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01-03: Introduction to biodegradable biomass

In the present chapter ("Putrescible"), the main focus is on industrial bio-waste, wastewater sludge, animal manure and to some extent landfill bio-waste. Household waste and municipal bio-waste is treated in more details in part 4 of this handbook, "Other biomasses".

01-03-01: Definitions and terminology

Biomass decomposition (degradation). Any organism (biomass), after its death, will either decompose, in the presence of oxygen, or be utilized by detritovores (microorganisms). Detritovores are organisms that feed on detritus or organic waste. Examples include millipedes, woodlice, dung flies, many terrestrial worms and burying beetles. By consuming dead organic matter (putrescibles) they speed up decomposition by increasing the surface areas available to detritovoric bacteria [1].

Putrescible waste - solid waste that contains organic matter capable of being decomposed by microorganisms and of such a character and proportion as to cause obnoxious odours and to be capable of attracting or providing food for birds or animals. Basically, putrescibles are the bits of garbage that decompose and get stinky. This can include food waste, used diapers, and pet waste.

Biochemical conversion processes - the use of living organisms or their products to convert organic material to fuel. Biochemical conversion makes use of the enzymes of bacteria and other micro-organisms to break down biomass. In most cases micro-organisms are used to perform the conversion process: anaerobic digestion (AD), fermentation and/or composting.

Biomethanation – "methane fermentation" or "anaerobic digestion" are the everyday words used to indicate biomethanation. It is a complex microbial process in which organic compounds are degraded into methane and carbon dioxide by a variety of anaerobes. Biomethanation is used as a technique of biofuel recovery from biomass and treatment of waste biomass.

The formation of methane (CH_4) is a biological process that occurs naturally when organic matter (biomass) decomposes in a humid atmosphere in the absence of air but in the presence of a group of natural microorganisms which are metabolically active, i.e. methane bacteria. In nature, methane is formed as marsh gas (or swamp gas), in the digestive tract in ruminants, in plants for wet composting, and in flooded areas and lands (rice fields).

Biogas (rich of methane) originates from bacteria in the process of bio-degradation of organic material under anaerobic (without air) conditions. The natural generation of biogas is an important part of the biogeochemical carbon cycle. Methanogens (methane producing bacteria) are the last link in a chain of micro-organisms which degrade organic material and return the decomposition products to the environment. In this process biogas is generated, a source of renewable energy.

Each year some 590-880 million tons of methane are released worldwide into the atmosphere through microbial activity. About 90% of the emitted methane derives from biogenic sources, i.e. from the decomposition of biomass. The remainder is of fossil origin (e.g. petrochemical processes). In the northern hemisphere, the present tropospheric methane concentration amounts to about 1.65 ppm.

01-03-02: Process introduction

Knowledge of the fundamental processes involved in methane fermentation is necessary for planning, building and operating biogas plants. Anaerobic fermentation (digestion) involves the activities of three different bacterial communities. The process of biogas production depends on various parameters. For example, changes in ambient temperature can have a negative effect on bacterial activity.

In principle, all organic materials can ferment or be digested. However, only homogenous and liquid substrates can be considered for simple biogas plants: faeces and urine from cattle, pigs and possibly from poultry and the wastewater from toilets. When the plant is filled, the excrement has to be diluted with about the same quantity of liquid; if possible, the urine should be used. Waste and wastewater from food-processing industries are only suitable for simple plants if they are homogenous and in liquid form. The maximum gas production from a given amount of raw material depends strongly on the type of substrate [2].

01-03-02a: Anaerobic digestion

Anaerobic digestion (AD) is the process by which organic materials in an enclosed vessel are broken down by micro-organisms, in the absence of oxygen. Anaerobic digestion produces biogas (consisting primarily of methane and carbon dioxide). AD systems are also often referred to as "biogas systems".

The AD process also produces a liquid effluent (called digestate) that contains all the water, all the minerals and approximately half of the carbon from the incoming materials (Figure 1-03 1).

