CENTRE DE RECHERCHE SUR LA PROPRETE & L'ENERGIE

Methodology for operating solid waste anaerobic digestion units

METHAPI-Expertise
Project

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Résumé

Guide méthodologique pour l’exploitation d’unités de méthanisation de déchets solides

Au cours de ces dernières années, le traitement de déchets solides par méthanisation s’est très fortement développé en Europe. Malheureusement, le niveau de fiabilité de ce type d’installation n’est pas encore optimum et de nombreux problèmes d’exploitation, d’origine mécanique ou biologique, peuvent être rencontrés sur ce type d’unité.

Le présent guide, élaboré dans le cadre du projet LIFE ENVIRONNEMENT appelé METHAPI EXPERTISE, a pour objectif de transmettre des données essentielles qu’il est important de prendre en compte lors de la conception ou de l’exploitation d’une unité de méthanisation de déchets solides.

La compréhension de la technologie étant primordiale, la première partie de ce document définit la méthanisation et présente les différents types de procédés pouvant être utilisés.

La deuxième partie du guide donne les préconisations essentielles pour faciliter l’exploitation de ce type d’unité. A ce niveau, les considérations sont aussi bien d’ordre mécanique que biologique.

Enfin, une ultime partie s’attache à rappeler l’importance des consignes de sécurité à respecter et de la formation du personnel exploitant.

Methodological guide for anaerobic digestion plant operation on solid waste

Summary

From the last decade, we are witnessing a great development of anaerobic digestion of solid waste in Europe. Unfortunately, the level of reliability of these plants is not yet optimized. Multiple operating problems, going from mechanical to biological, are reported.

The main objective of the present guide, produced during the LIFE ENVIRONMENT project called METHAPI EXPERTISE, is to transfer the essential information necessary to take into consideration during the design and/or operation of a solid waste anaerobic digestion plant.

The main element is the understanding of the technology. Therefore, the first part of the guide defines anaerobic digestion and presents the different processes that could be used.

The second part of the guide proposes basic recommendations to simplify operation of this kind of plant. Recommendations include mechanical and biological aspects.

Finally, the last part insists on the extreme importance of two key aspects in plant operation: respect of safety rules and training of plant personnel.

CONTENTS

I. INTRODUCTION - FOREWORD

A. What is anaerobic digestion? The principle, an overview and biological reactions.

1. What is anaerobic digestion?

The process of anaerobic digestion, or anaerobic digestion, is both ancient and modern. Ancient, since the natural phenomenon of fermentation into flammable gas in marshes was observed by Volta in 1776. Modern, since the industrial application of this biotransformation dates back only to the 1950s for sludge digestion, and the early 1990s for waste.

Anaerobic digestion has in addition experienced various stages of development. In the 1970s, in the wake of the first oil crisis, it was one method considered by the government to provide relative energy independence for users. Its application was subsequently mainly focused on decontamination (in particular of effluent produced by the food processing industry) owing to its ability to treat effluent with high concentrations of organic matter and to the low output of biological sludge that results (3 to 5 times less than conventional activated sludge treatment facilities). Overall, anaerobic digestion is now viewed as a method which enables both energy to be generated and waste to be eliminated (or reduced in volume).

Anaerobic digestion is a biological process occurring in the absence of oxygen, during which organic matter is converted into biogas (primarily comprising methane, CH_4, and carbon dioxide, CO_2). This conversion is carried out in the main by bacteria and archaea (micro-organisms close to bacteria). This transformation is a complex one, which in the case of waste matter involves conversion from a solid (a piece of cardboard, for instance) to a soluble form (such as sugars or proteins) which can be used by the bacteria.

Owing to this complexity, the transformation is not carried out in its entirety by a single species, but by a set (a consortium) within which each group undertakes one aspect of the decomposition process (Figure 1). The usual diagrammatic representation shows four transformation stages, namely hydrolysis, acidogenesis, acetogenesis and methanogensis.

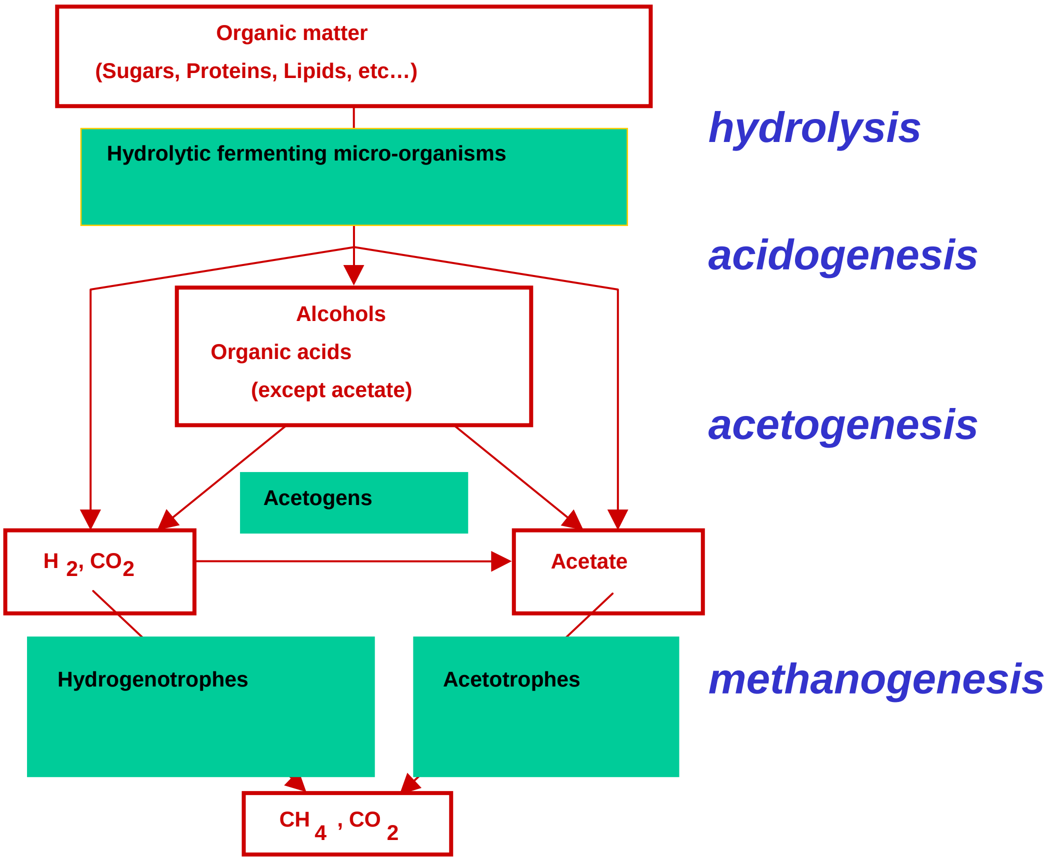


Figure 1: *Simplified diagram of anaerobic digestion*

a) Hydrolysis

This phase involves the decomposition of complex organic molecules into monomers. Compounds such as polysaccharides (e.g. cellulose), proteins and lipids are hydrolysed into simple sugars, amino acids and into glycerol and fatty acids respectively. This conversion is done by extracellular enzymes. The majority of soluble molecules are easily hydrolysed, although this stage may prove tricky where the compounds are insoluble or solid, which is the case for waste matter.

b) Acidogenesis

This phase, also known as the fermentation phase, transforms the various monomers resulting from hydrolysis into short-chain organic acids (2 to 6 carbons), the main acids produced being acetic acid, propionic acid and butyric acid. As the name suggests, the acidogenesis phase often results in acidification of the environment. It is generally quick owing to the high growth rate of the bacteria involved. Other by-products are also generated such as carbon dioxide and hydrogen, as well as ammonia nitrogen (in the form of NH_4^+ or NH_3) in the case of protein hydrolysis.

c) Acetogenesis

(1) Acetogenic obligate hydrogen producing bacteria

The acetogenesis stage covers the conversion of a small number of simple compounds into acetate, bicarbonate and hydrogen. The bacteria responsible for this stage are known as obligate hydrogen producing bacteria (OHPA). However, hydrogen accumulation blocks their development and it needs to be eliminated. This elimination is achieved either by hydrogen-consuming methanogenic bacteria or by sulphate-reducing bacteria (reducing sulphates into sulphides). The acetogenic bacteria group is often referred to as syntrophic bacteria (from *syn* meaning together and *trophein* meaning nourish) because they provide their metabolic partners with their carbon source or their energy (hydrogen, bicarbonate or acetate). Syntrophic relationships between species are often viewed as a cornerstone of the reaction.

(2) Mono or homoacetogenic bacteria

These organisms produce only acetate, either from bicarbonate and hydrogen, or by hydrolysing longer chain compounds. They contribute to hydrogen regulation in the environment, notably by using the hydrogen from OHPAs.

d) Methanogenesis

Methanogenic species mainly use acetate, carbon dioxide and hydrogen as substrates. Their growth rate is lower than that of acidogenic bacteria. Classified within archaea, they are significantly different from other bacteria both structurally and in terms of genetic material. The commonest methanogenic species are generally split into two groups:

- Acetotrophic methanogens responsible for 70% of the methane production in digesters using acetate
- Hydrogenotrophic methanogens which use hydrogen and carbon dioxide.

2. Biological reactions and anaerobic digestion

a) Principle of biological reactions

A biological reaction is actually one of the consequences of an organism's life. The organism carries out a function (its reproduction) which requires matter and energy. To synthesise matter, it uses the carbon source and nutrient additives (nitrogen, oxygen, hydrogen, etc.) making up its cell material.

Energy is drawn from the concomitant reaction. A biological reaction is therefore a chemical transformation carried out by a living species. For the living organism, the purpose of the biological reaction is to use the energy released as nourishment.

It is generally considered that the speed of a biological reaction consuming a chemical substance is related to the speed of growth of the living species consuming it. To measure that speed, the concept of a growth rate (symbol μ) is used. The speed of growth in a species of concentration X is proportional to the growth rate:

$$\frac{dX}{dt} = \mu X$$

Every biological reaction has its own metabolism, i.e. the way in which the energy drawn from the reaction is split between cell growth and maintenance. Anaerobic conversions such as anaerobic digestion are processes generating little energy over the course of which growth yields are low in comparison with aerobic conversions. For example, 100 grams of sugar will be converted into 50 grams of bacteria with an aerobic process, and into 10 grams with an anaerobic process.

