Biological Waste Treatment
Unit 6
Digestion Technics

Editor
Prof. Dr.-Ing. habil. W. Bidlingmaier
Bauhaus Universität Weimar

Authors
Prof. Dr.-Ing. habil. W. Bidlingmaier

A manuscript for students

Weimar 2016

6 Digestion Technics

6.1 Introduction

For reasons relating to climate, natural and environmental protection the Federal Republic of Germany is striving to support sustainable development of the energy supply. This includes preservation of fossil fuels and the further development of technologies for the production of energy from renewable resources. The Renewable Energy Sources Act (EEG) is one fundamental element of the implementation of these goals and went into effect on April 1st, 2000. The EEG (2000) regulates the inspection and compensation of energy, which is produced solely from renewable energy sources, by energy suppliers that operate the networks for general energy supply (network operators).

The last amendment to the Renewable Energy Sources Act was passed in April 2004 in the German Bundestag (Lower House of the German Parliament). That meant the completion of a body of law after a two-year-long discussion, which, among other things, gives farmers the security needed for investments in the innovative field of energy production from renewable resources. Aside from setting the level of compensation for the energy according to the size of the plant and treated biomass the EEG ensures that the compensation will remain unchanged for 20 years after the plant initially goes into operation. Clear improvements were made in comparison to the previous EEG for energy production from biomass (rape seed, wheat, dung, wood, organic waste etc) in, for example, biogas plants.

In this manner the operators of biomass recycling plants, for example for the sole usage renewable resources - organic substances originating from plants or animals, which are not used as raw materials for food or feed, but rather for industry or as a source of energy - and innovative technology receive a separate bonus compensation. This amendment will contribute to an intensification of the energy production from biomass due to the described financial incentive due to the fact that many farmers will consider building and operating a biomass recycling plant since new areas of business and income are able to be entered through energy production.

In addition, the motivation of this group to gain profit and income from other fields of business is increasing due to the relatively low net profits for agricultural products alone. As such a changeover from agricultural farmer to "energy farmer" will take place with many farmers. An "energy farmer" will no longer earn the majority of his income from purely agricultural activities, but rather from the production (and sale) of energy. The Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for Environment, Natural Protection and Reactor Security) is expecting an increase of the portion of renewable energy in the gross energy consumption due to the amendment of the EEG from 8 % in the year 2002 to around 20 % in the year 2020.

6.2 Type, Amount, Potential and Characterisation of Degradable Materials

Investments in biomass recycling plants are lucrative business for farmers. The produced agricultural raw materials have a secure consumer, the own biogas plant. Aside from that the investments have a good chance of paying for themselves within a few years with good operational management (plant set-up based on operation, trained personnel, etc.). The professional association for biogas and diverse operators allows for this a time span of five to eight years [13. Annual Symposium of the Professional Association for Biogas, Jan. 2004].

The fermentation of organic residues is already standard technology. Many plants already exist for the use of organic waste, as well as purely agricultural residual products, such as dung. According to Bundeslandwirtschaftsministerium (German Federal Agricultural Ministry) there were 550 agricultural biogas plants and 27 larger, centralised plants, with an annual capacity of around 4.1 million tons, in Germany in 1999. In spring 2001 the total number of biogas plants in Germany was estimated at 1200 by the Energieagentur NRW (Energy Agency NRW). By the end of 2002 the estimated number was between 1600 [Kaltschmitt 2003] and 1900 [Fachverbandes Biogas (Professional Association for Biogas) 2002]. These numbers give indications of a trend. At its symposium in 2003 the Professional Association for Biogas continued to expect a high number of newly-built plants in 2004 due to the incentives offered by the EEG.

The amount of the selected organic waste substances in Germany and their appropriateness for diverse recycling processes are represented in *Table 6.1*.

Tab. 6.1: Potential for Organic Waste in Germany [Kraft et al. 2004]

Waste type	Waste amount [Mg]	Use from fermentation [Mg]	Use from composting [Mg]	Use from biomass power plants [Mg]
Biowaste	4,264,000	3,496,480	4,050,800	205,000
Green waste (wood)	1,500,000	0	1,500,000	1,500,000
Green waste (without wood)	2,307,000	2,007,090	2,307,000	0
Catering waste	358,000	358,000	358,000	0
Slaughterhouse waste	3,500,000	2,100,000	3,500,000	0
Grape pomace	150,000	150,000	150,000	0
Lees	66,000	66,000	66,000	0
Apple pomace (wet)	250,000	250,000	250,000	0
Brewery waste	2,125,000	2,125,000	2,125,000	0
Rinds	3,750,000	0	780,000	3,750,000
Brewer grains	780,000	780,000	3,750,000	
Sum	**19,050,000**	**11,332,570**	**18,836,800**	**5,455,000**

In Germany biogas plants are used for the fermentation of organic materials (waste, also increasingly biomass grown for that purpose) from industry, agriculture and households. In biogas plants these organic substrates are degraded in a multi-level process, of fermentation or rotting, through the activities of anaerobic micro-organ-isms, which means with the exclusion of air or oxygen. The input materials have to be structurally weak and have a water content of at least 65 % for dry fermentation and at least 90 % for wet fermentation, which is predominantly practised in the field of agriculture. The final products of the process are the fermentation residues, which can be used as organic fertiliser in agriculture, and biogas. Biogas is comprised of up to around 60 - 70 % methane, 29 -39 % carbon dioxide and 1 % trace gases. The composition varies depending on the input materials. The role of the percentage of the plant cultivation materials carbohydrates, oils, proteins is especially important. Finally the ratio of C/H/O (carbon, hydrogen, oxygen) in the substrate determines the biogas composition. The quality of the biogas, and along with it the electricity production, can therefore be controlled by the composition of the input material. Only optimal plant conception and operation can guarantee optimal energy output.

Biogas has a calorific value of on average 6 kWh/m³ depending on the methane content (corresponds to around 0,6 l heating oil per m³ biogas) and can be generally used in all common gas instruments and machines. In agricultural biogas plants the biogas is used for the operation of a combined heat and power station. Here a motor (diesel or gas motor) is driven by biogas, which powers a generator. The energy in the biogas is transformed into around 30 % electricity and 70 % usable rejected heat. A portion of the energy, around 15-30% (depending on plant type) is necessary for plant operation. The rejected heat, however, which has a significantly higher energy potential than the electric energy, often can not be used since the necessary installations and/or consumers do not exist. The thermal energy can be used for heating, as well as cooling of objects and materials. The requirement for which is the choice of location, where potential consumers can be found. Only a few of the existing biogas plants fulfil this requirement. Most fermentation plants have no standardisation at the present time. Therefore, they represent time and again individual solutions. While in the area of waste water technology norms were created to assess plants for waste water treatment, the area of biomass fermentation remained vastly untouched. This developed led to the acquisition of medium and small-sized biogas plants today requiring very complex and costly planning and at the same time involving great risk. This is currently affirmed by the large number of legal conflicts regarding the compliance with guarantee criteria.

6.2.1 Substrates from Agriculture

Substrate, which is created as a residual by-product in productive livestock husbandry, is called *economic fertiliser*. A good example of which is liquid or solid manure from cattle, chicken and pig breeding. These substrates have great potential since they are produced in large quantities as a result of the predominant farm size and have to be treated due to environmental protection regulations. Liquid manure from cattle and pigs has a relatively low dry substance content and is therefore well-suited for being treated along with other substrates, so-called co-substrates, with higher dry substance content.

Solid manure, on the other hand, is usually thinned due to its high dry substance content in order to be able to be pumped and as a result plant compatible. This substrate has to be homogenised in wet fermentation plants before being treated.

Achievable biogas production and nutrient content of different economic fertilisers vary depending on the type of animal and husbandry. This is represented in *Table 6.2*.

Renewable resources are agricultural production plants or even residues, which can be applied in biogas plants for energy use. Renewable resources for use in biogas plants can be cultivates on so-called set-aside land in accordance with the effective legal regulations. The legal framework is provided by the EU ordinance Nr. 1251 (17.05.1999) and the related implementation regulations. In which case a difference is made between cultivation for use in the plant that belongs to the farm and for external plants.

A cultivation declaration with the responsible authorities is sufficient for the use of renewable resources in the farm's own plant. A cultivation and purchase contract between the producer of the renewable resources and the biogas plant operator has to be signed for use elsewhere. The renewable resources have to be entirely harvested, stored and made unusable as feed or foodstuff. This can take place by denaturisation, which means the treatment of the renewable resources with liquid manure, animal oil and special pigments.

Tab. 6.2: Economic fertiliser - Biogas production and nutrient content [Schattauer and Weiland 2004]

			Biogas production		CH_4 – Content [Vol.-%]	Nutrient Content				
Substrate	DS	ODS				N	NH_4	P_2O_5	K_2O	Mg
	[%]	[% DS]	[m³/Mg LS]	[m³/MgODS]		[% DS]				
Cattle liquid manure	8-11	75-82	20-30	200-500	60	2.6-6.7	1-4	0.5-3.3	5.5-10	0.3-0.7
Pig liquid manure	approx. 7	75-86	20-35	300-700	60-70	6-18	3-17	2-10	3-7.5	0.6-1.5
Cattle solid manure	approx. 25	68-76	40-50	210-300	60	1.1-3.4	0.22-2	1-1.5	2-5	1.3
Pig solid manure	20-25	75-80	55-65	270-450	60	2.6-5.2	0.9-1.8	2.3-2.8	2.5-3	-
Chicken solid manure	approx. 32	63-80	70-90	250-450	60	5.4	0.39	-	-	-

Renewable resources that are used as part of fermentation are above all maize, grain, turnips and grass or their silages. Silage is always wise since the biomass can only be harvested seasonally and is therefore not available year-round. Through silage the material is processed so that it is available year-round in the same quality.