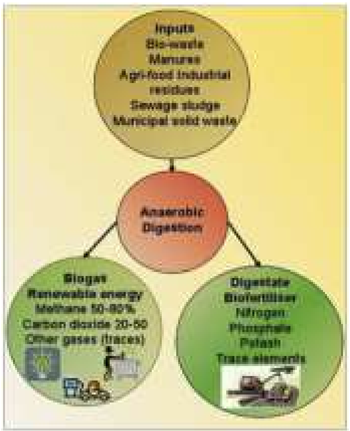

Figure 01-03 1: The anaerobic digestion process

Anaerobic digesters produce conditions that encourage the natural breakdown of organic matter by bacteria in the absence of air. Anaerobic digestion (AD) provides an effective method for turning residues from livestock farming and food processing industries into:

biogas (rich in methane) which can be used to generate heat and/or electricity
fiber which can be used as a nutrient-rich soil conditioner,
and
liquor which can be used as liquid fertilizer.

The process is already used for treating agricultural, household and industrial residues and sewage sludge.

There are three major types of AD processes.

Process	Typical temperatures	Typical residence times
Psychrofilic	15 – 22 °C	months
Mesophilic	25 – 38 °C	25 – 50 days
Thermophilic	50 – 70 °C	10 – 30 days

Low temperature or **psychrophilic** (< 20 °C) anaerobic digestion has recently been proven feasible for the treatment of a range of industrial wastewater representing a technological breakthrough for environmental management. Therefore psychrophilic anaerobic treatment is an attractive option to conventional anaerobic digestion for wastewaters that are discharged at moderate to low temperature.

Mesophilic digestion. The digester is heated to 30 – 35 °C and the feedstock remains in the digester typically for 15 - 30 days. Mesophilic digestion tends to be more robust and tolerant than the thermophilic process, but gas production is less, larger digestion tanks are required and sanitisation, if required, becomes a separate process stage. The mesophilic regime is the most common today, because it is a stable process, producing a reasonable amount of biogas, in an acceptable time frame.

Thermophilic digestion. The digester is heated to 55 °C and the residence time is typically 12 - 14 days. Thermophilic digestion systems offer higher methane production, faster throughput, better pathogen and virus 'kill', but require more expensive technology, greater energy input and more complicated operation and monitoring.

During the AD process 30 – 60 % of the digestible solids are converted into biogas. This gas must be burned, and can be used to generate heat or electricity or both. It can be burned in a conventional gas boiler and used as heat for nearby buildings including farmhouses, and to heat the digester. It can also be used to power associated machinery or vehicles. Alternatively, it can be burned in a gas engine to generate electricity. If generating electricity, it is usual to use a more efficient combined heat and power (CHP) system, where heat can be removed in the first instance to maintain the digester temperature, and any surplus energy can be used for other purposes. A larger scale CHP plant can supply larger housing or industrial developments, or supply electricity to the grid.

As fresh feedstock is added to the system, digestate is pumped from the digester to a storage tank. Biogas continues to be produced in the storage tank; collection and combustion may be an economic and safety requirement. The residual digestate can be stored and then applied to the land at an appropriate time without further treatment, or it can be separated to produce fibre and liquor. The fibre can be used as a soil conditioner or composted prior to use or sale. The liquor contains a range of nutrients and can be used as a liquid fertiliser which can be sold or used on-site as part of a crop nutrient management plan.

AD products can, therefore, help farmers reduce their requirement for non-renewable forms of energy such as fossil fuels, and the digestate, if correctly used, can reduce demand for synthetic fertilisers and other soil conditioners which may be manufactured using less sustainable methods.

As part of an integrated waste management system, anaerobic digestion reduces the emission of landfill gas into the atmosphere. Anaerobic digesters can also be fed with purpose-grown energy crops, such as maize.

Biogas is characterized based on its chemical composition and the physical characteristics which result from it. It is primarily a mixture of methane (CH_4) and inert carbonic gas (CO_2). However the name "biogas" gathers a large variety of gases resulting from specific treatment processes, starting from various organic wastes - industries, animal or domestic origin waste etc.