Metabolism is typically quantified in terms of yield:

- the growth yield of a species is defined as the ratio between the quantity of biomass manufactured over the conversion and the quantity of substance consumed by a particular biological reaction

- the product yield of a biological reaction is equal to the quantity of product generated by the reaction divided by the quantity of substance consumed.

b) Features of the anaerobic digestion reaction

As with any chemical reaction, the transformation results in end products. In anaerobic digestion, the end products resulting from each phase may be re-used by other species found in the consortium. As we can see in Figure 1, the products from acidogenesis such as organic acids are used in turn to feed acetogenic bacteria. It is therefore strictly speaking a food chain based on maximum utilisation of energy, up to the end products which are gaseous substances such as methane and CO_2, which cannot be used as an energy source in the absence of oxygen.

Overall, the speed of the anaerobic digestion reaction depends on many factors. In fact, given the large number of stages in the process, we realise that the slowest stage will be the one to alter the overall speed of the anaerobic digestion. For waste digestion, it is very often the hydrolysis stage which is the slowest. However, the acetogenesis and methanogenesis stages can also run slowly.

In terms of assessing the biomass, anaerobic digestion can be represented diagrammatically as per Figure 2. Using the previous definitions, we can attempt to explain the main factors characterising the overall anaerobic digestion reaction:

- biomass yield – it is generally held that from 5 to 10% (at maximum) of the ***decomposed organic matter*** is converted into biomass
- product yield (methane) – depends on the waste composition; nonetheless, if it is expressed relative to the COD (chemical oxygen demand) of the waste, then the methane yield is constant (equal to ***0.35*** $\boldsymbol{Nm^3}$ ***of*** $\boldsymbol{CH_4}$ ***per kg of COD eliminated***) with very few exceptions.

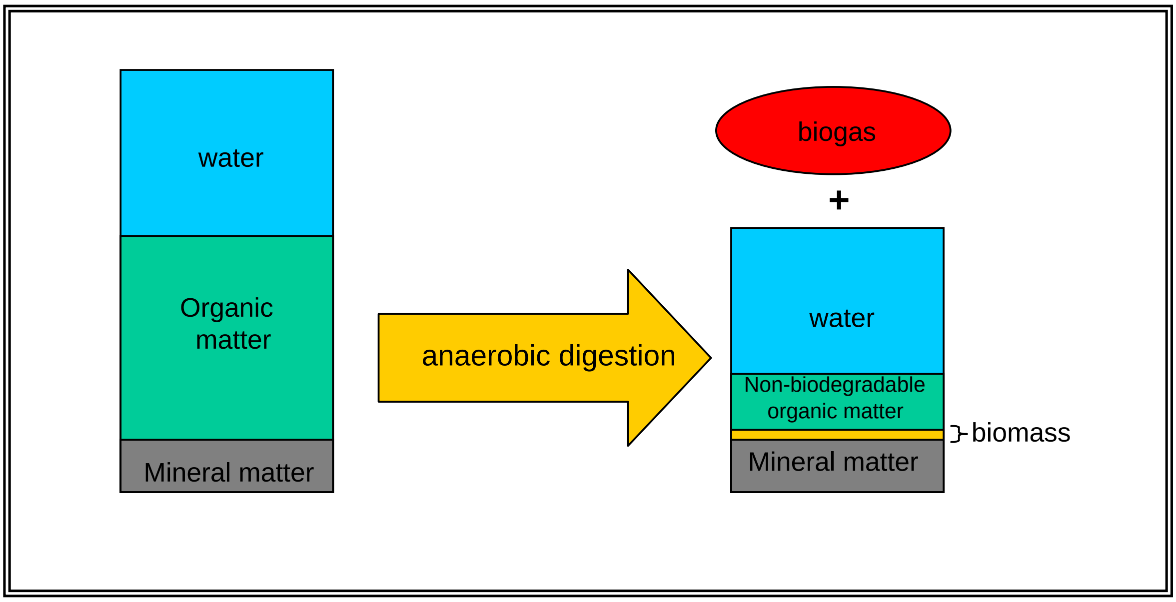


Figure 2: *Only the biodegradable portion of the organic matter is affected by anaerobic digestion. Bacteria growth (biomass) represents 5 to 10% of the degraded organic matter. The quantity of methane produced depends on the composition of the organic matter.*

B. Current processes – operating principles

Anaerobic digestion processes differ according to several factors, such as the operating temperature (ambient, regulated, mesophilic, thermophilic), the water content (wet or dry processes) or the number of treatment stages.

1. Wet digestion / dry digestion

Wet digestion systems are very similar to sewage sludge digestion processes. The water content is adjusted inside the reactor so as to achieve content close to 10-15% solid matter. The waste is mixed beforehand in a reactor which may possibly be attached to a mechanical and/or thermal treatment (pulper), which can be used to give the mixture the desired consistency for anaerobic digestion. The actual digester itself is typically a stirred tank.

Dry digestion is a technique used to keep residue in its original state without adding large quantities of water. It is characterised by water content between 20 and 40%, which gives the fermentation environment a consistency which is not dry but rather thick or semi-solid with a low quantity of free water. The pre-treatment needed is simply screening at a size of the order of 40 mm, although facilities operating with larger sizes (80 or even 100 mm) are also found.

2. Mesophilic / thermophilic

Temperature mainly affects the reaction speed, in the wider sense including both chemical and biological reactions, hence we find mesophilic (35°C) and thermophilic processes. [Higher] temperatures increase the speed of breakdown and methane formation (but not the quantity of methane produced). Consequently, anaerobic digesters for digestion of the fermentable portion of household waste operate using lower loads but longer running times under a mesophilic process than a thermophilic process. Running a thermophilic reactor improves hygienisation in terms of certain pathogens. Lastly, thermophilic digestion improves lipid (fats) fluidity. However, it is also reputed to be more delicate when inhibitors are present, in particular ammonia nitrogen. The recent trend in Europe has been to give preference to building thermophilic digesters, so much so that today they make up some 40% of household waste treatment facilities.

3. List of the various anaerobic digestion techniques

a) Extended processes

Processes in which simplicity of design is given priority over efficiency of treatment are described as extended. At the extreme end of the scale, the most extended anaerobic digestion process is landfill, where degradation time is of the order of twenty years. Ikos France sells a related storage technique which, through anaerobic digestion and waste pre-treatment, reduces treatment time to 4 years. More conventional extended processes, not involving burying, operate in batches, inside sealed units. The best known are the BIOCEL (Netherlands) and BEKON (Germany) processes, in which the waste fermentation time is in the region of 35 days. In these two processes, the waste (often the organic portion of household waste) is placed, as is, in hermetically sealed compartments, and leachate recycling may be used to speed up fermentation. The recycled leachate may also be heated in order to increase the treatment temperature. A particularly ingenious variation, the SEBAC process, was developed by Professor David Chynoweth at the University of Florida (USA), in which three reactors are used sequentially with leachate exchanges and recycling. This variation considerably reduces the waste treatment time to less than 40 days.

b) Wet digestion

Wet digestion processes are typically preceded by a waste preparation stage (mixer, pulper) before entering the actual anaerobic digestion reactor itself (Figure 3). The main processes that operate using this principle are the WAASA, BTA and Linde-KCA processes. Spanish company ROS-ROCA also markets a wet digester (BIOSTAB process).

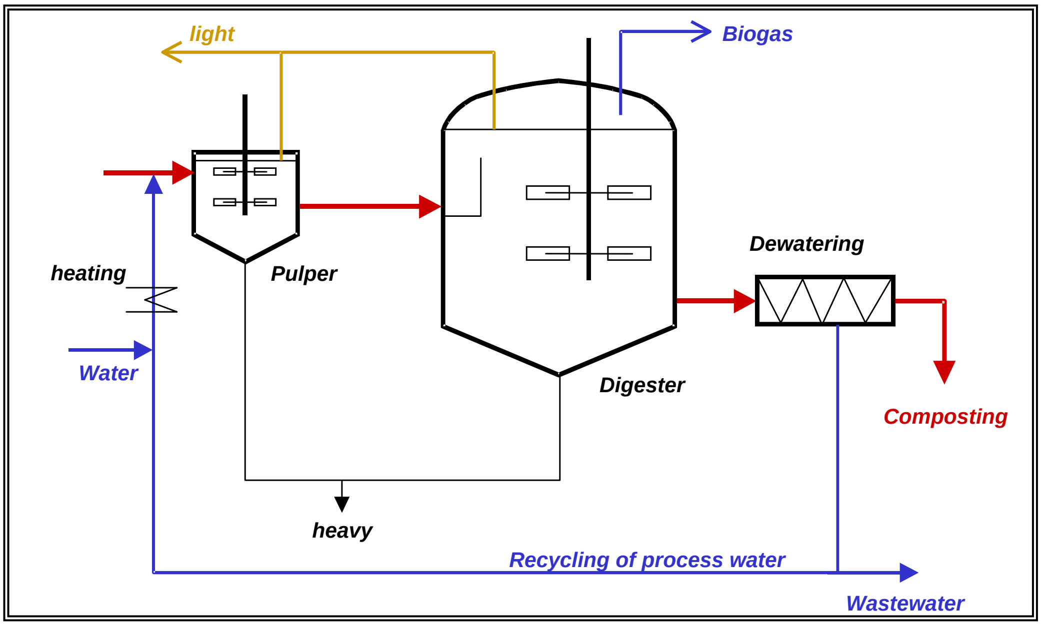


Figure 3: *Wet digester overview*

c) Dry digestion

Three types of technology are used in dry digestion processes - two vertical reactor systems (the DRANCO process, with digestate recirculation, and the VALORGA process, mixed by biogas recirculation), and horizontal processes (KOMPOGAS and BRV) with piston flow and where slow-speed impellers rotate the matter being digested.