6.2.1.1 Maize and Maize Silage

Maize has high energy production per hectare. The harvest yield can vary due to climate fluctuations, average is 45 t MS per hectare. Maize silage has only a small portion of foreign and waste particles and can be stored trouble-free. After the completion of the silage phase of four to six weeks it can be directly fermented. The fermentation of only maize is possible, but not recommended due to low process stability. It is better used as co-substrate in liquid manure fermentation. *Table 6.3* shows nutrient content and biogas production.

6.2.1.2 Grain and Grain Silage

It is principally possible to produce silage for fermentation from many different grain types. In this case emphasis is not placed on corn yield, as with the production of foodstuffs, but rather on the biomass yield of the whole plant. An example for potential whole plant silage (WPS) is rye whole plant silage. Rye has low requirements for soil quality and climate. It can therefore be cultivated under unfavourable conditions. It has a hectare yield of around 13-15 t moist substance. Gas production from rye whole plant silage is listed in *Table 6.3*.

6.2.1.3 Beets and Beet Silage

Mangold and sugar beets have a high mass yield and are therefore well-suited as renewable resources, although they require better climate and soil conditions. Beets need deep soil rich in humus and a relatively mild climate. The yield varies depending on the soil quality between five and six tons MS per hectare. There are further type determined variations in the hectare yield with mangolds. Beets and beet leaves are generally easily aerobically degradable. However, they need to be chopped well into small pieces beforehand. The use of beets in fermentation plants requires, aside from cutting, extensive removal of impurities. Stones and clinging soil have to be removed as much as possible in order to limit the inert feed in the fermenter. Since harvesting takes place seasonally the substrate is generally made available throughout the year by ensiling it. Due to the pulpy consistency of beet silage a fixed storage place has to be used. Gas yields and nutrient contents are shown in *Table 6.3*.

6.2.1.4 Grass and Grass Silage

Grass is available in large amounts. Planting and harvesting can be carried out mechanically. Depending on the soil and climate three to five harvests are possible in a year. The harvest yields vary depending on the soil quality, climate, grass type and time of harvest. Hectare yields from 20 to 30 tons MS are indicated [Wetter and Brügging 2004]. Gas yields and nutrient contents are listed in *Table 6.3*.

Tab. 6.3: Renewable Resources- Biogas Yields and Nutrient Contents [Schattauer and Weiland 2004]

Substrate	DS [%]	ODS [% DS]	Biogas yield		CH_4 -Content [Vol.-%]	Nutrient Content		
						N	NH_4	P
			[m³/Mg LS]	[m3/Mg ODS]		[% TS]		
Maize silage	20-35	85-95	170-200	450-700	50-55	1.1-2	0.15-0.3	0.2-0.3
Rye-WPS	30-35	92-98	170-220	550-680	approx. 55	4.0	0.57	0.71
Sugar beet	23	90-95	170-180	800-860	53-54	2.6	0.2	0.4
Maize beet	12	75-85	75-100	620-850	53-54	1.9	0.3-04	0.3
High content Beet	12	75-85	75-100	620-850	53-54	1.9	0.3-04	0.3
Beet-top	16	78-80	approx. 70	550-600	54-55	0.2-0.4	-	0.7-0.9
Grass silage	25-50	70-95	170-200	550-620	54-55	3.5-6.9	6.9-19.8	0.4-0.8

6.2.2 Substrates from Agricultural Industry

Further processing of agricultural products causes the most difficult organic residues, which are usually suitable for energetic use in a fermentation plant. Examples of which are by-products and waste products from beer, alcohol and starch production, as well as waste from the fruit and vegetable processing industry. Particularly these are malt spent grains, alcohol swill from wheat, potatoes and fruit, as well as process water, pomace, pulp etc. *Table 6.4* lists several substrates that come from the agricultural industry. Sources for further information are Schattauer and Weiland (2004) as well as Wetter and Brügging (2004).

6.2.3 Substrates from Municipal Waste Collection

Municipal organic waste is generally suited for fermentation as long as they do not have a too large portion of Lignin or wood-like components. However, the origin of these substrates from the municipal area also implies an increased hygienic requirements, which are provided by legislative framework [BioAbfV 1998, EU Ordinance 1774/2002 etc.]. Similarly certain requirements exist for the use of the produced fermentation products. Depending on the purity of the substrate a more or less difficult removal of impurities is necessary before use. This is true above all for the collected municipal waste.

Tab. 6.4: Agricultural Industry Substrates -Biogas Yields and Nutrient Contents [Schattauer and Weiland 2004]

Substrate	DS [%]	ODS [% DS]	Biogas yield		CH_4 -Content [Vol.-%]	Nutrient Content		
						N	NH_4	P
			[m³/Mg LS]	[m³/Mg ODS]		[% DS]		
Malt spent grains	20-25	70-80	105-130	580-750	59-60	4-5	-	1.5
Grain swill	6-8	83-88	30-50	430-700	58-65	6-10	-	3.6-6
Potato swill	6-7	85-95	36-42	400-700	58-65	5-13	-	0.9
Fruit swill	2-3	approx. 95	10-20	300-650	58-65	-	-	0.73
Pulps	ap-prox.13	approx. 90	80-90	650-750	52-65	0.5-1	0.04	0.1-0.2
Amniotic fluid	3.7	70-75	50-56	15002000	50-60	4-5	0.8-1	2.5-3
Process water	1.6	65-90	55-65	30004500	50-60	7-8	0.6-0.8	2-2.5
Pressed scraps	22-26	approx. 95	60-75	250-350	70-75	-	-	-
Molasses	80-90	85-90	290-340	360-490	70-75	1.5	-	0.3
Apple pomace	25-45	85-90	145-150	660-680	65-70	1.1	-	0.3
Fruit po-mace	25-45	90-95	250-280	590-660	65-70	1-1.2	-	0.5-0.6
Grape pomace	40-50	80-90	250-270	640-690	65-70	1.5-3	-	0.8-1.7

Substrates from municipal waste are especially separately collected organic waste, catering waste and out of date edibles from commercial kitchens and canteens, market waste, slaughterhouse waste and grease skimming tank contents. Characteristics and biogas yield are depicted in *Table 6.5*.

Tab. 6.5: Municipal Waste - Biogas Yield and Nutrient Content [Schattauer and Weiland 2004]

Substrate	DS [%]	ODS [% DS]	Biogas yield		CH_4 –Content [Vol.-%]	Nutrient Content		
						N	NH_4	P
			[m³/Mg LS]	[m³/Mg ODS]		[% DS]		
Biowaste	40-75	50-70	80-120	150-600	58-65	0.5-2.7	0.05-0.2	0.2-0.8
Catering waste	9-37	80-98	50-480	200-500	45-61	0.6-5	0.01-1.1	0.3-1.5
Market waste	15-20	80-90	45-110	400-600	60-65	3-5	-	0.8
Grease skimming tank	2-70	75-93	11-450	approx. 700	60-72	0.1-3.6	0.02-0.15	0.1-0.6
Stomach content (pig)	12-15	75-86	20-60	250-450	60-70	2.5-2.7	-	1.05
Rumen content	11-19	80-90	20-60	200-400	58-62	1.3-2.2	0.4-07	1.1-1.6
Flotate sludge	5-24	80-95	35-280	900-1200	60-72	3.2-8.9	0.01-0.06	0.9-3
Green cuttings	approx. 12	83-92	150-200	550-680	55-65	2-3	-	1.5-2

6.3 Fermentation Process

6.3.1 Anaerobic Degradation

The majority of all natural materials degrade aerobically, the smaller part anaerobically. Sediments of standing water, rice fields, swamps and mostly the intestinal tracts of many animals belong to the anaerobic ecosystems. They include, along with the ruminant animals, a substantial portion of insects, such as ants and termites, worms and other small animals.

Whereas during aerobic degradation, of for example glucose, a bacterium is able to respire the substrate in its cell completely to the end products CO_2 and H_2O, this is not possible under anaerobic conditions. Anaerobic degradation of organic substances to biogas (CH_4, CO_2) takes place in the absence of oxygen in four consecutive steps with the involvement of different bacteria groups.

1. In the first step, the hydrolysis phase, the higher-molecular-mass usually undissolved materials (Polymers) broken down into fragments by enzymes.
2. In the second step, the acidogenese phase, simple organic acids (such as butyric acids, propionic acids, acetic acids), alcohols, H_2 and CO_2 are formed by the fermenting bacteria.
3. This step is referred to as the acidogenesis phase, since mostly acetic acids are formed by the acetogenic bacteria from the previously formed organic acids and alcohols.
4. Acetic acids, as well as H_2 and CO_2 in smaller amounts, are converted to CH_4 by the methane-forming bacteria in the fourth step, the methanogenesis phase.

