (removal of hydrogen sulphide and carbon dioxide, drying).

- **Automotive fuel use:** Motor vehicle engines are essentially mass-produced and originally designed for the dominant fuels: petrol and diesel. A more or less costly conversion is therefore required. Furthermore, the nominal power output will be reduced by approximately 10 to 15%, and vehicle performance will decrease accordingly. Finally, if the vehicle is to have an acceptable range, pressurised storage (200–300 bar) is necessary. The limited weight and volume of such storage provides in practice only half the range compared to a petrol-powered vehicle, even after removal of the CO_2 contained in the biogas, which has no energy value. All these constraints mean that the use of biogas as automotive fuel should be reserved for supplying captive fleets operating within a limited geographical area.

- **Flare disposal:** In methanisation installations for industrial and household waste and effluents, it is necessary to provide a flare in order to handle situations involving breakdowns or maintenance of biogas recovery equipment, by burning the gas. Indeed, given that methane is a greenhouse gas 25 to 30 times more harmful than carbon dioxide, it is not acceptable to allow biogas to escape into the atmosphere. This equipment consists of one or more atmospheric burners protected from the wind by a cylindrical metal casing or one formed by two cones with opposing apexes.

4.1.1.2 Purification

Not all applications of biogas require the same degree of purification; the following table indicates which constituents must be removed according to the intended use.

Table 7: Required constituent removal according to biogas application

Biogas Application*	H_2S Removal	CO_2 Removal
Cooking	Yes	No
Water heating	Yes	No
Stationary engine	According to specifications	No

Vehicle**	Yes	Yes
Gas network injection	Yes	Yes

*For all applications, care must be taken to remove water. **When biogas is compressed, desulphurisation is essential.

The various purification methods applicable to biogas treatment are presented in the following table, which includes industrial processes for the removal of water, carbon dioxide and hydrogen sulphide.

Purification using solid products involves reagents that are relatively easy to handle; it exploits two physico-chemical phenomena: adsorption, which is reversible, and absorption, which consumes the reagent. Adsorption uses two-column devices, one for adsorption and the other for desorption or regeneration, which is carried out by pressure reversal, thermal reversal, or stripping using an inert gas. Absorption uses numerous chemical products that react with water; these materials should be low-cost (such as quicklime, CaO), easy to dispose of after use, and must not affect the operation of the purification unit (clogging, for example).

Gas-liquid contact purification consists of passing the gas through a device ensuring contact between the gas to be purified and the chemical washing products. Regenerative processes are all absorption-desorption or washing processes for the pollutant. The equipment then comprises an absorption tower where purification takes place and a desorption tower where, under the effect of heat and/or decompression, the solvent is regenerated. Complete purification cannot, in general, be achieved unless the number of absorbers is increased and their dimensions enlarged.

Physical purification processes make use of gas compression and cooling. One method consists of cooling the gas to cause water condensation; in practice, this must be carried out at low

temperature (to achieve dew points below 5°C), which limits the reduction in water content. Water vapour can also be condensed by simultaneous compression and cooling. As for the removal of carbon dioxide from biogas, this is reserved for the industrial sector, as well as for certain conditions where CO_2 recovery could present an economic interest; indeed, whilst carbon dioxide is a gas that can be liquefied by compression at ambient temperature, whereas the liquefaction of methane requires, in addition to compression, significant cooling, it should

be noted that the behaviour of the CO_2/CH_4 mixture is complex and requires study of the pressure-temperature diagram of the biogas. Amongst physical processes, separation by permeation through membranes made of porous polymers has been developed. This method uses the selective permeation of gases through a membrane under the action of a partial pressure difference; each gas having its own diffusion rate (hydrogen, helium, hydrogen sulphide and carbon dioxide are "fast" gases, whilst nitrogen, oxygen, methane and hydrocarbons are "slow" gases).

Biological purification, using anaerobic micro-organisms to transform a component of the biogas, has been developed over the past decade; it relates in particular to the removal of hydrogen sulphide and its conversion into elemental sulphur.

4.1.1.3 Storage

In general, a biogas installation includes a gas storage system designed to balance gas production and consumption. For economic reasons, the capacities of gas holders are usually limited to one or two days of production.