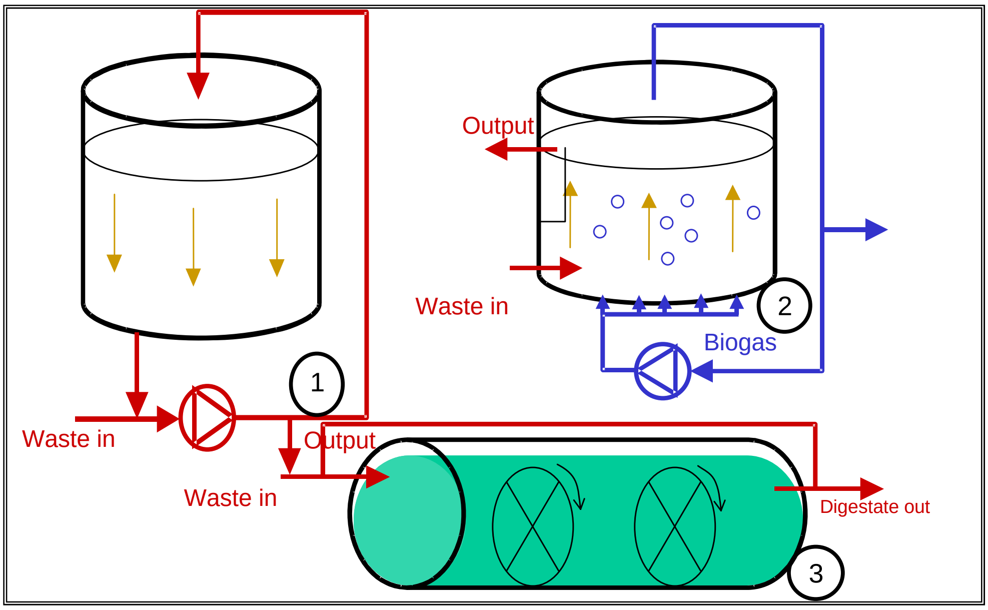


Figure 4: *The main dry digestion technologies 1: digestate recirculation (DRANCO); 2: biogas recirculation (VOLORGA); 3: horizontal piston digester (KOMPOGAS, BRV)*

d) Pre-treatment

The purpose of pre-treatment is to encourage decomposition and hydrolysis of solids to produce a residue which then will be treated during the second stage more efficiently. Very often, this will involve liquefying a portion of the organic matter in order to be able to use a “conventional” anaerobic reactor, like those used to treat wastewater.

- Mechanical pre-treatment and maceration: involves intensifying the size reduction of solid matter to the maximum, and speeding up its hydrolysis. Most of the wet processes already mentioned include this kind of stage. The BRV (dry digestion) process is preceded with a two-day aerobic maceration stage; the Arrowbio process consists of an intensive mechanical separation pre-treatment before carrying out digestion in two fermentation stages (acidogenic and methanogenic) in UASB reactors. In some cases, the maceration stage takes place at high temperature (70 or 90°) in order to encourage hygienisation of the residue.
- Two-stage bioleaching processes: the principle is to carry out, in two different reactors, hydrolysis and liquefaction of composite organic matter, and retrieve the liquid residue (leachate) in order to route it to a conventional anaerobic digestion reactor. In some cases, the solid portion is not completely digested and is re-used in composting (e.g. the Wehrle Werk Biopercolat process, Germany).
- Physical-chemical pre-treatment: This involves causing a chemical transformation of compounds, such that they become either open to digestion (bioavailable) or converted into biodegradable products. Many applications exist in the sludge treatment sector (ozonisation, heat treatment, ultrasound). In the waste treatment sector, in it mainly the biodegradability of lignocellulosic compounds which is the problem area. It has been shown that steam pressure disruption treatment (5 minutes at 240°C) can, by decomposing the fibre thus treated, improve the quantity of methane produced by some 40% [16], the corresponding commercial process is the SUBBOR system (Canada).

C. Relevant waste

Anaerobic digestion can be used for quick and effective treatment, even degradation, of various residues, generating electricity at the same time. Residues likely to be treated by anaerobic digestion are:

1. Household waste

More specifically, the fermentable portion of household waste (FPHW). The source of this portion may be mechanical sorting or the separate collection of this waste. Separation of the portion at source produces a FPHW with the best properties for anaerobic digestion. Use of anaerobic digestion to treat this waste has developed over recent years. The main objectives are to reduce the amount of waste sent on to other solid waste treatments and at the same time to recycle the nutrients contained in the waste.

2. Wastewater treatment plant sludge

Sludge is produced in the course of treating urban or industrial wastewater. The sludge’s properties depend on the source of the treated wastewater (municipal, industrial, etc.). Anaerobic digestion is used to stabilise and reduce the amount of sludge. The biogas generated partially meets the energy needs of the wastewater treatment plant.

In the case of wastewater treatment, there are three different types of sludge that may be anaerobically digested.

- Primary sludge: this is the result of settling the wastewater at the start of the process. This is the most highly fermentable sludge that a WWTP can produce. As the settling stage occurs before the treatment, the sludge has a very high content of biodegradable organic matter.

- Secondary sludge: this is the result of a settling stage occurring after the aeration tanks. Given that part of the organic matter has already been stabilised in the course of the treatment carried out in the aeration tanks, anaerobic digestion of this kind of sludge is less attractive in terms of energy yield.
- Mixed sludge: this is a mixture of the two previous types of sludge, primary plus secondary.

3. Industrial waste

Waste from the paper, food processing and pharmaceutical industries is able to be treated by anaerobic digestion before spreading as fertilizer or landfill. The energy generated often covers the power needs for the industrial process.

4. Agricultural waste

Comes from agricultural activities, or animal faeces and crop waste. The main objectives are energy production and improving the properties of products spread as fertilizer. It is an alternative most often used in countries with a high animal density.

5. Biomass

The growing of certain "energy crops" for the sole purpose of producing energy is increasingly becoming an alternative energy source for some countries.

D. By-products and their properties

1. Biogas

Biogas is primarily made up of methane fuel and inert carbon dioxide. Other gases may also form a minor fraction of biogas, e.g. hydrogen, hydrogen sulphide (H_2S). The amount of these gases is closely linked to the waste treated and the degree of anaerobic digestion. The calorific value of a fuel is the quantity of heat released by full combustion of a unit of that fuel. The NCV is the net (or lower) calorific value resulting when the water produced by the combustion remains as steam. The NCV of methane at 0°C and atmospheric pressure is 9.94 kWh/m^3. For biogas, the NCV will be proportional to the methane content (e.g. for a biogas containing 70% methane, the NCV will be 9.94 x 0.7 = 6.96 kWh/m^3).

2. Digestate

The undigested solid residue (or digestate) comprises that part of the feedstock that is not, or not easily, biodegradable. In the case of organic residue, anaerobic digestion is analogous, from the biochemical transformations viewpoint, to what occurs during the fermentation phase in composting; the digestate may then be post-composted and will, after maturing, have the agricultural properties analogous to those of compost produced from the same initial feedstock. For residual household waste, which contains significant amounts of plastics and metals, agricultural recovery is more problematic.

Depending on the anaerobic digestion process selected, the type of maturing planned and the local options for effluent treatment, it is possible to dehydrate the digestate to produce a liquid portion (or effluent) which can be partially re-circulated or which will have to be treated before discharge into the natural environment, and a solid portion (cake) which will be sent on to post-composting.

II. KEY RECOMMENDATIONS FOR OPERATING ANAEROBIC DIGESTION UNITS

E. Mechanical aspects

1. Acceptance – Pre-treatment

a) Objectives / Expectations

Anaerobic digestion is a technique the purpose of which is to biodegrade the organic matter contained in waste. There is currently a wide diversity in the type of waste likely to be treated by anaerobic digestion – liquid or solid waste, agricultural or urban waste, with high OM content, containing inert matter, etc.

To encourage degradation of the organic component in this waste, it is important to pre-treat it in order to adapt it for closed system anaerobic biological treatment and thus attempt to homogenise and standardise the digestion feedstock.

b) Resources / equipment

To achieve this objective, various pieces of equipment may be installed prior to the anaerobic digestion stage.

These various devices can be divided into the following categories:

- Physical treatment: mills, ballistic, densimetric or optical separators, screens and pulpers.
- Biological treatments: pre-composting unit, BRS

The presence and complexity of the pre-treatment sequence will depend on the type of waste being treated and the anaerobic digestion technology used.

c) Critical points and recommendations

➩ ***Iron removal: full and thorough iron removal is important***

Problem: premature wearing / jamming of mechanical parts throughout the entire process chain (pumps, valves, screws, presses) if iron removal is inadequate.

Solution: use of a sufficiently powerful magnet; compliance with a layer of waste shallow enough to ensure complete iron removal.

➩ ***Screening: size of mesh***

Problems: - mesh too wide: increases inert content, without always providing more OM.

- mesh to narrow or supply to rotary screen too great or rotation too fast: a portion of the OM is rejected, the overall rejection rate rises and the output of biogas per tonne of treated waste falls.

Solution: find the correct mesh size for the waste being treated and adapt the rotation speed of the screen and the rate of feedstock supply (no tests carried out at this level). For household waste, a mesh of 30 to 40 mm after a mill appears suitable. If screening occurs in isolation or prior to a mill, it is advisable to use a wider mesh (80 mm).

➩ ***Pre-composting (Linde type): retention time control***

Problems: When the pre-composting unit is full and so in the following two days, nothing can be supplied to the digester, the waste stored in the pre-composting unit dries out and solidifies. The hardening of part of the waste bulk causes splits in the moveable deck. This problem appears in that part of the deck closest to the pistons that move it.

Solution: Provide by-pass evacuation systems to avoid an accumulation of product at this stage and thus control the time that waste spends in this section of the process.

➪ ***Equipment wear and tear***

Problems: When the feedstock arrives with a high percentage of inert matter, in particular with household waste, wear and tear on the various mechanical parts in the facility, such as the mill, worm screws and screens, is observed. Example: Mill wear and tear – the mill blades wear out by rubbing and abrasion caused by glass.

Solution: Mill: Despite testing manufacture of blades from steels of varying hardness and various types of cutting (wet, etc.), the most economical solution found was to manufacture blades from 500 Brinell wear-proof steel and replace them every 3-4 weeks.

Worm screws: Some screw casings are fitted with inner reinforcements on the part in contact with the screw. In some cases (special type of screw and very abrasive waste), replacement is necessary.

Detail of wear on a mill blade

Detail of wear on a screw casing

Detail of split in moveable deck

It is therefore advisable to properly include the entire pre-treatment sequence (and the order in which equipment is used) for the sizing of each piece of equipment within it.

Secondly, for a given pre-treatment, prior testing is recommended, in order to determine the optimum operational settings, i.e. those providing the best compromise between OM levels /amount of inert matter. These tests could for example be carried out using small mills and then sieves with different meshes, simulating rotary screens. It must however be ensured that these tests are conducted on samples that are sufficiently representative – the more diverse the waste is, the larger the sample volume needs to be.

Conducting methanogenic potential tests (BMP tests) before and after pre-treatment is a good indication of the effectiveness of this stage.

Pre-treatment takes on major significance as it determines the quality, and reproducibility over time of the waste entering the digester.

Lastly, maintenance and replacement of some parts appears unavoidable, particularly where household waste is concerned.