During fermentation the substrate is split by glycolysis (fructose biphosphate pathway). The results are a reduced product, which absorbs the activated hydrogen, and an oxidised product, usually CO_2. Without oxygen the energy accumulated in the pyruvate is not available for the cells. Therefore, more energy is available for use in cell respiration (aerobic) than in fermentation. Cell respiration delivers altogether 18 times more energy per glucose molecule than fermentation. For this reason many micro-organisms convert their metabolism to aerobic digestion as soon as oxygen is present. Oxygen stops anaerobic respiration processes. Facultative anaerobic bacteria - organisms that receive ATP from both fermentation and respiration - switch immediately over to aerobic respiration, since the process is much more beneficial energywise. Fastidious anaerobic bacteria die upon the inflow of oxygen.

A large part of the acidogens belong to the facultative anaerobic organisms, which are able to grow both in the presence and absence of oxygen. The presence of low amounts of oxygen therefore does not play an important role in the first to phases of anaerobic digestion, the hydrolysis and acidogenese phases. On the contrary, in some two-phase processes oxygen is intentionally added to the first phase to achieve a faster and more effective hydrolysis and acidogenesis. Methane bacteria belong to the fastidious anaerobic organisms, for which oxygen is toxic. In the case of the one-phase fermentation process described later, in which all four phases of anaerobic digestion take place in one container, contact with oxygen should be avoided as much as possible.

A mass balance based on the example of biowaste fermentation is shown in *Figure 6.1*.

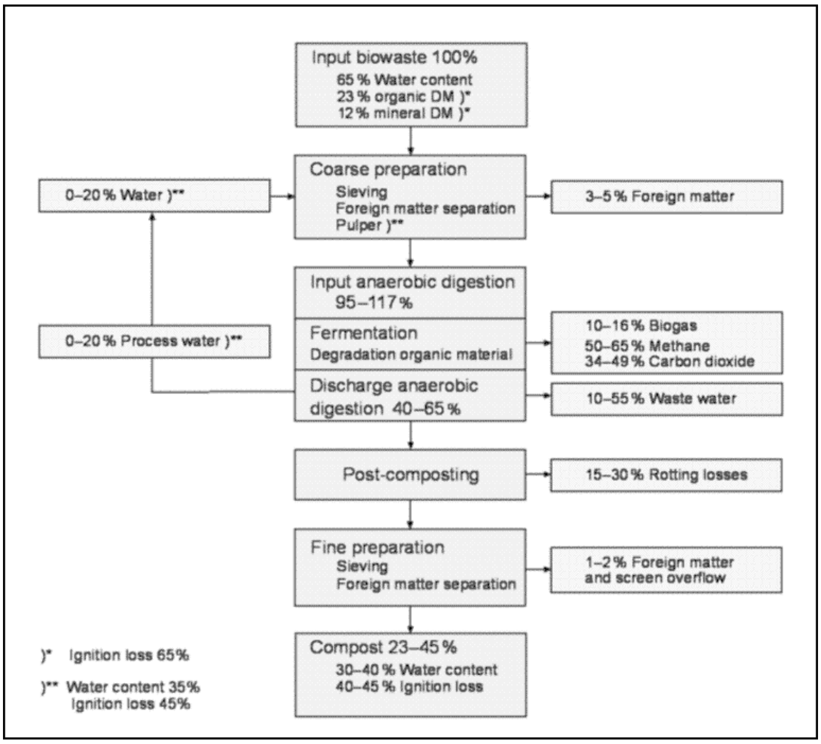


Fig. 6.1: Mass balance biowaste fermentation

An important process parameter for the anaerobic process, as well as in aerobic processes, the nutrient supply of the micro-organisms. Bio and green waste, the fine fraction of residual waste, as well as sewage sludges from municipal sewage plants, usually exhibit a balanced nutrient ratio. In the case of one-sided composed organic waste, such as diverse productions-specific waste, individual materials can be exhausted so that they become limiting factors, especially in anaerobic digestion [Böhnke et al. 1993].

The setting of optimal nutrient contents occurs by mixing proper fermentation raw materials and by systematically adding nutrients as a part of the material preparation and during the fermentation process. The requirements for the surrounding environment are listed in *Table 6.6*.

Tab. 6.6: Environmental Requirements for Fermentation [Weiland 2001]

Parameter	Hydrolysis/Acidogenese	Methane Fermentation
Temperature	25 - 35 °C	Mesophilic: 32 - 42 °C Thermophilic: 50 - 58 °C
pH-value	5.2 -6.3	6.7 -7.5
C/N-ratio	10 -45	20 -30
Solids content	< 40 % TS	< 30 % TS
Redox potential	+400 - -300 mV	< -250 mV
Nutrient requirements C:N:P:S	500 : 15 : 5 : 3	600 : 15 : 5 : 3
Trace elements	no specific requirements	essential: Ni, Co, Mo, Se

The pH-value also has a significant influence on anaerobic digestion of organic substances. The range of tolerance for anaerobic digestion processes lies between 6.8 and 7.5. In one-phase, mesophyllic digestion containers for the treatment of municipal sewage sludge a slightly alkaline pH-value generally appears. Just as with in the area of nutrient needs, material settings with the aim of regulating the pH-value in the raw material can become necessary for the fermentation of diverse production specific waste. Even in the case of poorly buffered sludges the formation of organic acids can lower the pH-value and as a result cause the blocking of methane bacteria [Schmelz 2000].

6.3.2 Process Variations

A large number of process variations and plant types are momentarily on the market. In principle fermentation processes can be sorted according to the dry substance content of the input materials, according to process temperature, as well as the number of process stages and the type of feeding.

6.3.2.1 Wet and Dry Fermentation

Fermentation processes can be separated according to the dry substance content in the reactor input into wet and dry processes. Fermentation processes that treat input materials with a dry substance content of more than 20 up to 25 % are called *dry processing* [Weiland 2003, Köttner and Kaiser 2001].

Wet processing treats input materials with an dry substance content of 10 to 15%. The substrate is mixed by adding process water so that a suspension capable of being pumped and agitated is created. Solid material content above 40 to 45% leads to degradation inhibition as a result of a lack of water, similarly process instability can be caused by a high concentration of volatile organic acids.

The area between 15 and 20% dry substance is referred to as *Semi-dry fermentation*. However, in practice it plays a subordinate role.

Wet processing exhibits advantages over dry processing in the following areas:

use of conventional feed and mix technology is possible,

more favourable substrate mixture in the fermenter,

more favourable conditions for heat and material exchange,

facilitated gas release.

A disadvantage of wet fermentation processing is the larger material flow. It leads to higher throughput , which in turn requires that the instruments and machines be dimensioned larger and have a clearly larger container volume available for storage and the actual fermentation.

The amount of waste water flow in wet and dry processing is similar as long as more water is not added during the process steps. The amount of waste water is determined - in the case of equal organic dry substance degradation - by the water content of the input material as the intended water content following the anaerobic phase. The former is given by the waste raw material and is therefore not specific to the process. The intended water content after fermentation is determined by the drainability of the fermentation residue and the requirements that are dependent on the further treatment, usually the post-composting. The stipulated water content varies, depending on the material structure, between 50 and 60 %.

Dry fermentation is in the development stages, the first prototypes have begun work. Dry fermentation is an alternative if biomass with relatively low water content should be treated and no low viscosity substrate such as liquid manure is available.

Container process: mobile or retractable container fermenters are filled with biomass and composted upon using inoculated substrate under aerobic conditions in a first stage. This process leads to the warming of the substrate. After achieving the desired temperature the process conditions change from aerobic to anaerobic and the produced biogas is fed to energy recovery through a piping system [Scholwin et al. 2004]. *Figure 6.2* shows a schematic representation of a process cycle.

The *Box process* takes place analogue to the container process. The difference lies in the model of fermenter. As opposed to the steel construction of the container process the fermenter in the box process is composed of prefabricated concrete elements [Scholwin et al. 2004].

Plastic wrapping fermentation uses a technique from agriculture for storing feed materials. The material to be fermented is warmed in a plastic wrapping under aerobic conditions. When the operational temperature is achieved the oxygen supply is stopped and the process changes over to the anaerobic sphere. External warming by means of a heat supply from tubes and the base plate and insulation are possible process variations [Scholwin et al. 2004].

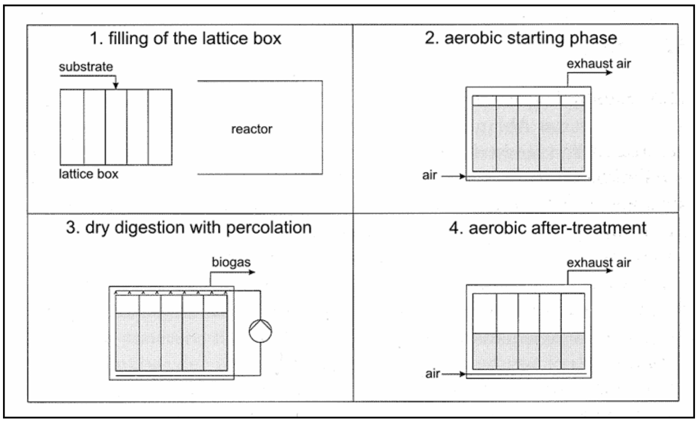


Fig. 6.2: Dry fermentation with slide-in fermenter [Weiland 2004]

Vat and tunnel fermenter make a virtually continuous fermentation process analogue to the wrap process possible. The advantage lies in the improved process control compared to the wrap process.

Plug-flow fermenters exist in lying or standing models for continuous or virtually continuous feeding. Due to the material characteristics the technical complexity for operation is very high. This currently leads to the technique playing a rather secondary role [Scholwin et al. 2004].