Three gas holder systems are used for biogas storage:

a) Flexible gas holders

These are industrially manufactured pieces of equipment using gastight membranes made of inert materials (polyethylene, chlorosulphonated polyethylene, butyl or fluorocarbon rubber, polychloroprene, neoprene, polyamide, etc.). They are generally housed within a structure and fitted with a ground anchoring device. Certain suppliers offer ballasting systems for pressurising the gas holder; the maximum pressure achieved is in the order of 25 to 50 mbar depending on the model and the size of the bladders, and it varies with the fill level of the gas holder, whilst remaining relatively constant when the fill level is between 20% and 80% of the total volume. If the flexible gas holder is not ballasted, gas pressurisation is achieved by means

of a centrifugal or vane compressor. The storage capacities of such systems range between 1 and 500, or even 1,000 m^3.

b) Bell-type gas holders

This is the storage system commonly used by the gas industry. Its principle is as follows: an inverted bell over a water-sealed tank is guided in vertical translation by girders or a helical

rail. In addition to their storage function, they also provide pressure regulation, which is independent of the fill level and therefore of the position of the bell. Furthermore, they can also be ballasted. These units require frequent maintenance of the interior coating of the bell. Indeed, the presence of hydrogen sulphide generates corrosion; the presence of carbon dioxide causes acidification of the water contained in the hydraulic seal and therefore rapid corrosion of the submerged metal parts. The bell gas holder can either rest directly on the digester, which is less costly but leads to thermal losses (difficulty in insulating the bell) or gas losses, or constitute a structure separate from the digester, leading to a significant additional cost, and with a risk of freezing of the water contained in the gas during winter. The storage capacities of such systems range between 50 and 5,000 m^3.

c) Rigid tanks

This form of storage may prove advantageous in cases where biogas is used as a fuel, as the gas must be compressed to provide sufficient energy for machinery and vehicles.

An ideal gas subjected to a doubling of pressure will occupy only half its initial volume. Up to pressures of approximately 400 bar, biogas behaves even more favourably: a biogas containing 67% CH_4 and 33% CO_2, under a pressure of 160 to 200 bar, will occupy only two thirds of the volume that an ideal gas subjected to the same pressure would occupy.

In other words, a given tank will contain, compared to an ideal gas, a quantity 1.5 times greater of biogas. This proportion obviously decreases as the CO_2 content increases.

For economic reasons, steel tanks for biogas storage do not exceed pressures of 10 to 20 bar, in order to remain within reasonable plate thicknesses and tank weights.

High-pressure storage (200 or 300 bar) in cylinders (30 or 50 litres) intended to be carried on board vehicles poses numerous technical problems and requires substantial investment.

4.2.2 Digestate

The product leaving the solid waste digester is characterised by the stabilisation of the fermentable fraction of the fresh substrate. This digestate humifies correctly provided it is subjected to aerobic post-maturation, at the outlet of the reactor and after pressing. Its physico-chemical characteristics are then comparable to those of a good-quality compost. The conditions of use and applicable quantities depend on the type of crop (arable crops, market garden crops, fruit crops, artificial soils); these are specified by the Ordinance on Substances Hazardous to the Environment.

4.2.3 Rejects

These inert materials originate from the manual sorting carried out after reception of the waste and prior to shredding. They are composed of glass, stones, plastics, textiles and other undesirable elements that may be found in bins and containers from selective collections. These by-products will be landfilled or incinerated.

4.2.4 Pressing Water

The liquid surpluses arising from pressing of the digestate are partly recycled within the treatment chain for seeding and moistening of fresh waste prior to digestion, or to help maintain the moisture conditions during the post-composting phase. The remainder must be treated so that it can be discharged into the wastewater sewer, provided the treatment plant is able to accept it. If this is not the case, dewatering techniques, which are energetically unattractive, will need to be employed. The following table provides some indications regarding the characteristics of this pressing water.

4.2.2 Digested Effluent

The characteristics of the treated effluent for discharge into a public wastewater sewer are laid down by the Ordinance on Wastewater Discharge and by cantonal regulations (notably for COD and BOD_5). Depending on the nature of the industrial influent and the performance of the digestion system, a supplementary aerobic treatment may prove necessary to meet discharge requirements. This is carried out following the anaerobic treatment, either on the industrial site or by directing the methanised industrial effluent to a public treatment plant where it will be treated jointly with domestic wastewater.

4.2.3 Digested Sludge

Excess digested sludge contains varying amounts of water, non-biodegradable substances, settleable degradable but undigested products, and soluble organic compounds. The quantities produced are significantly lower (3 to 10 times less) than those resulting from conventional aerobic treatment. For industrial wastewater, the production of excess sludge is in the order of

0.10 to 0.15 kg dry matter per kg of COD removed. After dewatering (sedimentation, filtration or centrifugation), this sludge is used as an agricultural amendment or disposed of by incineration, depending on local conditions and the quality of these products.