2. Feedstock

a) Objectives / constraints to be observed

As the heart of the process is biological, full control over the pre-treatment stage will allow the product entering the reactor to be standardised (both in quantity and quality). In fact, any break in the rate or composition of the feedstock is liable to create instability in the reaction environment and therefore a drop in system degradation rates (and thus in the biogas generated).

It is therefore essential to ensure a constant supply and, in the event of imbalance in the reaction environment, quickly alter the strategy for introducing waste into the digester.

b) Resources / equipment

Conventionally, two systems can be used to inject product into the reactor:

- a worm screw
- a concrete pump.

Screw systems will preferably be used where relatively dry and solid waste is concerned (DM approx. 45-55%).

On the other hand, pumps can be used to inject more fluid product, already mixed with digestate and re-circulated effluent (DM < 40%).

c) Critical points and recommendations

➩ ***Quantity of incoming product***

Problem: Lack of continuous weighing system for incoming product. It is impossible to conduct reliable matter assessments and check the incoming flow.

Solution: It is important to install dynamic effective weighing equipment from the outset in order to quantify inputs. For regulatory and traceability reasons, it is necessary to know exactly and at all times what quantities are being processed.

➩ ***Moisture levels***

Problem: an inappropriate moisture level is a source of jamming, poor waste entry into the digester, and then mechanical and biological malfunctions during digestion.

Solution: regular measurement of the DM level in waste must be carried out. Such measurement enables the rate of added effluent or water to be adjusted. The DM content of the effluent must also be taken into account.

➩ ***Inert matter levels***

Problem: too high a level gives rise to compression problems (to which the fibre content may also contribute) and may cause premature wear to the equipment (glass).

Solution: Reduce inert content at the pre-treatment stage, by ballistic separation or an equivalent system, suction of light items, etc.

➩ ***Homogenisation***

Problem: Lack of uniformity within a mixture of waste and effluent and/or re-circulated digestate during feedstock supply leads to mechanical problems and reduces the biogas output yield from the digester (a proportion of the organic matter will not be degraded because it will not be in contact with the digestate).

Solution: a correctly-designed concrete pump proves very effective in comparison with a worm screw system. It nonetheless remains much more costly and requires prior mixing of the matter to be digested with the digestate, if this matter has a high level of dryness (> 40% DM).

Detail of wear on a feed screw

Accumulation of waste in a feed screw

Digester feed screw blockage

3. Digestion

a) Objectives / constraints to be observed

For the greatest possible effectiveness, anaerobic digestion must be carried out in particular and stable physical and chemical conditions (complete absence of O_2, temperature, digestate DM, C/N, etc.). Uniformity of the environment is also viewed as a key factor in enabling the process to achieve its decomposition objectives.

b) Resources / equipment

To reach these objectives, the various manufacturers of anaerobic digesters present technical solutions having a wide variety of characteristics.

- reactor shape: vertical or horizontal; cylindrical or square cross-section
- operation: batch, semi-continuous, continuous
- temperature control: external heating system, heating of feedstock before injection
- feedstock homogenisation method: blades, biogas injection, loop outside reactor
- digestate DM content: liquid/solid
- operating temperature: mesophilic / thermophilic
- moisture adjustment to incoming mixture: internal or external

c) Critical points and recommendations

➩ ***Moisture and inert levels***

Problem: formation of blockages and non-uniform areas if moisture levels are not fully controlled. The consequences are mechanical jams and drops in biogas yields owing to lack of homogenised product (bacteria contact areas not optimised).

It is also possible to encounter liquefaction problems in the digester which may give rise to a phenomenon of foam formation.

Solution: prior preparation of the waste: see humidity levels and inert levels in the feedstock section. An effective digester contents mixing system ensure both homogenous digestate and recurring contact between bacteria and degradable matter. Daily inspection of the environment inside the digester is desirable.

➩ ***Reactor shape***

Problem: where dead zones are found, waste accumulates, preventing circulation inside the digester and which may cause blockages.

Solution: reactor shape to be free of acute angles, reduce changes of direction inside the reactor, reduce space between screws and valves to prevent waste stagnating.

➩ ***Digestate re-circulation***

Problem: poor re-circulation / stirring of the digestate can lead to a phenomenon of localised or total reverse settling in the digester, whereby solid matter in the digestate takes on biogas (which has not been discharged owing to poor stirring) which makes this matter lighter than the effluent, which settles at the base of the digester.

Solution: the digestate is to be properly stirred regularly or continuously in order to avoid unstirred areas forming.

➩ ***Effluent re-circulation***

Problem: uniform distribution of effluent throughout the incoming feedstock: poor distribution can create dry areas and areas that are too moist, a source of mechanical (and biological) problems;

effluent/waste mixing - before entering the digester, the mixing system must result in even distribution of the dewatering liquid within the waste in order to obtain uniform matter for decomposition.
Solution: understanding the equipment, and matching the flow of effluent to the flow of waste. The mixture should be prepared before it enters the digester.

4. Dewatering

a) Objectives / constraints to be observed

The purpose of this stage is to separate the digestate into two flows:

- A liquid flow: dependent on the quality, effluent from dewatering may be re-circulated into the anaerobic digestion system to alter the moisture content of the incoming waste to match the optimum value set by the manufacturer in terms of DM.
- A solid flow: destined for composting and, depending on its end quality, it may be used agriculturally.

The DM proportion and content for each of these portions is to be determined depending on the stages that follow dewatering. Consequently, depending on the type of maturing planned, on the presence of surplus liquid in the treatment unit, on the type of waste treated, etc., systems can be put in place, sophisticated or otherwise, enabling a set quantity of by-products to be produced.
For dry digestion, not carrying out dewatering is also an option, but that implies systematic composting, with the addition of bulking agent.

b) Resources / equipment

Dewatering of the digestate may be achieved using equipment such as screw presses. It is also possible to increase dewatering stages by adding a centrifuge after the press, the purpose of which will be to separate solids from liquids in the pressing effluent.
Centrifuges can also be considered in isolation where liquid digestion is concerned.
The type of waste treated, the type of digestion put in place, the settings for the various pieces of equipment, the complexity of the dewatering system and the potential addition of flocculating agents are the factors which will determine the proportions and quality of the outgoing flows.

c) Critical points and recommendations

➪ ***Digestate extraction and dewatering system supply***

Problem: a badly-designed and inflexible extraction system makes balancing quantities of incoming product difficult.
Solution: Confirm over the course of production testing whether extraction provides some room for manoeuvre as regards the conditions stipulated by the manufacturer (output flow rate, diameter of the extraction pipes).

➪ ***Managing the dewatering system supply***

Problem: difficulty in finding a reliable sensor capable of handling automatic alterations to the digestate (problems with sensor clogging). For example, management at the hopper level, which causes irregular supply to the press and therefore variations in the dryness of the press cake produced.
Solution: find reliable sensors, sturdy enough for this type of product – radar sensors may be one route.

➩ ***Pressing efficiency***

Problem: overproduction of liquid leading to extra operating costs. Find a balance between the effluent produced and moisture requirements for the press cake in view of its subsequent treatment. The liquid produced cannot always be re-circulated into the top of the treatment.
Solution: adjustment to the press (back pressure), addition of polymers. Designing an effective liquid treatment unit enables part of the liquid portion to be re-used, and produces surplus runoff compliant with required discharge standards.

➩ ***Equipment wear and tear***

Problem: Organic matter entering anaerobic digestion treatment may contain a high percentage of unsuitable items (glass, stones, etc.) which results in wear and tear to mechanical equipment, in particular presses.
Solution: Follow a full servicing and maintenance schedule in order to avoid failures as much as possible (cleaning and greasing in particular). Digestate is in fact highly corrosive and has a tendency to be very difficult to clean up once it has dried. Make provision for spare parts for crucial equipment such as screws, pressing grids, etc.

Close-up of the press block

It is also useful to plan a by-pass system, enabling the dewatering stage to be omitted. In fact, constructing this stage in series results in a blockage for the entire treatment chain (output from the digester, feedstock supply into the digester, etc.) during maintenance or when a significant failure has occurred in the dewatering system.
Under such circumstances, direct routing to maturing (composting), mixed with green waste (which will have an altered ratio on this occasion) will enable excessively low DM levels for the product to be overcome.

5. Biogas circuit

a) Objectives / constraints to be observed

The purpose of the biogas system is to channel the gas produced during waste decomposition to the gasometer storage facility, itself installed upstream of the energy recycling equipment.

b) Resources / equipment

It is imperative that the system is hermetically sealed and kept pressurised to avoid any infiltration of air.
Flame arresters are fitted at various points in the network to avoid any risk of fire spreading.
Gas condensation (with purging), filtration or purification systems could also be installed to purify the biogas and facilitate its recycling.

Obviously, a flow-rate measurement system and a gas analyser is the minimum equipment needed on an industrial facility to monitor the yield from decomposition.

c) Critical points and recommendations

➪ ***Pipes***

Problem: condensation in the system

Solution: keep the system at the right temperature (thermal insulation) by paying special attention to sensitive spots (corners, valves, flow meters, sensors, etc.); install condensate capture points around the circuit. Condensate trapping is to be done as upstream as possible from sensitive equipment (flow meters, analysers, etc.).

➪ ***Equipment***

Problem: condensation and corrosion in measuring and safety devices and in recycling equipment; deposit formation

Solution: factored in when selecting apparatus and equipment. Thermal insulation as close to the equipment as possible, condensate trapping, additives to prevent the formation of corrosive compounds in the gas (add $FeCl_2$ into the digester to prevent H_2S formation). Removal of H_2S through biological treatment (NB: which results in H_2SO_4 which needs to be eliminated too). Ensure spare parts are available (filters, flexible hose, etc.). Air blower in upper section of digester to oxidise the H_2S (sulphur formation). Regular dismantling and cleaning of security devices such as flame arresters.

Problem: boiler failure owing to variations in biogas quality. Unable to achieve continuous, regular operation.

Solution: the boiler settings must be continuously adjusted to the quality of the biogas. Automated control of the air intake valves, through analysis of the biogas before it enters the boiler (regulation combined with methane level), enables continuous operation to be maintained.

Problem: the gasometer is permanently subjected to biogas pressure and corrosiveness. While it is designed to withstand these conditions, the risk of a split in the wall exists.

Solution: Have regular inspections (annually at least) of this equipment carried out by an approved company.