6.3.2.2 Introduction According to Types of Flow

In the case of liquid substrate (wet fermentation) processes with plug-flow, complete mixing and special processes can be applied. Anaerobic reactors can be classified according to the type of biomass accumulation and retention:

1. Reactors without biomass accumulation and
2. Reactors with biomass accumulation by
   - separation and retention,
   - allocation of growth area and
   - aggregation of the biomass, for example in the form of pellets and flakes.

Types of anaerobic reactors and their throughput characteristics are described in *Table 6.7* and *Table 6.8*.

Tab. 6.7: Mixture of Aerobic reactors [ATV 1990, Fricke et al. 2003]

Reactor description	Mixture
Complete mixture reactor	mechanical, hydraulic, gas circulation
Plug-flow reactor	mechanical, gas circulation
Sludge bed reactor	hydraulic
Fixed bed reactor	hydraulic, upwards or downwards directed flow through
Suspended bed reactor	hydraulic
Fluidised bed reactor	hydraulic, gas circulation

Complete mixture reactors as slough reactors without bacteria accumulation should be set up with consideration for generation times of the micro-organisms that are involved in the anaerobic digestion process. Slough reactors are usually used for the recycling of substrates with an adequate supply of active biomass, such as in agricultural biogas plants for the fermentation of cow and pig liquid manure.

Plug-flow reactors are used solely for dry fermentation since in a wet process mixng with the wet attentuation substrates can not be avoided. *Plug-flow* reactor process (see *Figure 6.3*) or container through flow plants are usually made up of a lying, round or square container, in which the fresh substrate feed displaces the fermented substrate (plug-flow). The mixing of the material is assured by the mixing machine oriented lengthwise or several horizontal transversely located agitators and/or through the substrate guidance in the fermenter. The agitators have the task of improving the degasification of the fermented material. The actual mixing of the waste with sufficiently fermented material for inoculation already takes place in external mixing units during the dry process.

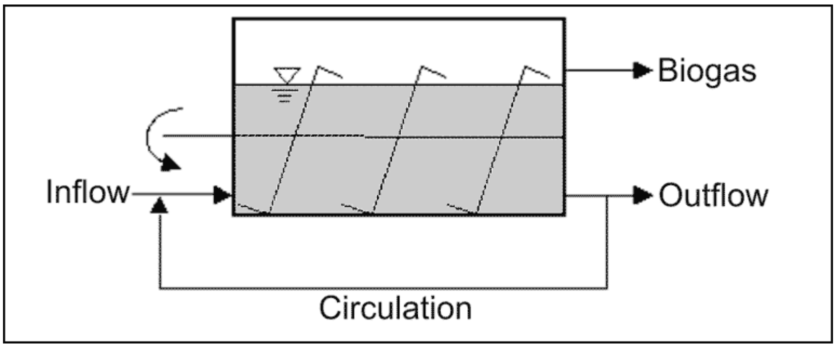


Fig. 6.3: System schema of a Plug-flow reactor [Fricke et al. 2003]

Sludge, solid, suspended and fluidised bed reactors are high-efficiency reactors and are usually applied as methane reactors in two-phase fermentation processes since high degradation capacity can be achieved due to biomass fixing and accumulation.

Tab. 6.8: Description of Anaerobic Reactors [ATV 1990, Fricke et al. 2003]

Process technology	Biomass concentration ratio in the reactor	Biomass enrichment and/or separation	Biomass growth
Flush reactor	marginal differences	without	suspended
Plug-flow reactor	marginal differences	external separation and refeeding	suspended, surface-fixed
Contact reactor (anaerobic activation process)	marginal gradient intended	external separation and refeeding	suspended
Sludge bed reactor	distinct concentration gradient	internal separation and refeeding, aggregation, skimming of aggregated sludge is also integrated	suspended, pellets (aggregated sludge)
Fixed bed reactor	large differences	growth on non-moveable carrier material	surface-fixed, (in the best case: secondary)
Suspended and fluidised bed reactor	marginal differences	growth on moveable carrier material, separation and refeeding internally and externally	surface-fixed, suspended (secondary)

Contact reactors are characterised by the separation of sludge and liquid outside the reactor by means of an external skimmer (for example deposit basin) (*Figure 6.4*). The sedimented sludge phase is refed into the reactor as concentrated biomass. The separation of sludge and liquid can pose a problem, since the sludge tends to float as a result of the on-going fermentation process. The phase separation can be improved by inserting auxiliary materials and mechanical treatment (for example: vacuum de-gasification, agitator application). As a result of the accumulation of the inert materials, which are in sludge, concentration of these materials in the methane reactor is possible, which interferes with the digestion capacity.

Sludge bed reactors, such as the UASB-Reactor (Upflow Anaerobic Sludge Blanket - Reactor) shown in *Figure 6.5* use the improved deposit behaviour of the sludge from the formation of flakes. The substrate is fed from below and flows in the upper part through an internal system of guide plates, in which gas and sludge are separated. Above the guide plates a slow-down zone is created for sludge deposit so that the purified water can be siphoned off from the upper overflow. The reactor is mixed only by the formation of gas. Due to the height of the reactor a sludge gradient is formed. One advantage of the UASB-Reactor is the flooding out of poor-flocculating micro-organisms and accumulation of well-flocculating micro-organisms, since the former are constantly washed out. The degradation rate can reach 45kg CSB/m³ d.

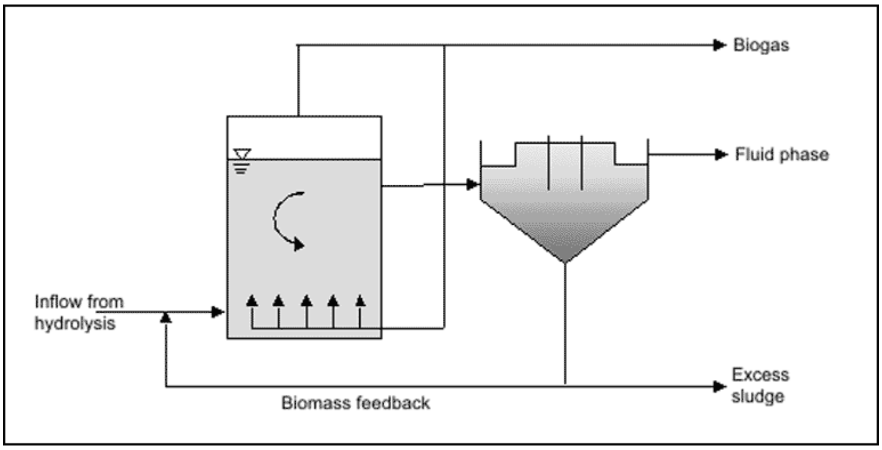


Fig. 6.4: System schema of a contact reactor [Fricke et al. 2003]

Fixed bed reactors or *anaerobic filters* provide the micro-organisms with carrier material with specific higher surface area than growth area. Above all, plastic rings, ceramic, cellular glass, porous stone as loose ballast, as well as sorted fixtures, such as concentrically-sorted slabs, are used as carrier material. Fixed bed reactors are operated in upflow and downflow modus with the respective specific advantages and disadvantages with reference to flow behaviour, CSB-degradation grade, adaptation time and susceptibility to blockage. One differentiates between *upflow and downflow modus* depending on the feeding point in standing fermenters. The differences of the two methods are shown in *Table 6.9*.

The carrier material determines the growth rate, the pore size is decisive for the type and number of biomass to be accumulated. The volume load of fixed bed reactors can be up to 30kg oTS/m^3 d. The hydraulic retention time lies in the area of hours up to around 5 days.

Fluidised bed reactors are equipped with a growth area for the bacteria. The growth areas are made up of materials such as sand with a particle size of 0.2-1mm. *Figure*

6.6 shows a principle schema of this reactor type. The particles are held in suspension due to the high rate of flow of the inserted liquid phase. The thinning effect from the high recirculation rate of the liquid phase helps prevent the inhibition of the process due to problem substances. Since the entire surface of each particle, which is covered with micro-organism growth, is overflowed with substrate an effective surface area of up to300 m2/m3 can be achieved. Fluidised bed reactors are characterised by high bio mass concentration and usually have no problem with canal formation, agglutination of particles and gas discharge. Due to the good separation from the solid phase high throughput rates can be achieved.

The feed location for the raw substrate and the removal of the fermented attentuation residues orient themselves on the type of mixture and the form of the attentuation reactor. In the case of feeding of thoroughly mixed reactors the substrate is generally added to the area with the most circulation. It is then possible to mix the raw substrate with the material already in the reactor as quickly as possible. The fermented substrate is pulled as much as possible into the areas that require extensive digestion. An exception is the lying attentuation reactors, which are run with a so-called plug-flow.