01-03-02b: Fermentation

Fermentation is the process of extracting energy from the oxidation of organic compounds, such as carbohydrates, using endogenous electron acceptors which are usually an organic compound [3]. Fermentation is important in anaerobic conditions when there is no oxidative phosphorylation to maintain the production of ATP (adenosine triphosphate) by glycolysis. Sugars are the most common substrate of fermentation, and typical examples of fermentation products are ethanol, lactic acid, lactose, and hydrogen.

Fermentation products contain chemical energy (they are not fully oxidized), but are considered waste products, since they cannot be metabolized further without the use of oxygen. Advances in microbiology and fermentation technology have continued steadily up until the present. For example, in the late 1970s, it was discovered that microorganisms could be mutated with physical and chemical treatments to be higher-yielding, faster-growing, tolerant of less oxygen, and able to use a more concentrated medium [4]. Strain selection and hybridization developed as well, affecting most modern food fermentation.

01-03-02c: Composting

At the simplest level, the process of composting simply requires making a heap of wetted organic matter (leaves, food waste) and waiting for the materials to break down into soil after a period of weeks or months. Modern, methodical composting is a multi-step, closely monitored process with measured inputs of water, air and carbon- and nitrogen-rich materials.

The decomposition process is aided by shredding the plant matter, adding water and ensuring proper aeration by regularly turning the mixture. Worms and fungi further break up the material. Aerobic bacteria manage the chemical process by converting the inputs into heat, carbon dioxide and ammonium.

01-03-03: An introduction to substrates [5]

Biomass which is suitable to be digested (fermented) is named “substrate”. In general, all types of biomass can be used as substrates as long as they contain carbohydrates, proteins, fats, cellulose, and hemi-cellulose as main components.

The following points have to be taken in consideration to select the biomass:

- The content of organic substance should be appropriate for the selected fermentation process.
- The nutritional value of the organic substance, hence the potential for gas formation, should be as high as possible.
- The substrate should be free from pathogens and other organisms which would need to made innocuous prior to the fermentation process.
- The content of harmful substances and trash should be low to allow the fermentation process to take place smoothly.
- The composition of the biogas should be appropriate for further applications.
- The composition of the fermentation residue should be such that it can be used, e.g., as fertilizer.

Some substrates legally require a proper sanitization before and after the fermentation process.

01-03-03a: Digestible biomass from livestock

Almost any organic material can be processed using anaerobic digestion. The selected feedstock may include animal manure, agricultural crops, agro-food processing residues, food residues, the organic fraction of household waste, organic fractions of industrial wastes and by-products, sewage sludge, municipal solid waste, etc.

The feedstock, sometimes referred to as substrate, can be either a single input (e.g. animal manure) or a mixture of two or more feedstock types (this is termed co-digestion). Most biogas plants use more than one substrate. When the dry matter content of the feedstock is below 15% the AD process is called ‘wet’ digestion (or ‘wet’ fermentation); when it is above this level the process is referred to as ‘dry’ digestion. Figure 01-03 1 summarises the AD process [6]. Data about biogas production and energy output potential from 1 tonne of various fresh feedstocks are listed in table 01-03 1.

The rules of use and processing animal by-products are laid down in Regulation (EC) 1069/2009 (“ABP-Regulation” or “Hygiene Regulation” in circles working at environmental issues). In the ABP-Regulation animal by-products are divided into 3 categories [7, 8]:

- Category 1 contains those materials with the highest risk for public health, animals, or the environment (hygienic risk, risk of BSE, etc.).
- Category 3 comprises those animal by-products which would be fit for human consumption, but are (for commercial reasons) not intended for human consumption,
- Category 2 includes all animal by-products which can be allocated neither to Category 1 nor to Category 3 (e.g. manure or digestive tract content or animals not fit for human consumption).