Problem: the biogas system is often kept pressurised by a liquid seal which also has a safety role (biogas blisters the seal in the event of excess pressure). If its level is not correctly adjusted, this may cause excess pressure or loss of pressure in the digester.

Solution: Regular inspection (every three months) of the condition and levels in the liquid seal.

Do not overlook warranty and maintenance contracts for equipment.

F. By-product management

1. Biogas

a) Managing production variation (quantity and quality)

Biogas output depends directly on the supply of waste (in terms of quantity and quality). Consequently, irregularity in the frequency with which fresh waste is supplied or the intrinsic variability of waste over time will result in variations in the volume of methane produced per input tonne. Such variation may be harmful to the recycling equipment installed further down the process.
The presence of a gasometer should enable fluctuations in terms of input into the recycling process to be minimised. In fact, the gas reserve thus created can be used to homogenise the biogas quality at a given time, or to supply the recycling systems in the event that output falls.

b) Treatment

Irrespective of the planned recycling method, the presence of a very wide variety of ingredients in the biogas, including some such as organic halogenated compounds, hydrogen sulphate and sometimes even heavy metals which have corrosive and/or toxic properties, requires the installation of biogas purification to a greater or lesser degree, to achieve optimal recycling posing no threat to the health and safety of staff.

One or more purification stages are therefore needed: The commonest techniques are as follows:
- biogas precompression
- decarbonation
- desulfuration
- dewatering
- dehalogenation
- compression
- quality control on treated biogas.

c) Recycling

Several methods are available in terms of biogas recycling. It is, in fact, possible to generate, either in isolation or in combination:
- heat/steam
- electricity
- purified and enriched gas able to be introduced into the natural gas network
- bio fuels.

The selection of one recycling method over another will happen on a case-by-case basis, depending on the local circumstances (for example: a heating network close to the treatment unit), the quantity and indeed quality of the biogas produced and the technical and economic options at the time.

The first two solutions listed above are the most common. Beyond the local circumstances, the technical aspects required for the last two energy recycling options are more involved (in fact, these two solutions need highly advanced purification of the biogas before use).

2. Digestate

a) Treatment

Digestate, output from the digester, is a relatively moist product which is not fully stabilised. In fact, anaerobic degradation reactions do not result in complete decomposition of the organic matter (OM) contained in the waste. Anaerobic bacteria do not reach some portions of the OM.

Dewatering of the digestate will allow a proportion of the water in the digestate to be extracted, also taking with it part of the OM.

Despite this reduction in OM from the digester and the separation of part of the liquid portion during dewatering, digestate cannot be recycled agriculturally as it is.

Therefore, when one of the treatment centre’s objectives is production of organic fertiliser, it is essential to include a composting stage (also known as aerobic maturing) for the digestate. Depending on the anaerobic digestion process and composting techniques used, this maturing may be carried out on the digestate alone or mixed with some other product. However, given digestate structure, it is highly recommended to always add a bulking agent such as green waste. Otherwise, this digestate maturing stage would amount to mere drying out.

This post-composting is used to:

- increase the DM in the end product, which improves the efficiency of the ultimate refining treatment
- improve stability of the product by ending the decomposition of OM contained in the anaerobic digestion residue
- hygienise the final compost
- give real fertilising value to the digestate.

b) Recycling

The only method for recycling the compost produced is agricultural spreading, for which the end product must comply with the various standards in force (in France, NFU 44051 or NFU 44095 if sludge present). However, it should be noted that the status of digestate, either with or without post-treatment remains ill-defined both in France and in Europe.

With this is mind, the end quality of the compost will depend entirely on the type of waste treated and the effectiveness of the various sorting stages (pre-treatment before anaerobic digestion and final refinement).

Where treatment of household waste is concerned, it will be difficult for the resulting compost to comply with the various regulations in force owing to the presence of considerable quantities of inert matter and metal trace elements.

Therefore, if these pollutants are still found after the post-composting stage (owing to inefficient separation of inert matter and/or no prior separate collection of specific waste from households), a suitable outlet (landfill or incineration) will have to provided for from the planning of the project. Sophisticated preparation of the feedstock will facilitate compliance with these standards.

3. Liquid effluent

a) Treatment

The liquid effluent from pressing the digestate is in part recycled within the treatment sequence to culture and moisturise the fresh waste before digestion, or possibly to contribute to maintaining the moisture conditions in the post-composting phase.

The surplus portion needs to be purified in order to be able to be discharged into the wastewater network. If discharge into the natural environment or wastewater network is not possible, weighty treatment solutions must be put in place (evapo-concentration, reverse osmosis, etc.).

b) Recycling

Surplus effluent may be difficult to recycle, and its composition prevents direct discharge into the natural environment.

Where treatment of organic waste not contaminated by inert matter is concerned (e.g. agricultural waste), agricultural spreading may be considered.

4. Rejects

a) Treatment

The various sorting stages in the treatment (pre-treatment before anaerobic digestion and compost refining) generate a proportion of rejects which, depending on the type of waste, may be significant.

These rejects are mainly composed of course matter containing little that is biodegradable. The only solutions that can be considered for disposal of this type of waste are incineration or landfill.

G. Biological aspects

1. Understanding the incoming waste

a) Parameters

Dry matter and volatile matter

The prime importance of properly describing the waste needing to be treated can never be emphasised enough. The idea is, on the basis of this description, to be able to estimate how the waste will decompose, and what quantity of biogas (or methane) is liable to be produced during treatment. The most important factors are the dry matter and volatile matter content. This data is obtained by evaporating the water in a drier and by calcination of volatile matter respectively. Volatile matter is comparable to organic matter, and, we stress, only organic matter is able to be disposed of by anaerobic digestion, provided it is biodegradable. Furthermore, a low portion of the degraded organic matter will be converted into bacterial biomass (between 5 and 10%). As regards volatile matter, the conditions under which its presence is determined (550°C oven) must induce caution in interpreting its value. In fact, for waste such as household waste, non-biodegradable volatile matter (plastic) is included in the measurement and may distort the results significantly.

Chemical Oxygen Demand (COD)

Rarer, this measurement however provides, when combined with methane potential (BMP), a decent estimate as to the biodegradability of waste, and thus a prediction as to the quantity of non-degraded organic matter which will be found in the digestate (see the BMP section).

Measuring waste COD requires special treatment, as it is usually conducted on liquid samples. We recommend gentle drying (72 hours at 60°C or freeze-drying) followed by grinding so as to reduce the waste to a powder, then suspend it in water again for measurement (with sampling during stirring).

Carbon / Nitrogen / Phosphorous ratio

Anaerobic digestion is only possible if bacteria manage to grow, for which they will need the main elements which allow them to manufacture cell material to be available.

The most used elements are nitrogen and phosphorus. The recommended ratio per 100 grams of degraded COD is:

- approximately 2 grams of nitrogen (N-NTK)
- approximately 0.25 grams of phosphorus (P total).

In particular, if the COD/N ratio is greater than 80, then it is possible that not all the organic matter will be degraded owing to a nitrogen deficiency. Similarly, if the COD/N ratio is less than 40, then there is a nitrogen surplus which may lead to a rapid accumulation of ammonia forms in the reactor, which may cause reaction inhibition.

Where waste from various sources is being digested together, special attention must be paid to the mixture's carbon / nitrogen balance.

The recommended C/N ratio is between 20 and 30. The recommended C/P ratio is between 100 and 150.

Other chemical elements are necessary to bacteria development, such as iron and certain trace elements (micronutrients); however it is unusual for these to be lacking in anaerobic digestion of waste.

Methanogenic potential (BMP)

Methanogenic potential is a fundamental measurement in waste categorisation. This involves experimental determination of the maximum quantity of methane which can be obtained from a given waste. Known as BMP (Biochemical Methane Potential), this measurement is carried out under controlled conditions (no inhibition, essential nutrients present, ideal conditions) in such a way as to obtain the maximum quantity of methane.

The BMP value is generally given in litres of CH_4 per gram of volatile matter under standard conditions (0°C and 1013 mbar), which corresponds to m^3 par kg.

There is an interesting relationship between the methane potential and COD. In fact, one kg of degraded COD always produces the same quantity of methane (0.35 m^3). It is therefore possible to estimate the biodegradability of a waste product according to the following formula:

Biodegradability = BMP /(DCOx0.35)

This information is of value, since it enables estimation of:

- the maximum quantity of methane it is possible to obtain from a given waste
- the residual quantity of organic matter which will not be degraded and will be found in the digestate.
- verification that the reactor is working properly (by comparing actual methane output with the BMP).

Particular properties of waste

Over the course of anaerobic digestion, specific groups of micro-organisms will degrade the organic matter. Consequently, methane output will be dependent on the quantity of organic matter contained in the waste. Yet the quantity of OM contained in the untreated waste is not the only factor affecting the expected quantity of methane. In fact, the quality of OM will also have a by no means insignificant effect on the course of degradation reactions. In order to best assess the “OM quality", several analysis methods can be used, including the following:

- Assessment of the fibre content:

The purpose of determining this indicator is to assess the complexity of the OM present in the waste. In fact, the micro-organisms in the reactor are incapable of degrading complex compounds such as lignin or, to a lesser extent, cellulose. This type of indicator is thus used to determine whether an organic waste is suitable for anaerobic digestion or whether it should be re-directed towards some other type of treatment (such as composting, where the micro-organisms used are able to degrade very complex organic molecules).

The method employed to define the fibrous nature of OM is the result of a method used of to analyse the digestibility of fodder, i.e. the Van Soest method (1963). This method breaks the OM present in the waste down into 4 groups (soluble, hemicellulose, cellulose and lignin). Although the terminology used to define these four categories cannot be applied to all waste, this classification is useful for assessing the complexity of the untreated OM.

In fact, waste where the OM has a large “soluble fraction” will be viewed as easily biodegradable, whereas waste high in compounds similar to lignin will be only slightly degraded by anaerobic digestion.

- Assessment of the sugar, protein and fat content:

This categorisation is also used to assess the potential degradation of OM present in the untreated waste. It is possible to classify these families of molecules by increasing methane production potential, i.e. protein, carbohydrates and lipids.

Beyond theoretical degradation reactions, grading the OM may help prevent some inhibitions – fatty waste cannot be digested alone without resulting in an accumulation of reactive intermediaries, acidification of the environment, and eventually blocking the reactions that produce biogas.

Too high a protein content in the untreated waste is to be watched for in order to avoid introducing too much nitrogen and sulphur into the environment. These elements would then be converted into NH_3 and H_2S, which are system inhibitors.

b) Some reference values

By way of information, the following are some example of the composition of various waste materials.