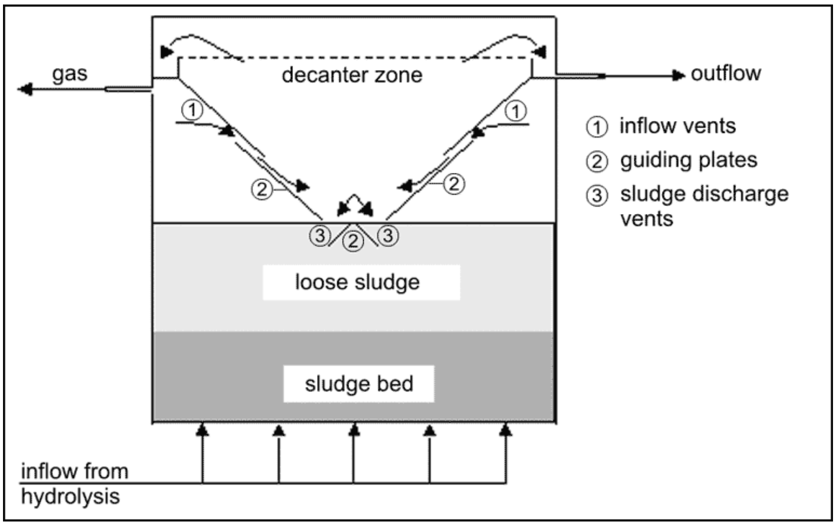


Fig. 6.5: System schema of a USAB reactor [Fricke et al. 2003]

Tab. 6.9: Comparison of Upflow and Downflow Modus

	Upflow modus / Anaerobic Filter	Downflow modus / Fixed-Film-Reactor
Advantages:	Flow behaviour without rotation, therefore more biomass accumulation	Flow behaviour with rotation, therefore better mixing
	higher CSB degradation rate	more even flow dispersion
	Start phase in less than 3 months	not as susceptible to shock treatment
	Biomass gradient from bottom to top, discharge potential for sludge	
Disadvantages:	susceptible to shock treatment, since less thoroughly mixed	less biomass load, due to abrasion through rotation
	if stones as fill material there is the danger of blocking in the lower part (not the case with plastic rings)	lower CSB degradation rate
	susceptible to uneven flow dispersion with canal formation	Start phase over 3 months
		Effluent quality is more sensitive since there is no buffer gradient

The feeding and removal usually takes place nearly continuously. The rule is: the more difficult a substrate is to digest (for example: light acidification, high protein content), the more carefully it has to be dosed. Overloading the system should be avoided. The more evenly the dosage is carried out, the more even the produced biogas amount and quality are. To avoid foam formation water and steam pipes are sometimes mounted on the upper container edge and/or underneath the roof [Fricke et al. 2003].

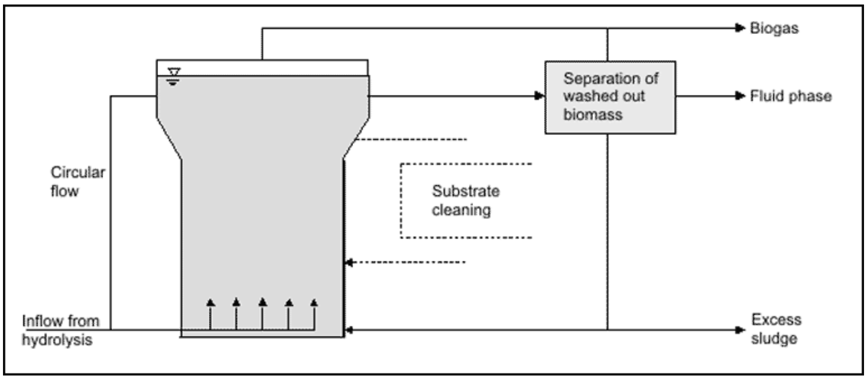


Fig. 6.6: System schema of a fluidised bed reactor [Fricke et al. 2003]

Fermentaion processes with complete mixture are generally used in agriculture. Most of the standing reactors have a cylinder form and correspond to the form and construction of normal liquid manure storage containers. The mixing is assured by stirring, which are affixed in or on the reactor [Scholwin et al. 2004].

The substrate mixture by *double chamber processing* can be given as an example of a special process, in which the mixture of attentuation materials is assured by the pressure difference resulting from the gas production. These process have, however, only regional relevancy [Scholwin et al. 2004].

6.3.2.3 Classification According to Temperature

The total digestion can not be performed by one organism as is the case under aerobic conditions, but instead from several different organisms in a food chain. The participating organisms are linked to one another through syntrophic relationships. Nutrient mechanisms with mono and bi-directional substrate transmittal occur alternatingly. Different organisms are responsible for the digestion of organic substances in anaerobic processes. Their type, capacity and specific tasks are, among others, dependant on the process temperature. In the thereby occurring microbial processes three closely defined temperature ranges exist, in which the respective organisms exhibit their optimum capacity:

Psychrophilic temperature range < 25°C
Mesophilic temperature range 30-37°C
Thermophilic temperature range 50-60°C.

Psychrophilic fermentation plays a subordinate role in the local latitudes. Slow digestion procedures and the related large container volume make the process seem generally uneconomical unless existing containers can be used.

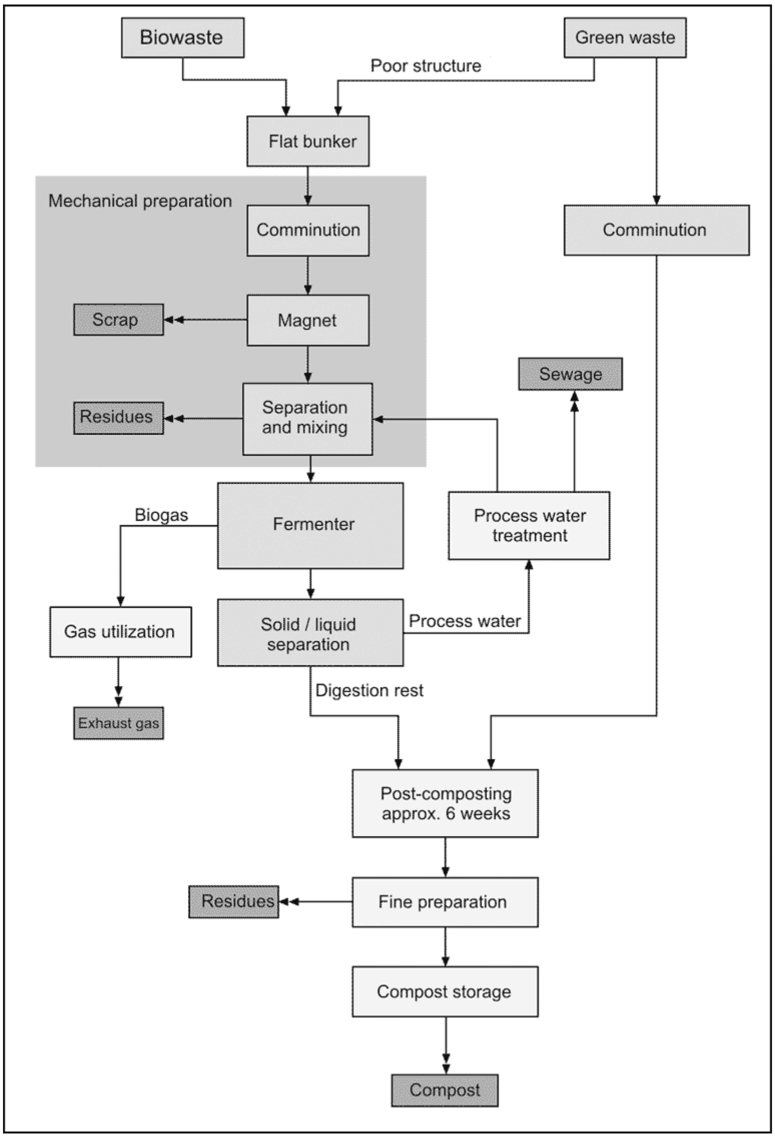
Mesophilic process behaviour is characterised by high process stability due to the fact that more microbial diversity exists and the inhibiting effect of ammonium nitrate is not as strong as a result of a smaller amount of free ammoniac [Weiland 2001].

Thermophilic process behaviour leads to higher digestion rates compared to *mesophilic process behaviour*. The higher process temperature leads also to improved microbial availability of fatty substrates and thereby a higher gas yield and if the retention time is sufficient even to a higher level of hygienisation. The higher thermal energy demand in thermophilic processes generally does not represent a real disadvantage in comparison with mesophilic operation since the excess energy can simply be used under special constraints depending on the plant location. The comparatively wide temperature corridor for thermophilic anaerobic digestion from 50-60°C is based on results that were acquired from residual waste fermentation [Fricke et al. 1999].

6.3.2.4 Classification According to Process (one, two or multiple phases)

Figure 6.7 shows the schematic process procedure for a one-phase and two-phase fermentation process with subsequent post-composting of the attentuation residues.

In some cases it might make sense to spatially separate the biological phases. In a two-phase process the hydrolysis and the acidification of the methane are separate. The first phase of the hydrolysis of the attentuation material is measured so that the retention time corresponds to the growth cycle of the hydrolytic and acid-forming micro-organisms. The hydrolysis takes place so rapidly with easily hydrolysible substrates that no or only a very small amount of methane bacteria can be formed [Kaltschmitt and Hartmann 2001].