Category 1 materials are not designated for treatment in biogas plants. Category 2 and 3 materials can be used for biogas production, but additional sterilization can be needed. Additional national rules can be applied for biogas plants which process animal by-products. [7]

Manure, digestive tract content (separated from the digestive tract), milk and colostral milk are materials of category 2. These materials can be fed directly and without any pre-treatment to an approved biogas plant. [7]

The fermentation end product of the "transformation" of manure processed in a biogas plant together with other substrates which are not covered by this regulation (e.g. renewable raw materials or energy crops) may be considered as untreated manure.

Conditions for the placing on the market of "untreated" manure within the boundaries of a member state, as well as special requirements for transport (marking as "manure", cleaning of containers, etc.) may be laid down by national legislation.

Manure is simply animal feed that was not fully digested, as well as additional water and bedding. It contains significant amounts of energy that can be harvested in an anaerobic digester.

The following rules of thumb should be considered:

- Digestion of dairy and cattle manure has been successfully implemented in many jurisdictions,
- Digestion of only poultry or swine manure may present more challenges because of their higher nitrogen levels – other materials may be added to optimize the blend,
- Sand or other inorganic materials will settle out in the digester and must be considered in the design. Many digesters will require shutdown and removal of built-up materials after 10 years of usage,
- AD systems work best with fresh manure – manure that has been stored for some time may not be as suitable,
- AD systems are not effective with highly diluted manure. As an example, the bypassing of milk house wash water should be considered,
- AD systems can use solid manure. However, floating material and non-digestible material from livestock bedding may make the system difficult to operate.

High proportions of P (phosphorus) and K (potassium) in animal diets are also excreted. Animal manures and slurries are therefore rich in plant nutrients. This is also the case for many other types of AD feedstock, making the digestate a valuable bio-fertiliser. By making the best possible use of digestate as a fertiliser, nutrients are returned to the land through natural cycles to replace the input of inorganic fertiliser. Recycling in this way closes the loop to create more sustainable agricultural production systems.

The composition of animal manure depends mainly on the digestive system of the animal (ruminant, omnivore, etc.) and on its diet. Other factors that effect the composition of manure include the species, sex and age of the animals as well as geographical and climatic conditions.

Since manure alone gives relatively low biogas yields per unit of fresh weight it is frequently mixed and co-digested with other feedstock types which have higher biogas yields [9].

Commonly used co-substrates include residues from food processing industries, vegetable residues from crop production and even specially grown crops (energy crops). In practice, the selection of AD feedstock usually depends on what is available locally, in combination with the aim to optimise the biogas output. Within the EU, use of animal by-products that are not intended for human consumption as AD feedstock is governed by EC Regulation No 1774/2002.

Feedstock	**Animals to give 1 tonne/day** (*number*)	**Dry matter content** (*% by weight*)	**Biogas yield** (*m^3/tonne feed*)	**Heating value** (*MJ/m^3 biogas*)
Cattle slurry	20 - 40	12	25	23 - 25
Pig slurry	250 - 300	9	26	21 - 25
Laying hen litter	8 000 - 9 000	30	90 - 150	23 - 27
Broiler manure	10 000 - 15 000	60	50 - 100	21 - 23
Food processing waste	-	15	46	21 - 25

Table 01-03 1: Biogas production and energy output potential from 1 tonne of various fresh feedstocks
Notes:
1 Figures should be taken as indicative values
2 Cattle slurry covers both dairy and beef cattle
3 Poultry manures are highly susceptible to ageing and should be used as fresh as possible

From the numbers in the table one may estimate the potential of useful energy based on that 1 m^3 of biogas (at an assumed 20 MJ/m^3) would typically give the following:

- electricity only: 1.7 kWh of electricity (assumed conversion efficiency 30%)
- heat only: 2.5 kWh of heat (assumed conversion efficiency 70%)
- combined heat and power: 1.7 kWh of electricity and 2 kWh heat.

The liquid manure from any animal species may contain foreign matter. Some of these substances can be processed in the biogas plant, e.g. litter and residues of fodder. Others are unwanted foreign matter because they impair the fermentation of the liquid manure.

These are:

- Sand from mineral materials present in feed of pigs and poultry,
- Sawdust from scattering,
- Soil from roughage,
- Soil which is carried from meadows,
- Skin and tail hair, bristles, and feathers,
- Cords, wires, plastics, stones and others.