Physical-chemical properties of putrescible waste found in household waste in 1993 (source: ADEME [French Agency for the Environment and Energy Management] 1998)

Putrescible waste 15.8% of the dry mass of household waste	Unit	Average level	Range of values
Moisture level	% WM	63,3	38,8 - 85,3
Organic matter	%DM	82,2	80 - 83
Carbon	%DM	41,3	41 - 45
Hydrogen	%DM	5,6	5,5 - 5,9
Chlorine	g/kg (DM)	8,1	6,3 - 8,6
Sulphur	g/kg (DM)	3,3	2,5 - 6,6
Organic nitrogen	g/kg (DM)	17,9	15 - 26
NCV (wet)	kJ/kg (WM)	4246	4057 - 5221
NCV (dry)	kJ/kg (DM)	15773	15257 - 18430
GCV	kJ/kg (DM)	17006	16473 - 19717

Chemical analysis of putrescible organic matter in household waste

Product		*g/100 g concentration of total dry matter*
Proteins		2,06 - 2,6
Lipids		4,50 - 5,7
Carbohydrates		46,6 - 59
	of which cellulose	36
	Others	1,15

Average composition of fresh urban sludge in Europe (after Williams, 1998)

Organic matter	**% of DM**
Total	**55 - 75**
Proteins	30
Lipids	13
Carbohydrates	33
Non-fibrous hydrocarbon compounds	24
Carbon	45 - 50 %
Hydrogen	8%
Oxygen	33%
Nitrogen	3 - 6 %
Phosphorus	3 - 8 %
Potassium	0,5 - 1,5 %
C/N ratio	**5 - 10**

Guideline methane output for various matter

FM	DM%	OM% (of the DM)	OM% (of the FM)	C/N	Litres of CH4/kg OM
Livestock effluent					
Liquid cattle manure	8,5 (6 - 11)	76,5 (68 - 85)	6,5	10 - 17	230 (200 - 260)
Fresh cattle manure	18,5 (12 - 25)	75 (65 - 85)	13,9	14 - 25	250 (200 - 300)
Liquid pig manure	6,1 (2,5 - 9,7)	72,5 (60 - 85)	4,4	5 - 10	355 (260 - 450)
Liquid poultry manure	19,5 (10 - 29)	76 (75 - 77)	14,8		300 (200 - 400)
Diluted poultry droppings	10,3 (7 - 13,5)	74,9 (70 - 80)	7,7		350 (250 - 450)
Fresh sheep manure	27,5 (25 - 30)	80	22	14	450 (400 - 500)
Fresh horse manure	28	75	21	18	350 (300 - 400)
Agricultural waste					
Ensilage	44 (26 - 62)	82,5 (67 - 98)	36,3		500
Clover	20	80	16	12	450 (400 - 500)
Cereal straw	87,5 (85 - 90)	87 (85 - 89)	76,1	70 - 165	450 (300 - 600)
Corn straw	86	72	61,9	30	650 (600 - 700)
Sugar beet leaves	16,5 (15 - 18)	79 (78 - 80)	13	15 - 18	450 (400 - 500)
Potato haulms	25	79	19,8	16 - 25	550 (500 - 600)
Food processing waste					
Apple pulp	2,9 (2 - 3,7)	94,5 (94 - 95)	2,7	6	330
Potato pulp	13,5 (12 - 15)	90	12,2	3 - 9	250
Crushed fruit	45 (40 - 50)	61,5 (30 - 93)	27,7	30 - 50	400
Brewing draff	18 (15 - 21)	90	16,2	9 - 10	380 (370 - 390)
Molasses	80	95	76	14 - 27	300
Vegetable waste	12,5 (5 - 20)	83 (76 - 90)	10,53	12 - 27	600
Municipal waste					
Organic household waste	27,5 (40 - 75)	50	28,8	25 - 80	400 (200 - 600)
Grass cuttings	29,5 (22 - 37)	94,5	27,9	23	500
Sludge (wastewater treatment plant)	14,5 (5 - 24	90,5	13,1		700 (600 - 800)

The tables above provide some results of analysis conducted on various waste matter. The values they show give an order of magnitude for each parameter measured and waste category defined. When conducting a study to assess the possibility of treating a feedstock by anaerobic digestion, it is advisable to accurately categorise (see properties listed above) the waste in question. In fact, although bibliographical data gives an idea of the degradation potential of a waste, the diversity of waste (variation between countries and regions, seasonal variations, etc.) within a single category makes it risky to simply take this data at face value.

2. Key factors in digestion

a) Temperature

In order to be performed under optimal conditions, the anaerobic digestion process can take place within two temperature ranges: 35-40°C (mesophilic) and 50-55°C (thermophilic). Temperature checks within the digester should therefore be accurate (reliable measurement system with regular calibration), regular, and representative of the whole digester. Taking the data gathered, the digester's heating system must be able to reach a target temperature (double casing, heating of the reactor or of the incoming product, etc.).

b) DM levels

The micro-organisms found in the reactor need a large quantity of water in order to properly develop. Moisture levels of 50% within the reactor environment consequently appear to be the minimum for bacteria populations to grow. As mentioned above, there are two categories of anaerobic digestion, these processes being known as “wet” (<15%) and “dry” (>15%). Over and above technology selection (the DM level of the digestate is a decisive factor in selecting the equipment used), variations in the digestate’s DM content have consequences on the organic load introduced into the reactor, the effect of anaerobic digestion inhibitors, the retention time, etc.

c) Retention time

This is another fundamental factor in anaerobic digestion. It is the time for which a unit of feedstock to be digested remains inside the digester. Thus, up to certain limit, the longer the retention time, the greater the yield from degradation of OM.

It is not an isolated factor since it is linked to the organic load, the level of solids and many other physical factors directly related to the properties of the environment and the digester’s operating technical configuration.

d) Organic load

This is amount of waste that can be introduced into the digester. It is expressed in terms of kg of OM per m^3 of digester volume or of digestate and per day. It is important to check this parameter in order to avoid problems with organic overload which cause acidification of the environment. Benchmark values depend on the type of process in question, dry or wet, mesophilic or thermophilic, and range between 2 and 12 kg OM / m^3 per day.

e) Biogas production and CH_4%

The quantity of biogas produced and its methane content are key parameters that can be easily obtained using flow-meters and gas analysers fitted to the unit. It appears decisive from a viewpoint of process monitoring and correct biogas recycling to carry out continuous data acquisition for these parameters. In particular, the correlation between the quantity of input waste and the associated methane production will confirm how the digestion of a product is progressing. When degradation appears deficient compared to the targets calculated from the theoretical methane potential (based on BMP tests), it is advisable to reduce (or even halt) the waste supply and quickly identify the source of this drop in yield to avoid system saturation. Return to a normal level of supply should then take place gradually.

f) pH

The range of pH values within which anaerobic digestion should take place is defined as a function of the optimum conditions for life for the various groups of bacteria. The optimum operational range is between 6.8 and 7.4 [4].

When the pH is too low (values under 6.5), it can be increased by adding lime. Nevertheless, this emergency measure will not solve the root cause of the problem which is an inhibition of the bacterial populations.

Comment: pH cannot be the only parameter used to assess the behaviour of a digester. In fact, pH stability does not necessarily testify to a reactor’s good operational health, being merely the outcome of balances between families of compounds. Under some circumstances, the buffering effect of carbonates may be on such a scale as to mask high levels of VFA or NH_4^+. Secondly, pH changes are the consequence of changed conditions in the reactor. It appears therefore useful to track parameters such as VFA, which are the root cause of such changes. Detection of potential digester malfunctions can only be faster as a result.

g) Total alkalinity

Measuring total alkalinity is used to show the environment's buffering capacity, i.e. its capacity to accept acid or alkaline additions with no change in its pH value. In the context of anaerobic digestion, this stability is essentially provided by HCO3- bicarbonate ions (in equilibrium with dissolved carbon dioxide) and HPO3- phosphate ions (Couturier, 1998). These ions in fact allow the organic acids released to be neutralised.
A minimum total alkalinity of 2 g/litre is thus recommended to ensure successful completion of the anaerobic digestion process (Farquhar, 1973).

h) VFA

Determining the concentration of Volatile Fatty Acids ensures that the digestion reactions work correctly.
In fact, the main cause of acidification of the environment is the accumulation of volatile fatty acids. A VFA concentration of less than 3 g/L is recommended (Farquhar, 1973). However, when digesting solid waste, and in particular in digesters operating a dry process, VFA levels above 5 g/L may be observed, without affecting the degradation yield. The VFA/total alkalinity ratio is also important; it is advisable that it remains under 0.8 (Ehrig, 1983).
Furthermore, VFA accumulation is not only problematic as a cause of acidification; volatile fatty acids can also be responsible for process inhibition by entering the bacteria cells., It should however be noted that this occurs only when they are in molecular form, or under a slightly acid pH. With an alkaline pH, VFA are in ionised form and this reduces their inhibitor effect (TRIVALOR, 2001).
Lastly, different VFA are inhibitors to differing degrees. Thus, propionic acid is more toxic than acetic acid or butyric acid (Adib, 2004).

In order to assess this parameter, it is therefore necessary to plan for a "simplified laboratory" on-site including basic materials for carrying out simple procedures.
While the total VFA concentration can be used to monitor the digester's general condition, details of acid categories can be used to more accurately establish which degradation stage is an obstacle. Use of this kind of detailed analysis can however only be sporadic, or when the digester malfunctions, since it requires special, expensive equipment which it is not profitable to keep on an industrial facility.

When high VFA values are recorded (8 to 10 g/L), it is advisable to slow down or even halt the waste supply in order to give the system time to correct itself and consume the VFA produced. If such a high level has caused significant acidification (pH < 6.5), it is then advisable to re-establish a slightly alkaline pH in order to re-establish conditions favourable to bacteria.

i) Nitrogen

Nitrogen is a key nutrient for bacteria and it must be available in sufficient quantities. Over the course of anaerobic digestion, nitrogen compounds, such as proteins or amino acids, are converted into ammonia, which is found in free/non-ionised NH_3 form or ionised NH_4^+ form (ammonium).
At low concentrations, ammonia, a strong alkaline, can neutralise the VFA produced during acidogenesis, which helps maintain a neutral pH, favourable to anaerobic digestion. Conversely, strong concentrations of ammonia are toxic to the bacteria involved in anaerobic digestion. It is

therefore important to maintain a sufficiently high nitrogen concentration to meet the bacteria's nutritional needs, but not too high, to avoid excessive, and toxic, ammonia production.