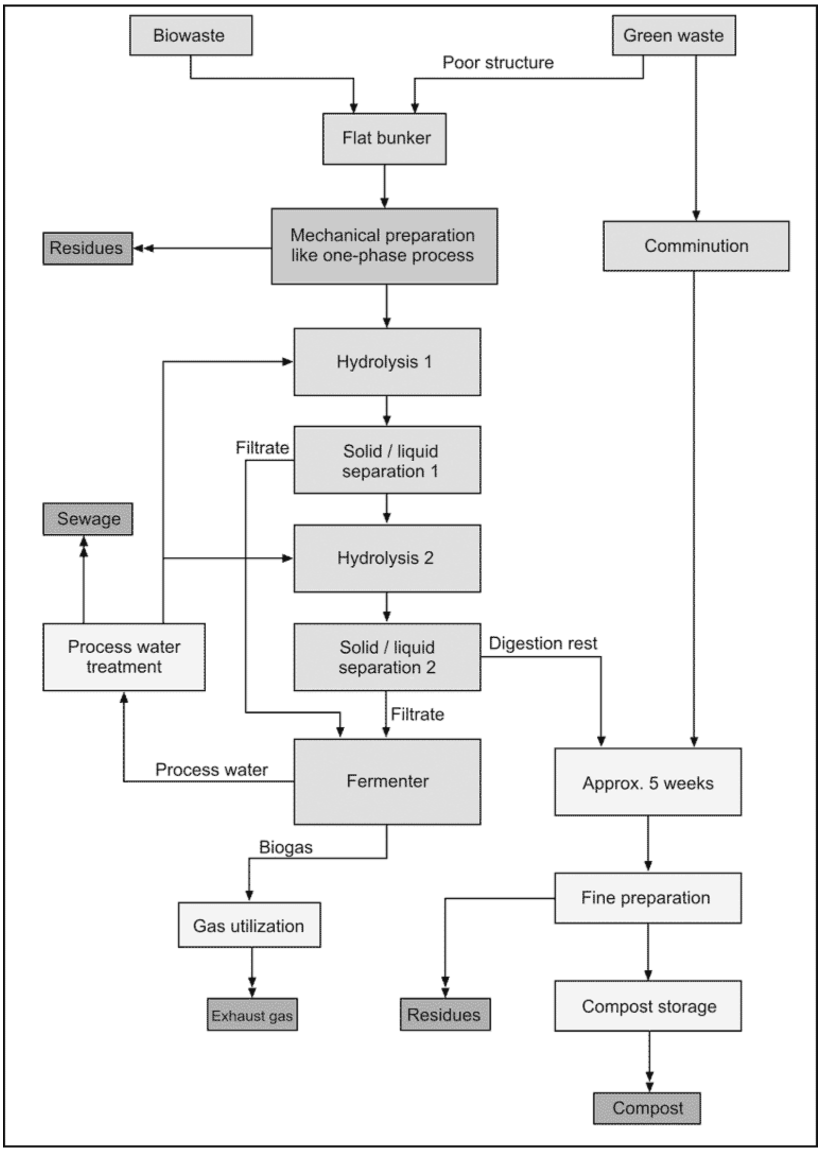


Fig. 6.7: Schematic procedure for one-phase (top) and two-phase fermentation processes (bottom)

The mass balances of one and two-phase processes are only marginally different. Examples of both process variations are shown in *Table 6.10*.

The portion of the attentuation residues lies on the average at 40 - 60 Weight-% of the input. The differences between large and small plants are negligible.

Two-phase plants have an advantage based on the fact that due to the spatial separation of the different fermentation phases both can be carried out under ideal conditions. This leads to improved usage of the input biomass with respect to the gas yield. The disadvantage is, however, the increased sensitivity to substrate fluctuations and other external influences.

Tab. 6.10: Mass Balance of One and Two-phase Fermentation Processes (Selection)

Parameter	Unit	One-phase process	Two-phase process
Input Biowaste	[%]	100	100
DS Input	[%]	25 - 30	25 - 30
Input Water	[%]	0 - 20	0 - 15
Physical contaminant	[%]	< 5	< 5
Attentuation Residue	[%]	40 -70	40 - 65
DS Attentuation Residue	[%]	30 -40	30 - 40
Waste water	[%]	20 -45	25 - 60
Biogas	[%]	10 - 20	5 -20
Specific gas production	[m^3/Mg]	280 - 550	180 -580
CH_4 -content	[%]	60 -65	60 - 70
Degradation DS	[%]	35 -45	35 - 50
Degradation ODS	[%]	50 -55	45 - 70
Compost	[%]	25 -45	30 - 45
DS Compost	[%]	50 -60	35 - 50
ODS Compost	[%]	40 - 50	40 - 50
Rotting grade	[]	IV	IV

In *Table 6.11* and *Table 6.12* the throughput dependent energy use and the corresponding specific energy production are reflected.

Tab. 6.11: Specific energy consumption of selected one and two-phase fermentation processes in [MWh/Mg] with reference to the input

Parameter	One-phase process	Two-phase process
Small plant	0.1 -0.16	0.07 - 0.15
Medium plant	0.1 -0.2	0.07 - 0.15
Large plant	0.1 -0.16	0.07 - 0.20

Tab. 6.12: Specific energy production of selected one and two-phase fermentation processes in [MWh/Mg] with reference to the input

Parameter	One-phase process	Two-phase process
Small plant	0.5 -0.73	0.27 - 0.49
Medium plant	0.54 - 0.75	0.28 - 0.70
Large plant	0.53 - 0.74	0.28 - 0.72

6.3.2.5 Types of Feeding

The type of feeding determines the availability of substrates for micro-organisms. One can generally differentiate between continuous, semi-continuous and discontinuous (batch) feeding.

6.3.2.6 Discontinuous Feeding

One can differentiate between exchange container and batch procedure with discontinuous feeding. Discontinuous feeding is mainly used in the dry fermentation process.

Batch procedure: The fermenter is filled completely with substrate and closed gastight in the batch procedure. After the retention time is over the fermenter is emptied and filled with fresh substrate. A portion of the fermented substrate remains in the container as inoculation material. During the fermentation process neither fresh substrate is added nor fermented substrate removed. In order to speed up the filling and emptying operations a storage container for the attentuation residue and a supply container for the substrate are necessary.

The gas production is not constant in the batch procedure, it begins slowly after filling, reaches a maximum and decreases again afterwards. It is as such not possible to achieve constant gas amounts and quality. The desired retention time is determined by the size of the container.

Exchange Container Procedure: Two fermenters are used in this procedure. The first container is filled slowly, during which the material is digested in a second fer menter. When the first container is completely full the digested material is removed from the second container and filled into a storage tank and the second container is then finally slowly refilled from the first. Constant gas amounts and qualities can be made possible by the use of several digestion containers.

6.3.2.7 Continuous and Semi-continuous Feeding

Principally, continuous and semi-continuous procedures can be classified as flow-through, storage and combined storage-flow procedures. In semi-continuous feeding a certain amount of fresh substrate is fed into the fermenter at least once, but usually many times a day.

Flow-through procedures: The substrate is added to the fermenter from a collection container, while at the same time the same amount of digested substrate is removed from the fermenter The fermenter is constantly full in this procedure. The attentuation container has to be emptied for emergencies and repair. The even gas production and well-used capacity of the containers are advantages of this procedure variation. Input and output openings in the fermenter have to be arranged so that bypass flow is not as possible, in other words that unfermented material is immediately removed after application.

Storage procedure: Only one container is used in this procedure as fermenter and for attentuation residue storage. The container is emptied when the substrate is fermented.

Whereby the amount necessary for the inoculation of fresh substrate remains. Afterwards the container is filled once again. This procedure is advantageous with longer retention times, although due to the batch operational method the gas production is not as constant.

Storage-flow procedure: In this procedure both previously described procedures are combined and the attentuation residue storage container is covered. This procedure makes the gas production more constant, but bypass flow in the through-flow fermenter can not be ruled out.

6.3.2.8 Summarisation

The consideration of microbial fundamentals, such as the sequential degradation of organic compounds and the specific environmental conditions of the involved mi-cro-organisms, leads to a plethora of potential procedure variations. The procedure variations that are preferably used in practice are exhibited in *Figure 6.8*.

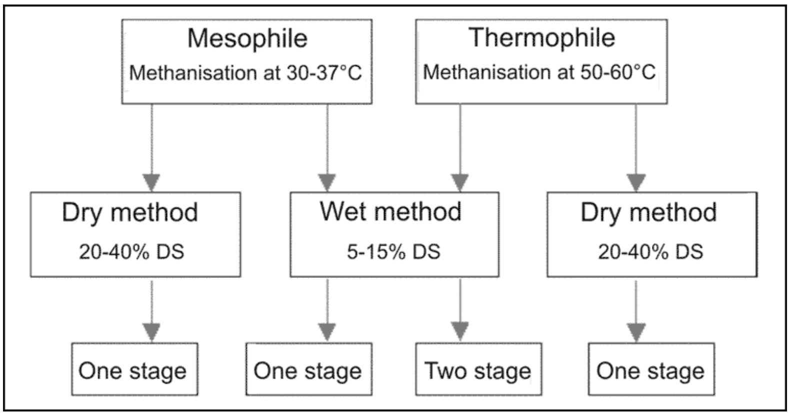


Fig. 6.8: Typing of fermentation procedures according to process management

6.4 Delivery, Storage, Processing and Transport

The technical equipment of a fermentation plant depends, above all, on the substrates to be treated, their quality with respect to foreign materials. In treating municipal biowaste foreign material separation is usually necessary since this waste contains between 2 and 5 weight-% foreign materials. The treatment of pure mono-charges from the agricultural industry or farm operations that recycle their own organic waste usually do not require foreign material separation.

Depending on the type of substrate it could be useful to mix the input material with water or process waste water. If hygienically problematic materials are used a hygienisation phase has to be applied. Mechanical pulping of the material, usually through milling, can also be handled as a separate processing phase.

The delivery in the use of co-substrates, especially materials declared to be waste, it is necessary to control and document the input to meet detection requirements. The input control is usually carried out visually, the evaluation by weighting the delivered materials. Administrative and legislative general conditions are described in detail in Matthias (2004), and Wetter and Brügging (2004).