The presence of foreign matter leads to increased complexity and expenditures of the plant operation. Organic acids, antibiotics, chemotherapeutic agents, and disinfectants found in liquid manure can impair and even disrupt the fermentation (digestion) process in biogas plant. In the liquid manure of pigs the high content of copper and zinc derived from additives in feed can be the limiting factor.

The degree to which the organic substance in the biomass is decomposed in the bioreactor depends on the origin of the liquid manure. The organic content in liquid manure derived from cattle is only 30% decomposed because of the high content of raw fibres in the fodder, while about 50% of pig liquid manure and more than 65% of chicken liquid manure is broken down.

The more decomposable the organic substance, the higher is the content of ammonia in the liquid manure compared to the untreated material [5].

01-03-03b: Digestible biomass from society (incl. BD fraction of MSW)

Industrial residues suitable for anaerobic digestion include

- waste from food and drinks preparation (sugar beet processing, meat and fish processing, dairies, vegetable processing, breweries, olive oil processing etc);
- blood and gut contents from abattoirs and rendering plants;
- sludge from pulp and paper industry;
- textile waste;
- waste from the leather and tannery industry.

Food by-products

Typically, food by-products (and un-marketed food products) can be secured for the digester at little cost or for a tipping fee. In addition to the considerations below, see the section in this document on off-farm source material for more details.

- Most food by-products break down rapidly in the digester.
- Optimizing the carbon: nitrogen ratio will be necessary, especially for materials with higher protein levels.
- When introducing different food by-products, it is important to make changes to the recipe slowly to allow the micro-organisms to adapt to the new menu.
- When food by-products come from a variety of sources (for instance, a blend of processing facilities, restaurants and retail food store materials), there may be less certainty about the consistency or quality of material compared to material from one consistent source. Agreements with reputable material handling companies are a key to success.

Sewage sludge

The anaerobic degradation of sewage sludge is called digestion, stabilization, or sewage sludge fermentation. The first step in the process is the removal of large impurities such as wood, clothing, etc., using rakes and sand trap separators. The sewage sludge from the pre-purifier and from the final clarification basin is segregated with pumps, then dehydrated after sedimentation and stabilized by forming biogas (sewage gas). Finally it is concentrated up to 30% of dry matter. The dry sludge could be used agriculturally as fertilizer or be burned together with MSW in incineration plants.

Waste grease or fats
Waste fat is another source for energy. For instance in Germany approx. 150 000 – 280 000 tons per year of dripping and chip fat can be collected. Around 330 000 t/y of waste fat of excellent quality could be considered for production of biogas.

Industrial Wastes
Organic solid wastes from industry are increasingly treated in biogas plants. Even if some of the substances might be difficult to digest as a sole substrate, in mixtures with manure or sewage sludge they don't pose any problem. The combined digestion of different wastes is called co-digestion. Most of the waste products from the food industry have excellent gas potential and therefore are in demand by plant operators. Until recently the industry paid the operators reasonably high gate fees (up to 35 Euro per ton) to accept the waste products.

Now, the operators are starting to pay for the waste materials with the highest gas potential like fat and vegetable oil. With current high feed-in tariffs they can easily recover the cost of these wastes. AD of industrial waste waters is becoming a standard technique. Whilst AD is only an initial stage in the treatment of high quality water discharge, it can significantly reduce the cost and size of plant compared to wholly aerobic treatments.

Municipal Solid Wastes
Organic wastes from households and municipal authorities provide potential feedstock for anaerobic digestion. The treatment of clean source separated fractions for recycling of both the energy content and the organic matter is the only method in which the cycle can be completely closed. In most of the European countries, the source separation of MSW is actively encouraged. This includes separation of the putrescible organic fraction, also known as 'green waste' or 'bio-waste'.

Experience has shown that source separation provides the best quality feedstock for AD. The digested material is a valuable fertilizer and soil improver, especially after aerobic post-treatment. Where source separation has been widely introduced, the results are encouraging.