A concentration of ammonia of between 50 and 200 mg/L stimulates, between 1,500 and 3,000 mg/L (pH between 7.4 and 7.6) is slightly inhibitory and is toxic above 3,000 mg/L (Malina, 1994). NH_3 toxicity is reversible and can be removed by diluting the environment. Furthermore, bacteria can adapt to ammonia toxicity. It should be noted that the free form of ammonia is considerably more toxic than ammonium.

Ammonia toxicity depends on temperature and pH, as these factors determine the form of the ammonia, with the proportion of total ammonia that is found in free form increasing with temperature and pH.

j) H_2S

H_2S production comes from reduction of sulphurated products such as sulphates found in household waste (e.g. plaster) or proteins found in agro-food waste (from an abattoir, for example).

Such production varies widely for disparate waste such as household waste, from a few ppm to 5,000 ppm and more.

H_2S may be the source of disruption to the environment owing to its toxic nature and may even cause inhibitions. It is recommended that the level is kept below 5,000 ppm.

This can be achieved by regularly adding $FeCl_2$ (or $FeCl_3$) into the digester when supplying feedstock. This is a very effective method, but requires monitoring of chloride content (Cl-), a reaction by-product which may have toxic or even inhibitory effects on the bacteria.

Other parameters can be monitored on a less regular basis: chloride for the digestate and biogas H_2 level.

An occasional detailed analysis (biochemical fractional distillation, element analysis) of the organic matter found in the incoming waste and the digestate may aid understanding of a unit's malfunctions.

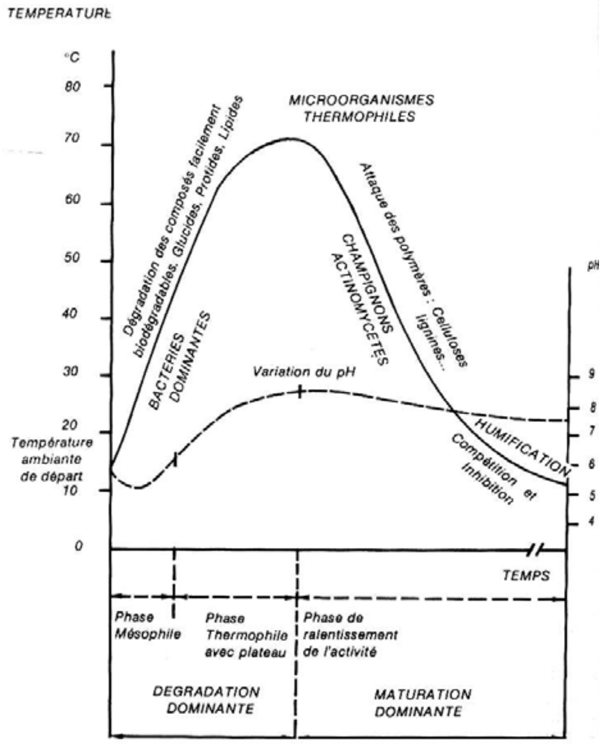
Lastly, the only way to ensure consistent performance from the unit is to ensure the uniformity of the incoming waste (or the incoming mixture in the case of co-digestion) and that operating conditions are stable (feed rate, humidity, recirculation, temperature etc.).

3. Key factors in composting

a) Temperature

Temperature change in theory consists of two phases (see Figure 1):

- A thermophilic phase during which the temperature increases reaching 60°C or even 70°C which corresponds to **degradation** of the labile organic matter during exothermic fermentation
- A mesophilic phase where the temperature drops, corresponding to degradation in the more stable organic matter and reorganisation of degradation residue – the **maturing** phase.



Mustin, 1987

Figure 1: Temperature change in the different phases of composting

Temperature can be an indicator of the quality of the composting, and in fact an irregular temperature rise or a sudden drop in temperature is a sign of a fault.

The temperature increase destroys pathogens and parasites, evaporates water and speeds up degradation of organic compounds.

Similarly, a falling temperature can be an indicator of compost maturity. This parameter must however be used with caution, owing to composts' thermal inertia. With no turning, compost can retain a high temperature even if micro-organism activity has dropped off.

Secondly, temperature monitoring is essential to ensure that the product complies with regulations.

If a lack of temperature increase is observed at the start of composting, this means a deficiency or surplus in one of the two factors described below.

b) Oxygen

The oxygen requirements of aerobic micro-organisms change over the course of fermentation. They are at their peak when composting starts, during the initial phases of intense degradation of fermentable organic matter. The gradual reduction in this portion causes a proportional reduction in oxygen requirements, until the compost is mature when low residual oxygen consumption is still recorded. Oxygen consumption by microbial respiration, differing depending on the composting stage, is used to determine the compost's development and adjust the optimum oxygen supply.
In any event, a level of oxygen sufficient to ensure aerobic conditions in the windrow is to be provided, i.e. a level over 5%. Under this level, there is a significant risk of anaerobic areas appearing, which would produce methane, this phenomenon being supported by the presence of the digestate being a favourable environment. An average value of between 15 and 20% is therefore recommended to remove this risk.

The lack of a temperature rise mentioned in the previous paragraph may result from oxygen deficiency in the windrow. There are several possible solutions to this problem:

- add more bulking agent such as green waste to encourage air circulation in the windrow.
- adjust aeration from the ventilator (if forced ventilation) – 2 possibilities: settings too low: not enough air, or settings too high: cooling of the windrow
- turn the windrow to ventilate.

c) Moisture

A minimum water content is needed to ensure successful composting. The water content of a windrow tends to drop over the course of composting owing to rising temperature, forced ventilation or turning, which causes loss through evaporation.
This therefore involves maintaining an optimum moisture level of between 50 and 60%.

The moisture level in the compost must therefore be monitored during composting to ensure that it does not fall below a critical value (between 35% and 40% moisture), failing which microflora development may be inhibited, resulting in the temperature failing to rise.

Similarly, moisture greater than 65% may cause anaerobic conditions. Such conditions result in the temperature failing to rise and the appearance of methane. It is then advisable to turn the compost to encourage evaporation and bring about a fall in moisture levels.

III. BIOLOGICAL MANAGEMENT AND MONITORING DEVICES FOR THE UNIT

A. Monitoring devices

A number of factors, analysed relatively quickly and easily, can be used to ensure effective monitoring of the process and detect the principal faults.

The first indicator of the process operation is **biogas** – if there is little or no biogas produced, this means that the digester is not working, or working very poorly.

Continuous monitoring of biogas **production** and **composition** is therefore essential since it indicates the digester's performance level, providing as it does the percentage of methane produced compared to the total potential for the degraded waste. Such monitoring also enables faults to be detected, so a low level of methane (excluding the normal drop observed post feedstock supply) may indicate methanogenic bacteria inhibition.

The **volatile fatty acids level**, the **pH** and the **total alkalinity** are all factors that it is important to regularly measure in the digestion environment.

pH is a factor which it is **necessary but not sufficient** to monitor over the course of the process. In fact, even if the pH is within the recommended range for anaerobic digestion and changes little during the process, significant and fluctuating concentrations of VFA may be "masked" by a significant buffering effect. It is therefore advisable to monitor pH and also VFA and total alkalinity to ensure the most appropriate monitoring possible.

The **VFA level** may be viewed as the **critical** factor in anaerobic digestion operation and control. A rise in VFA can be one of the first indications that the process is not running properly. It is therefore particularly **essential** to measure it as regularly as possible (at least once a week).

Regular measurement of the **total** and **ammonia nitrogen** in **solution** in the digestion environment may prove necessary, in particular where nitrogen-rich waste is concerned (wastewater treatment plant sludge, abattoir waste, liquid manure, etc.). Nitrogen (in particular in its ammonia form) may in fact be responsible for inhibition. Measurement of this level in the solid portion is less relevant.

Lastly, measuring the temperature and dry matter levels of the digester's contents can ensure that targets in terns of operating procedure (thermophilic or mesophilic, dry processes) are being reached.

In order to achieve this monitoring in real time on a production unit, a dedicated area and a certain minimum equipment level must be provided on-site. The essential equipment for monitoring these various parameters is as follows:

- worktop scales (0 – 2 kg)
- worktop centrifuge
- pH meter
- magnetic stirrer with hot plate
- 2 burettes
- a halogen moisture analyser
- effluent analysis device in kit form (spectrophotometer and hot plate)
- 2 micropipettes (1,000 – 5,000 µL and 100 – 1,000 µL)
- glassware (beakers, flasks), magnetic bars, etc
- acid (H_2SO_4; 0.1N) and soda (NaOH; 0.1N) solutions.

If the dedicated area allows, acquiring a muffle furnace may also be of benefit. The furnace could enable the OM contained in the incoming waste to be assessed and therefore the expected gas output to be estimated.
DM and OM can also be measured in treatment by-products (such as dehydrated digestate) to assess the digester's degradation rate and possibly adjust the retention time, and also alter the planned post-treatment (composting).

In order to ensure reliable analysis results, it is important to plan a maintenance and calibration schedule for the various measurement devices used.
Any undetected analysis discrepancy will result in errors in determining and interpreting the monitoring parameters and therefore run the risk of poor process management.
Lastly, although these analyses are relatively easy to carry out, it is preferable to train a limited number of operators in carrying out this monitoring. The results obtained may in fact vary from one operator to another, depending on habits and the attention paid to procedures.

B. Units and conversions

Following the routine presented above is relatively straightforward. However, we draw your attention to the importance of preparing procedures and interpreting results. In fact, carrying out such procedures can lead to dilution errors during analysis or computation errors during results write-up. This type of error could have repercussions on how the unit is managed (lack of corrective measures if a problem is not spotted, or treatment restrictions when the process is working properly).

Secondly, some of the parameters listed above may be expressed in different units, depending on the reference materials consulted.
It is therefore advisable to always express a given factor using the same units. Each unit (each reference used) gives information about the system. It is therefore necessary to properly identify the information to be brought out during an analysis.