Chapter 5. Project Development

5.1 Anaerobic Digestion: A Link in the Treatment Chain

In this final section, the elements necessary for the development of an anaerobic digestion project are addressed. This includes understanding the position of anaerobic digestion amongst the treatment pathways for solid and liquid waste, in terms of both economic and ecological comparisons. A presentation of the technical aspects of biogas recovery will be followed by an overview of the economic and legislative data whose consideration is essential throughout the development of a project.

a) For household organic waste

- **Incineration:** in the long term, the development of selective collections of the organic fraction of household waste will remove these tonnages from disposal by incineration. Furthermore, the low calorific value and the technical problems associated with the combustion of wet waste will encourage operators of incineration furnaces to reject these materials. Finally, the economic comparison of treatment costs will encourage the adoption of biological treatment options.

- **Composting:** this aerobic biological conversion pathway only constitutes competition for anaerobic digestion insofar as decentralised treatment schemes (individual or neighbourhood composting) could, within a given area, reduce the available organic waste resource. For medium to large capacity treatment installations (i.e. from 3,000 t/a to 5,000 t/a), aerobic and anaerobic bioconversion processes are complementary, the former for woody and dry waste and the latter for wet by-products.

b) For industrial waste

- **Direct land spreading:** certain market gardening industries practise the direct spreading of their production waste as an organic amendment.

- **Composting:** this form of treatment can be combined with the composting of household organic waste. However, it proves problematic for technological reasons (excessively high moisture content of the waste and/or a deficiency in carbon-based substrates) or economic reasons (dispersal of waste sources leading to composting units of insufficient capacity).

- **Ethanol production:** this form of recovery can be considered for by-products from sugar mills, starch plants or cheese dairies; it allows the production of drinking alcohol, solvents, energy agents or products for synthetic chemistry. Only large-scale units are feasible.

- **Animal feed:** the use of waste and by-products from the agri-food industry as animal feed is certainly the most widely practised pathway at present. However, the agricultural policy context could reduce the outlets for these products. The following table provides some indications regarding the nutritional values of certain by-products.

c) For industrial wastewater

- **Aerobic treatment:** the implementation of free cultures (activated sludge) or fixed cultures (biological film, bacterial beds, granular beds, biological discs) constitutes the conventional treatment pathway for industrial effluents. When a project leads to the evaluation of both biological treatment routes, a fair assessment of operating costs must be carried out (energy consumption, sludge disposal, etc.).

- **Direct land spreading:** spreading on agricultural land constitutes a treatment technique based on the purifying capacity of the soil (filtration, colloid absorption, degradation of organic compounds) and the export capacity of crops. It requires a study of the spreading area (soil suitability, groundwater pollution risks, dosage according to crop type) and the implementation of storage, homogenisation and irrigation equipment. It can only be considered in rural areas.

- **Animal or human consumption:** certain liquid by-products from the agri-food industry can be recycled as cattle feed or in the preparation of foodstuffs. This is notably the case with whey (a yellow-coloured liquid derived from cheese-making; soft and fresh cheeses yield an acid whey whilst pressed cheeses yield a sweet whey). This by-product constitutes a traditional liquid feed for pig farming (5–15 l/day per pig). It is also used in the manufacture of powdered infant formula, in biscuit-making, confectionery and industrial patisserie, as well as in the production of ice cream and beverages.

In order to assess the possibilities of integrating anaerobic digestion into waste treatment chains, wastewater treatment systems and industrial production processes, it is recommended

to follow the approach below:

- Determination of the minimum size of an installation that would allow waste to be digested under acceptable economic and ecological conditions, by comparison with competing treatment pathways;
- Determination of the catchment area or by-product production capacity (waste and effluents) corresponding to the minimum size defined.

5.1 Technical Aspects of Biogas recovery

5.1.1 Characteristics and adaptability of biogas

5.1.1.1 Composition

Biogas is a mixture of gases containing corrosive or problematic constituents, the removal of which allows for more numerous, more sophisticated and potentially more economically viable applications.

The main disadvantage resulting from the presence of water is the deposition of condensates in pipework, causing potential blockages and promoting corrosion. This is easily remedied by an appropriate design of the pipe layout (gradients) and systematic draining (condensate traps). Residual water vapour does not interfere with the majority of biogas applications. It should be noted, however, that the calorific value calculated from the methane content is in practice generally lower due to the presence of water vapour.