6.4.1 Storage of the Input Substrate

The *storage* of the input materials compensates for the seasonal fluctuations of input availability.

The construction of the substrate storage container is based on the fermenter capacity, area availability and substrate characteristics; fluid materials are stored in containers that are constructed modelled on the fermenter or designed as a silage trailer. The size of the input storage container is based on the intended plant through put, amount of accrued co-substrates and potentially agreements with the suppliers of co-substrates. Different types of bunker systems are used for the interim storage of the delivered waste. The following construction methods are significant in practice: Flat bunker, low bunker, combined flat/deep bunker, direct feed bunker, tanks and silos.

In *flat bunkers* the loading and bunker area are on the same level. Loading vehicles unload the waste directly in the flat bunker. As a result specific waste qualities or types can be stored in special segments or boxes. In this way they can be used systematically quantitatively or added to the input material at special feed points. Systematic material separation into fermentable and non-fermentable waste components is possible in this concept in the bunker area. The transport of the input is usually carried out with a wheel loader.

Deep bunkers are usually used for the storage of residual waste. The delivery trucks unload the waste directly onto a dumping edge in the bunker. The layout is created based on the required storage capacity, the required tilting space, area availability and the building soil. The transfer of the material for processing to avoid bridge building and wedging make the use of a deep bunker more difficult. Systematic material separation into fermentable waste components is not possible in this bunker concept.

Combined flat/deep bunker concepts combine the advantages of both types. The delivery truck empties the residual waste over a pivot edge with a height of max. 3m into a flat bunker. The material feed in the processing or interim storage boxes takes place based on the type described for the flat bunker.

In *direct feed bunkers* delivery trucks empty directly, depending on the delivery frequency, into one or more bunkers located next to one another at ground level furnished with a discharge conveyor. Chain belts and steel plates have been maintained as conveyors. This bunker type can be integrated into the closed receiving area or installed separately. In the case of the latter the direct feed bunker should be constructed entirely enclosed with exhaust air ventilation.

The material characteristics of liquid and pasty waste usually make it necessary for it to be stored separately from the solid waste. This waste is then generally pumped directly through a tank nozzle into a *sludge silo* or tank by the delivering vehicles in order to avoid odour emissions. The containers are continuously or periodically mixed to inhibit the formation of suspended and sink layers, as well as sediments. Catering and canteen waste are delivered in separate water-tight trash bins, large trash containers or boxes, which are usually emptied directly into the feed funnel of a pulping mill. The necessary cleaning of the emptied transport container should take place as soon as possible in the delivery hall as long as the transport vehicles do not have their own container cleaning [ATV 2003, Fricke et al. 2003].

Sealed areas are usually sufficient for solid substrates and co-substrates from farms and the agricultural industry. Substrate storage containers should be dimensioned so that service intervals and operational disturbances can be compensated. In order to minimise odour emissions substrate storage containers are usually closed in i.e. are located in halls that are equipped with an appropriate exhaust air purification system.

Hygienically problematic substrates can not be mixed with safe materials. This should be guaranteed by strict separation during storage.

6.4.2 Fundamentals of Substrate Processing

The *processing* of the fermentation substrate influences the energy utilisation and along with it the fermentation process, as well as the quality of the end products, the digestion residues. By material processing the following (broken down into steps) is understood: foreign material separation, mechanical digestion by means of milling, the separation of material flows and homogenisation and/or mashing. A hygienisation phase can also be applied before the actual fermentation process.

The processing can be categorised into dry and wet processing depending on the implemented fermentation technology. In which case "*dry*" means that the source materials are processed in their delivered state without the addition of process water. Wet processing means that the materials are treated with the addition of process water or already have such a high water content that they are pumpable. *Table 6.13* gives an overview of the potential processing procedures.

Procedure steps in the processing of the input are milling, sieving and metal separation. These steps are carried out by standard units, just as they are used in building material and resource processing.

Tab. 6.13: Mechanical processing possibilities for substrates [Fricke et al. 2003]

WET	DRY
Magnet separation Inductive metal separation	Hand sorting Magnet separation Inductive metal separation
Sink/suspension separation	
Wet sieving / percolation	Sieving
Wet milling	Milling
Dissolution	Homogenisation drum
Waste-pulper	
Hydrocyclone with up-current classification	Air classification
	Ballistic separator

6.4.2.1 Material and Disturbing Additive Separation

Foreign material separation is only necessary when it is to be expected that the input material contains foreign materials, such as plastic, metal, glass etc., as well as disturbing additives, for example stone. In which case the separation of waste material that could potentially interfere with the fermentation process is indispensable. The transportability of the waste within the feed system should be ensured.

The first inspection for foreign materials and their removal takes place upon delivery. During mechanical processing the foreign materials are sorted systematically mainly with the use of sieve levels, sorting stations and metal separators. Coarse and bulky waste or waste components, such as green cuttings, are chopped before feeding in order to ensure transportability in the in the feed system; packaging such as refuse sacks are opened either with a sack opener or due to the chopping process.

Foreign material removal is essential in biowaste recycling especially with respect to quality of the fermentation residues and their use in agriculture as fertiliser. This can usually only be guaranteed in dry processing by manual sorting of the entire input flow on a sorting conveyor belt and with the accumulated foreign material sieve overflow at a special sorting station.

Wet processing methods use physical material properties, such as the swim-sink principle, individually also in connection with sieve layers. Coarse heavy materials (for example cullet, stones, Ne metals and Fe metals) are extracted after a mashing process through the heavy material sluices on the floor of the processing container. Floating coarse foreign material (for example plastics, textiles, wood) are extracted through so-called light material rakes or separated through special wet sieve layers.

6.4.2.2 Material Flow Separation Before Biological Treatment

Individual waste components are partially suited for different recycling and treatment processes. Material flow separation is targeted at making the most suited treatment for the different types possible.

With mechanical-biological conditioning processing (residual waste) components rich in heating value in particular are separated and fed into the thermal treatment and/ or energetic recycling. The Fe and Ne metal extraction takes place with the goal of metal recycling and removal of harmful materials.

It has been proven to be useful to separate the input in aerobic and anaerobic degradable waste with respect to the post-composting of the fermentation residues that is practised at most of the fermentation plants. With biowaste recycling a material flow separation can also take place as an additional aid for foreign material removal.

6.4.2.3 Confectioning

The main goal of confectioning is to ensure ideal degradation conditions. Confectioning of the material before the actual fermentation can encompass the following steps:

- Chopping to improve the material's thermal digestion and transportability;
- Setting the desired nutrient and water content;
- Homogenisation/mashing to set the desired water content and improve the transportability

Dry conditioning includes sieving and chopping. Particles sizes from max. 30 - 40 mm are set. This takes place through combined sieve and chopping steps.

Due to sieving the particles are classified into given particle sizes. If particular waste components are mostly found in certain particle class they can also be sorted out through sieving.

Drum sieves are generally used in biological processes. In the mechanical conditioning step for municipal waste the implemented sieve size usually between 100 and 150 mm for unchopped waste, and normally 80 -100 mm for pre-chopped waste. The use of sieving with a sieve size of 40 mm immediately before the fermentation step allows the chopping phase to be skipped [Fricke et al. 2003].

ODS: Organic Dry Substance

DS:	Dry Substance
MS:	Moist Substance
UASB:	Upflow Anaerobic Sludge Blanket - Reactor
CHP:	Combined Heat and Power Unit eqivalent to BHKW
AbfAblV (2001):	German Waste Disposal Ordinance
TA-Luft:	Technical Instructions for Air Purification

6.5 Fermenter for Fermentation Plants

Reactor Systems, Fermenter Construction Forms

Form and design of reactors is determined based on diverse factors such as the type of mixing, necessary discharge techniques for sink and swim layers, substrate characteristics and built-in components. The accumulation of sediments in the reactor should be avoided for disruption-free operation. The discharge systems for the removal of sediments from the reactor space should be planned, if accumulation due to the mixing components can not be avoided with certainty. Standing cylindrical reactors are sometime equipped with a conical reactor floor that allows for the removal of sedimented material in its point. Difficult constructive designs can be avoided if the reactor floor is planned with, for example, a small slope. The sediments are transported to the centre due to the so-called "tea cup effect" and can be selectively removed there. A further possibility lies in the cone-shaped design of the reactor floor, through which the sediments make their way into outer-lying sloped gutters. The sediments are removed from the fermentation space at two places opposite of one another with the use of feed spirals. Discharge devices can also be carried out in the form of a drawer or similar mechanical apparatus. This discharge devices are used, for example, in lying plug-flow reactors. The avoidance of accumulation is also possible with the directed addition through pressing of fluids or substrate.

The reactors are carried out in concrete as well as steel construction. The construction of steel containers is composed of , for example, enamelled or epoxy-coated, welded as well as screwed steel sheets made of black or stainless steel. The type and execution of the coating of the reactors is determined mainly by the surrounding conditions. The reactor roofs are constructed from steel as well as glass fibre reinforced plastics. The roofs of reactors in agricultural biogas plants are often carried out as membrane roofs made of fabric strengthened plastic film, which at the same time can be used as for biogas storage since it is equipped with an inner membrane.

In the roof and cladding area the reactors are generally carried out with insulation, but not usually in the floor area. The implemented insulation materials are usually mineral wool, PU-foam etc. The reactors located in unsheltered areas require that the insulation be covered with weather protection. The reactors are generally cladded with aluminium or steel sheets as weather protection.