Alternatively, the unsegregated wastes or the 'grey waste' after separation of the 'bio-waste' can be treated to gain the biogas from the waste as well as stabilizing it to prevent further problems in landfill.

Landfill gas
Until the 1990s, residual waste (i.e. household waste) was discarded on landfills, by default Biological components of the waste were degraded quite slowly and the digestion process took about 20-40 years. The landfill gas produced during the process was gathered by using horizontal drainages and gas pits for disposal. About 12-300 m^3 of landfill gas was produced in total per Mg (ton) of residual waste, but it contain quite high level toxic and corrosive organic components, so that the damage to CHP units often resulted.

Anaerobic digestion is also the basic process for landfill gas production from municipal solid (biodegradable fraction or green) waste (MSW). It has a significant potential, but it is characterised by relatively small plant size.

Anaerobic digestion is increasingly used in small-size, rural and off-grid applications at the domestic and farm-scale. The rising cost of waste disposal may improve its economic attractiveness. In modern landfills, methane production ranges between 50 and 100 kg per tonne of MSW. In general, some 50% of such gas can be recovered and used for power and heat generation.

After purification and upgrading, biogas can be used in heat plants, stationary engines, fed into the natural gas grid, or used as a transport fuel (compressed natural gas). Large-size plants using MSW, agricultural wastes and industrial organic wastes (large-scale co-digestion) need some 8 000-9 000 tonne MSW per year per MW of installed capacity. Some 200 such plants are in operation or under construction world wide using more than 5 million tonnes of MSW.

01-03-04 Planning aspects

An individual community (parish) is often too small to host a waste-fuelled CHP-plant, simply because the specific cost for MSW combustion is higher than for clean biofuels, but small-scale biogas plants construction can be rather suitable for parishes.

Hence, planning for waste-to-energy must most often be based on a regional perspective and the systems for waste collection and separation, as well as the technologies used for the collection and transport, need be co-ordinated between municipalities.

Planning and construction of a biogas plant is usually a part of municipal development plan and general plan. Also the waste management is organized based on this of these documents.

When selecting a suitable location for a biogas plant in combination with CHP, the following aspects should be considered:

- sufficient resources available within a radius of about 20 km (energy-rich substrates eg, fat are worth bringing also from longer distances);
- sufficient number of heat consumers in the vicinity ≤ 1 km of biogas plant (biogas plant reaches maximum efficiency if all surplus heat can be sold to consumer);
- electrical substation of sufficient capacity close to planned biogas plant (large distances increase costs of connection);
- large roads proximity (with sufficient flow of vehicles). If there is no possibility to sell heat, and the electricity connection point is too far off, it would be possible to clean the biogas and sell bio-methane as transport fuel.

If the resources and consumers are located close enough to each other, there are no other obstacles to constructing biogas plant than the presence of an investor.

To conclude, some indicative values for the biogas yield and quality from different substrates are given in the following table, from Jurgensen [10].

Biomass (substrate)	**Typical gas yields** m^3 biogas/kg DM	m^3 methane/kg VS	**Methane content** % by volume	**VS content** weight-% of TS
Pig slurry	0.37	0.32	65	75
Cattle slurry	0.24	0.21	65	75
Mink slurry	0.40	0.35	65	75
Deep bedding	0.24 – 0.37	0.21 – 0.32	65	75
Chicken manure	0.40	0.35	65	75
Flotation sludge from wastewater treatment plant	0.41 – 0.86	0.36 – 0.75	70	80
Offal	0.49 – 0.57	0.40 – 0.46	65	80
Primary sludge	0.38	0.33	65	75
Biological sludge	0.11 – 0.23	0.10 – 0.20	65	75
Source-separated household waste	0.43	0.35	65	80
Maize	0.61	0.37	55	90
Grass	0.57	0.35	55	90

Table 01-03 2: Indicative values, gas yield and quality from different biomasses.
DM is the dry-matter weight of the biomass, VS is the organic biomass (volatile solids) and TS is the total solids

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