Condensation increases when the gas is compressed, and the condensates become more corrosive as pressure increases.

- **Hydrogen sulphide**

This is the most undesirable pollutant in biogas. At low concentrations (0–2,000 ppm), it is highly corrosive towards copper and its alloys, but can be conveyed in galvanised steel pipework. In these proportions, the use of biogas as a fuel proceeds normally with certain precautions, such as stainless-steel lining of the flue. Use with discharge of combustion products into an occupied space is, however, more problematic due to the production of SO_2, which is irritating.

At higher concentrations, which may reach up to 2%, corrosion of all non-stainless metal parts is to be expected. Furthermore, accidental inhalation of biogas becomes very dangerous. It should be noted that an H_2S concentration of 1,000 ppm is rapidly fatal.

The toxic effects of hydrogen sulphide are presented in the following table 8:

Table 8: Toxic effects of hydrogen sulphide on human health (ppm)

Concentration (ppm)	Observed Effects
10	Threshold limit
5–40	Odour threshold (but paralysis of olfactory sensitivity)
20–100	Mild headache, blurred vision, eye irritation
100–200	Dizziness, migraine
500	Nervous system disorder, vertigo, vomiting, fainting
1,000	Loss of consciousness, death (often by asphyxiation due to inhalation of vomited matter)

- **Ammonia**

It is not present in all methanisation cases. It generates slight corrosion of copper compounds, and its combustion, which produces nitrogen oxides, also has irritating and harmful effects.

- **Carbon Dioxide**

This is a principal constituent of biogas. Its dissolution in condensates gives it significant corrosive activity, as in solution it leads to the formation of carbonic acid. Its removal is generally not necessary for thermal applications. In certain cases (automotive fuel use, injection as a blend into a natural gas network, high flow rates), it may be economically worthwhile to proceed with its removal.

Table 9: Concentration ranges of major biogas constituents (% vol)

Constituent		**Concentration [% Vol]**
Methane	(CH_4)	40–75
Carbon dioxide	(CO_2)	25–60
Hydrogen sulphide	(H_2S)	0–1
Nitrogen	(N_2)	0–7
Oxygen	(O_2)	0–2
Hydrogen	(H_2)	0–1

5.2.1.2 Physical Characteristics

- Density

The density of a gas depends on its constituents and their relative concentrations. The density of biogas as a function of its methane content is indicated in the table 10:

Table 10: Relative density of biogas to air vs. CH_4 content

CH_4 content (%)	**50**	**60**	**80**	**90**
Relative density to air	1.040	0.942	0.745	0.652

This means that biogas is lighter than air and will not accumulate at ground level in the event of a leak, unlike propane, for example.

- **Critical point**

This is the thermodynamic state in which the gaseous and liquid phases of a substance coexist in equilibrium. The critical point for methane is –82.5°C, regardless of pressure. This represents a major limitation in the storage and recovery possibilities of biogas.

- **Calorific value**

The lower calorific value represents the quantity of energy released during the complete combustion of a unit mass or volume of fuel, at 1 atm and 0°C, assuming that the water produced remains in vapour form. The lower calorific value (LCV) is determined by the methane content. The two tables below present the LCV of biogas and several other fuels, followed by the volumetric equivalences between biogas and these same fuels.

Table 11: Volumetric fuel equivalences for biogas

Fuel		**MJ kg^{-1}**	**MJ m^{-3}**
Methane		50.0	35.9
Purified biogas	(90% CH_4)	45.0	32.2
Average biogas	(60% CH_4)	30.0	21.5
Natural gas		48.7	36.1
Butane		45.7	118.5
Propane		46.4	90.9
Methanol		19.9	15.9×10^3
Ethanol		26.9	21.4×10^3
Petrol		45.0	33.3×10^3
Diesel		42.1	34.5×10^3

- **Combustion air requirement**

This is the dimensionless number expressing the ratio of the volume of air required for the stoichiometric combustion of a unit volume of gas, under standard conditions (0°C, 1 atm). Some values of this air-to-fuel ratio are given in the table 12.

Due to the heterogeneity of air/gas mixtures, the volumes practically used are higher than the stoichiometric volumes in order to avoid the formation of unburnt gases. The composition of a combustible air/gas mixture can be expressed by the ratio:

λ = (actual fuel/air mass ratio) / (stoichiometric fuel/air mass ratio)

When λ < 1, the mixture is referred to as "lean", and when λ > 1, the mixture is described as "rich". This ratio is also called the excess air factor.