In order to avoid misunderstandings, the list below shows the abbreviations and terms generally used when categorising various products:
- Fresh Matter (FM) [also Fr: *Matière Brute (MB) = Matière Fraîche (MF)*]
- Dry Matter (DM) – Total solids (TS) [also Fr: *Matière sèche (MS)*]
- Organic Matter (OM) = Volatile Matter (VM) [also Fr: *Matière organique (MO) = Matière Volatile (MV)*]
- Organic Matter in Dry Matter (OM in DM) = Volatile Solid (VS)
- Biodegradable Organic Matter (BOM) = Biodegradable Volatile Matter (BVM)

For ease of conversion from one unit to another, the following equations may be used:

$$Q_{DM} = \%_{DM} * Q_{FM}$$

$$Q_{OM} = \%_{OM\ \text{in dry}} * Q_{DM}$$

$$Q_{BOM} = \%_{BOM} * Q_{OM}$$

$$Q_{OM} = \%_{DM} * \%_{OM} * Q_{FM}$$

The following equivalents applying to units encountered in the field of anaerobic digestion may also be noted:

For quantification and categorisation of gas output:

1 Nm^3 = 1 m^3 of gas under normal temperature and pressure conditions (0°C and 1 atm).

1 ppm = 1mg/m3 = 0.0001%

For quantification of energy production and yield

1kW=1000 W= 3,600,000 Joules/hour

NCV of 1 m^3 of methane = 9.94 kWh

The following parameters are used to compare the performance of more than one unit:

- Retention time:

The average amount of time matter is kept in a digester. For a liquid reactor, the term is hydraulic retention time (HRT).

$$HRT_{\text{(in days)}} = V_{\text{useable from digester}} / V_{\text{extracted daily}}$$

- Organic load:

This is the rate at which the digester is supplied with fresh matter. For biowaste or household waste, this is expressed in kg of organic matter (or VM) per cubic metre of useable digester volume per day. For liquid effluent, this is expressed in kg of COD per cubic metre of useable digester volume per day (or per hour).

$$\text{Organic load} = Q_{OM} / V_{\text{useable from digester}} / \text{day}$$

- Biogas and methane output yield

Measured biogas and methane output can be metered in m^3 or Nm^3 and compared to the quantity of fresh waste, or DM, or OM, entering the digestion system.
The following equivalents can be used here:

$$V_{CH4} / t_{FM} = \%_{CH4} * V_{biogas} / t_{FM}$$

$$V_{CH4} / t_{DM} = (V_{CH4} / t_{FM}) / \%_{DM}$$

$$V_{CH4} / t_{OM} = (V_{CH4} / t_{DM}) / \%_{OM} \quad \text{or} \quad V_{CH4} / t_{OM} = (V_{CH4} / t_{FM}) / (\%_{OM}*\%_{DM})$$

IV. SAFETY AND TRAINING

Given the type of process, the working environment, the products treated and the by-products generated, it is important to highlight certain risks which operators may face. From the various hazards identified, we will mention two which we see as significant on a waste anaerobic digestion unit, namely biogas-related hazards and those related to pathogenic micro-organisms.

A. Safety

1. Biogas

During the reaction, decomposition of organic matter results in biogas being produced. As this gas is essentially made up of methane, it is combustible and its presence within the process means that ATEX zones have to be defined. It is therefore essential to identify all risks related to the presence of gas, and to use suitable equipment (methane detectors, automatic biogas network isolation system, etc.) and procedures which will allow incidents to be avoided (e.g. ban the use of mobile phones in certain areas, etc.). Signage for ATEX zones is therefore a priority, as is compliance with instructions. Consequently, once such a zone has been identified, apparatus used must meet ATEX criteria to be able to be used, in order to limit heat sources that could cause an explosion in the event of a gas leak. These heat sources could be e.g. flames (welding torch, cigarettes and buts, lighters, etc.), mechanical sparks (grinding, chopping, etc.), electrical sparks (arc welding, earth connections, **static electricity**, lightning, poor contacts, etc.) and hot surfaces (mechanical friction, thermal conduction, non-cooled parts, etc.).

ATEX Zoning

Determining ATEX zones (for Explosive Atmospheres) is governed in Europe by the ATEX Directive 1992/92/EC, transposed into French law by decrees 2002-1553 and 2002-1554.
The Directive in particular required the employer to prevent ATEX formation and classify as ATEX zones those locations where there is a risk of ATEX forming.
Zoning is applied depending on the risk of ATEX forming.

There are three zones for gas:
Z0: CONTINUOUS HAZARD – location where the explosive atmosphere is present continuously, or for extended periods
Z1: POTENTIAL HAZARD – location where an explosive atmosphere is likely to occur under normal operation
Z2: MINIMUM HAZARD – location where an explosive atmosphere is unlikely to occur under normal operation and where any such atmosphere, should it arise, will only last for a short time.

All electrical, mechanical or pneumatic equipment, protective apparatus and safety devices installed in such areas must carry labelling showing that they may be used in such areas: CE marking, the Ex logo Ex, approved as Group II 1 G equipment (for zone 0), or II 2G (for zone 1), or II 3G (for zone 2).

Biogas may also contain many other gases, potentially toxic to humans, in varying quantities. The best-known example is H_2S. This gas can be fatal if inhaled in certain proportions. This hazard is essentially encountered during maintenance work on safety equipment (e.g. flame arresters), or treatment or biogas recycling equipment. Under these conditions, it is desirable to provide for the use of portable gas detectors and cartridge respirators (appropriate for the gases likely to be encountered).

Explosive and toxicity limits

Certain compounds in the biogas or released from the digestate are potential sources of explosion or poisoning. In particular, three compounds are to be monitored on anaerobic digestion facilities:
For explosion: methane (in the biogas)
For toxicity: hydrogen sulphate (H_2S) (in biogas) and ammonia (NH_3) when handling the digestate.

Explosive limit

A mixture is explosive when the concentration in the air of a combustible substance falls between two values:

- the lower explosive limit (LEL)
- the upper explosive limit (UEL)

Methane CH4: LEL 5 % - UEL 15 %

Toxicity limits

Several concepts must be understood:
IDLH: maximum level of exposure in a work environment for a period of 30 minutes:
Hydrogen sulphate H_2S: 300 ppm, or 420 mg/m^3
IDLH threshold: immediate danger to life and health threshold:
H_2S: 100 ppm, or 140 mg/m^3
ELV: Short term (15 mins) Exposure Limit Value
H_2S: 7 to 9.8 ppm, or 10 to 14 mg/m^3
Ammonia NH_3: 50 ppm, or 36 mg/m^3
AEV: Average Exposure Value (over 8 hours)
H_2S: 5 ppm, or 10 mg/m3
NH_3: 25 ppm, or 18 mg/m3

H_2S

IDLH VALUES		IMPACTS ON HEALTH
ppm	mg/m3	
50 to 100	70 to 140	Conjunctivitis, respiratory irritation after 1 hour
170 to 300	238 to 420	This is the concentration that a population can withstand for 1 hour without irreversible effects on health
400 to 700	560 to 980	Hazardous to health where exposure is between 30 minutes and 1 hour, irreversible effects and possible death
700 to 1000	980 to 1400	Rapid unconsciousness followed by death
1000 to 2000	1400 to 2800	An individual subjected to this concentration loses consciousness and dies within minutes

Concentration		Exposure time	Effects on humans
ppm	mg/m3		
0,0005 - 0,13	**0,0007 - 0,2**	< 1 min	Olfactory threshold
10,5 - 21	**16 - 32**	6 - 7 h	Ocular irritation threshold
50 - 100	**75 - 150**	> 1 h	Irritation of ocular and respiratory mucus
150 - 200	**2 - 15 min**	2 - 15 min	Sense of smell lost
600	**15 min**	15 min	Immediate death

Given the various hazards related to the presence of biogas listed above (poisoning, explosion, fire), erection of signs on the site must be carried out carefully, with clear identification of all zones and equipment.

Another important point is the occasional involvement on the site of outside companies (specialising in repair or servicing of particular equipment, e.g. worm screw or pump, etc.). All staff having to work on the site must be informed beforehand of the hazards and of the regulations to be observed on-site. Such an approach will thus allow those involved to prepare suitable equipment for maintenance or repair work under satisfactory safety conditions.

2. Pressurised working conditions

The biogas in the reactor and system is pressurised. Maintaining constant pressure in the system is necessary to avoid any air seeping into the system and to ensure continuous supply to the biogas recycling equipment.

This modus operandi results, in fact, in a risk of explosion either in the reactor or the biogas system.

To reduce this risk, certain key equipment must be installed:

- an overpressure device (flushes gas when the pressure reaches a predetermined threshold)
- a rupture risk on the digester roof
- a liquid seal
- a flare (in addition to biogas recycling equipment)
- pressure sensors installed in the reactor and the biogas system
- effective monitoring of the digestate level in the reactor (volume + mass summary)

The hazards related to pressurised working conditions are therefore controlled when suitable equipment is installed. Maintenance of this equipment is also very important to prevent the risk of explosion.

Lastly, tracking the reactor’s input and outputs can help to check the consistency of the data supplied by the online pressure sensors.

3. Biological hazards

Waste treated by anaerobic digestion is naturally contaminated by pathogenic micro-organisms. Over the course of treatment, other than when hygienisation is involved, the majority of them will survive, and even grow. In order to avoid becoming contaminated, operators must wear gloves when carrying out the various tasks. Wearing a dust protection mask may also be recommended in some cases to avoid ingesting airborne pathogens.

Lastly, basic hygiene rules are to be kept in mind at all times (in particular the washing of hands).

B. Training

The various points addressed in this document show that running an anaerobic digestion unit requires a range of skills and some specific expertise. Staff training is therefore the key to successful management of such facilities. Every unit (including those from the same manufacturer) is unique, at least in terms of the waste they treat, and therefore requires a period of learning how the digester behaves.

It is therefore important, wherever possible, to involve the people responsible for operating the unit from the construction stage. Secondly, the start-up and warranty testing phases are also to be monitored systematically, and must be an opportunity to acquire the maximum of practical detailed information and recommendations from the manufacturer.

Staff responsible for maintenance should also receive specific training and be particularly aware of safety issues, especially when it comes to servicing the biogas system equipment.

Besides conventional operating training (occupational first aid personnel, approved electrician, fire training, heavy plant operation, etc.), it is recommended to put the main staff through specific training such as ATEX risk training, biological hazards or basic training in fundamental physical-chemical analysis.

V. CONCLUSION

RMW is waste with complex physical behaviour and properties, causing difficulties at anaerobic digestion plants, and mechanical issues can result from problems of a biological nature.

This observation highlights the great importance of the pre-treatment phase, which affects the outcome of all following stages of the process.

In addition to a good understanding of the properties and potential of the untreated waste, accurate and regular monitoring of various physical-chemical parameters of the digestate is also a determining factor for trouble-free management of this type of unit.

It is also essential that the operating personnel have a good understanding of the installation and the biological processes that take place.

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