Table 12: Stoichiometric combustion air requirements

Fuel	**(m^3 air / m^3 gas)**
Methane	9.52
Average biogas (60% CH_4)	5.71
Purified biogas (90% CH_4)	8.57
Propane	23.78
Butane	30.97

- **Flame speed**

If a lit match is brought close to the open end of a tube containing a combustible gas mixture, a flame forms and immediately enters the tube; the flame propagates inside the tube at a certain speed known as the flame speed.

For normal combustion of a gas to occur, the flow velocity of the combustible mixture at the outlet of the mixing tube must correspond to the flame speed. Below this value, the flow velocity being too low, combustion propagates back towards the mixer. At a high flow rate and therefore a flow velocity greater than the flame speed, the flame lifts off the burner and is extinguished.

In the case of methane, the flame speed reaches 25 $cm \cdot s^{-1}$ for a biogas containing 60% CH_4 and 40% CO_2. The flame speed also depends on the air-to-fuel ratio; it reaches its maximum for a slightly rich mixture.

- **Flammability limits**

A gas mixture is only flammable if the proportion of combustible gas in the fuel-air mixture lies between two flammability limits: the lower limit corresponds to a fuel-lean mixture, and the upper limit corresponds to a fuel-rich mixture. These limits depend on the dimensions of the enclosure containing the gas mixture, the flammability range widening as dimensions

increase. They may also be affected by variations in temperature and pressure around standard conditions. The flammability limits of a gas composed, like biogas, of a combustible (CH_4) and a neutral gas (CO_2) can only be determined experimentally. The diagram below shows the flammability range of biogas. It will be noted that below 23% methane, a biogas is not combustible.

Explosion risks exist when two conditions are met: the existence of a potentially explosive air-biogas mixture and the presence of an ignition source. The methane-air mixture becomes explosive at a methane content of between 5 and 15% vol.; if the biogas contains approximately 35% carbon dioxide, these limits narrow to 5–12% vol.

Ignition sources consist principally of open flames, sparks from electrical switches, lightning strikes, or very hot surfaces. Explosion hazards are particularly important to take into account in enclosed or poorly ventilated spaces where risks of unintended biogas release may arise.

5.3 Costs and Revenue

The economic aspects of biomethane production by anaerobic digestion of solid and liquid waste are influenced by numerous factors resulting not only from the treatment scheme and process selected, but also from local financial conditions. These factors include the size of the installation, the use of the products, environmental constraints, market conditions, tariff and policy incentives, and the cost of the capital required for implementation, amongst others. It is important to take all of these parameters into account in order to determine the profitability of each project.

Due to the multiplicity of factors involved in the economic analysis of a project, it is not possible to generalise the conditions to be met in order to ensure a favourable economic framework. Each project must be subject to an individual and thorough analysis.

The components comprising an anaerobic digestion installation can be grouped into four main areas:

1. Preparation and pre-treatment of the fresh substrate;
2. Anaerobic digestion;
3. Treatment and recovery of biogas;
4. Storage, treatment, disposal/recovery of the digested substrate.

5.3 Legislative aspects

The construction of an industrial anaerobic digestion installation is subject to a number of legal provisions. This section of the course provides a detailed review of these.

These consist primarily of provisions under federal, cantonal and indeed municipal public law:

- **Location.** The siting of such a facility must comply with the provisions of planning and construction law.
- **Environmental protection.** A biogas installation operates on the basis of waste (fresh material) and itself discharges residues: liquid effluents, sludge, solid waste and biogas (output). It is subject to federal environmental protection law and must observe the various provisions accompanying it.
- **Nuisances.** The operation of such an installation may generate nuisances: noise, odours, and discharge of polluting substances into the atmosphere. It is subject to compliance with the standards provided for in these areas by federal environmental protection law.
- **Operation and safety.** Due to the hazards that these installations may present (explosion risks in particular), they must strictly conform to the applicable safety standards, notably those issued by the CNA and by the AEAI (Association of Cantonal Fire Insurance Establishments). These standards, although purely technical and non-legal in nature, may indirectly acquire legal force insofar as a law or regulation (cantonal or municipal) declares them applicable. Likewise, if the building and/or operating permit makes compliance with them a condition thereof, they acquire legal force.

Finally, insofar as the biogas produced is subject to public distribution, further legal issues may arise, such as the necessity of an agreement for the transport and distribution of energy, or the laying of pipelines on public land.

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