The design of the reactors is usually set up for an over pressure from 2-50 mbar, since low pressure is not possible in tempered usual operation. The substrate mixture due to the pressing-in of biogas can, however, lead to pressure fluctuations. Securing the containers for over and under pressure takes place with hydraulic or mechanical safeguards. An additional design criterion for the reactor are the mixing devices, sludge pockets, occurring loads, etc. (ATV 2003).

Heating and Insulation

Fermenters are usually planned with *insulation*, in order to minimise heat loss. Customary insulation materials can be used. However the insulation materials have to exhibit suitable characteristics depending on where it is implemented, for example near the floor. Fermenter insulation layers are usually covered with, for example, metal plates as weather protection.

Anaerobic processes generate little warmth as compared to aerobic processes so that the substrate warming is necessary in order to maintain the process temperature. The practically relevant process temperatures lie at 30-37°C in mesophilic and 50-60°C in thermophilic areas. The necessary thermal energy is usually available through the use of the waste heat that is created by the use of the biogas in combined heat and power unit (CHP).

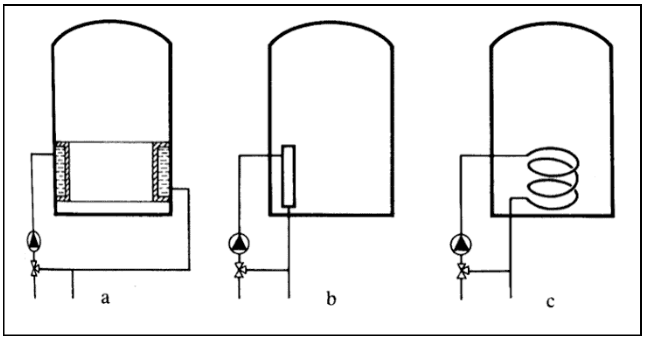
Cooling water from the motor and the emission gases from the CHP at a temperature level of 85-95°C are usually the carriers of the heat. Warmth for use is usually available in sufficient quantities due to the location specific conditions and the lack of other possible uses. Warmth for use at a higher temperature level can be realised through separate usage of the emission gases from the incineration motors that occur at approx. 420-460°C. Approx. 35-40% of the thermal warmth for use is obtained from the emission gas warmth.

The temperature level from 85-95°C is for the availability of process warmth sufficient. Further requirements for product hygiene, such as the hygienisation of catering waste at 70°C for more than an hour, can be realised at this temperature level. The processing of waste that has to be sterilised according to the animal carcass disposal law requires additional technical output. The required temperature level of 133°C has to be maintained for a time period of at least 20 minutes and operational pressure of 3 bar in the sterilisation unit. This temperature level can no longer be directly achieved through the use of the warmth from the cooling cycle of the standard CHP. The sterilisation can take place by the injection of steam directly into the material or the heating of the material on a heat-conducting surface [ATV 2003]. The selection of the heat-conducting system is fundamentally dependant on the type and material characteristic of the substrate. In fermentation double pipe and spiral conductors are preferable used, in individual cases also plate conductors [Fricke et al. 2003].

Double pipe heat conductors exhibit a substantially larger construction form and along with it a higher spatial need due to the lower heat-conductivity coefficient as opposed to the spiral conductors.

Spiral conductors should be constructed with canal heights of 25-50 mm with the use for the heating of waste suspension. Apart from that distance pins should be avoided in the production-side canals since the build-up of plugs through fibre materials could be caused [Langhans 2000].

Bio and residual waste tend to from crustaceans on heat-conducting surfaces that have to be removed with a more or less a high amount service and cleaning time and effort. The soiling causes a decrease in the heat conductivity of up to 50% of the theoretical value and should therefore be considered during development. The improvement of the service friendliness and the extension of the standing time are the most important factors in the diverse special constructions of heat conductors. As such rotating brushes are sometimes used on the product-side cleaning of concentrated heat-conducting surfaces. The built-in possibilities in such systems are, however, limited so that only a situation analysis can decide on a sensible application [ATV 2003].



a double coating

b heating wall

c heating spiral

Fig. 6.9: Schematic representation of a fermenter heating system [Wellinger et al. 1991]

Pre-heating of the fermentation material is preferably carried out in wet and dry processing with a heat exchanger located before the actual fermenter. *Figure 6.10* through *Figure 6.11* shows a schematically representation of the methods for preheating the fed fermentation substrate.

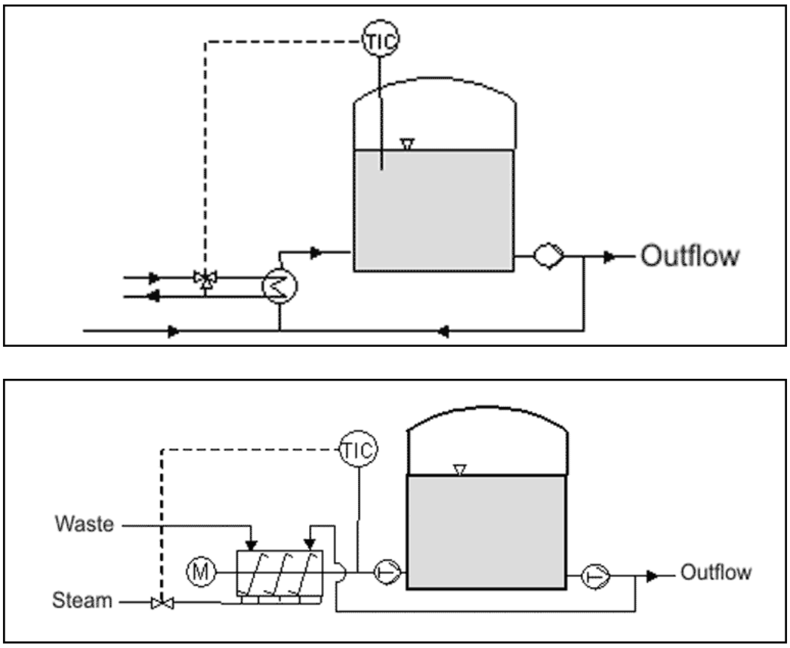


Fig. 6.10: Upstream substrate heating (top) and heating by steam injection (bottom) [Fricke et al. 2003]

Pre-heating the fermentation material in dry processing takes place in several processes through the injection of steam into the material. The steam is thereby simultaneously used for thinning the fermentation material and setting the necessary dry substance content. Doing without pre-heating can be achieved by using the own warmth from aerobic processes. For this the waste is specifically aired into a container and the aerobic process is set into motion. Exact setting of the necessary process temperature is, however, only possible to a limited extent with this method.

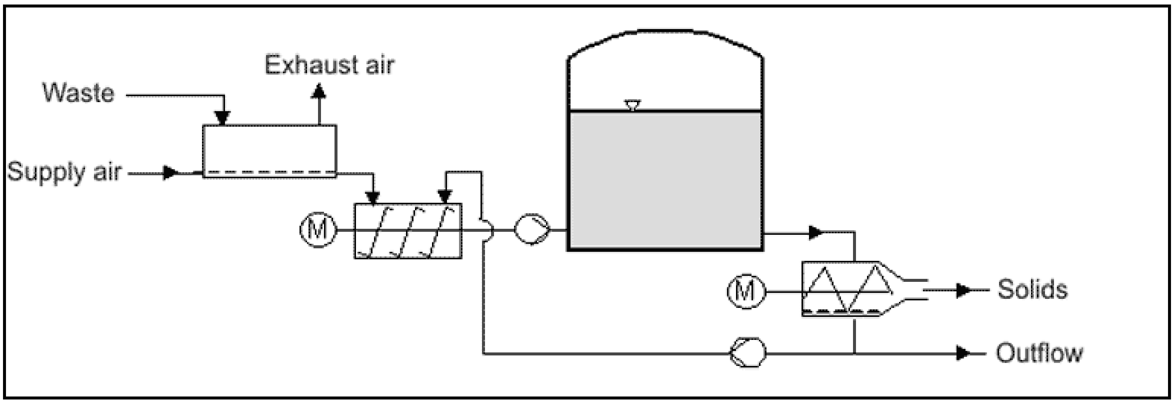
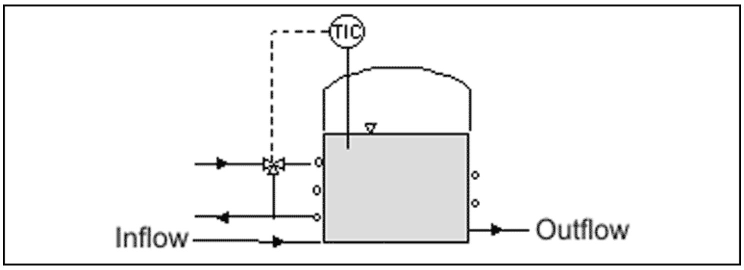


Fig. 6.11: Biological substrate heating [Fricke et al. 2003]

Heat exchangers can be located inside or outside. The heat exchangers are realised in steel-construction reactors by inside or outside welded on heating lines, while the heating pipes in reactors constructed in concrete are poured onto the container wall or circulate it (accordingly *Figure 6.13*). Inner-lying heat conductors can be constructed as pipe with double coating (*Figure 6.12*), which is equivalent to the principle of a double pipe heat exchanger. A further possibility is heating the reactor content on a outer-lying heat conductor together with the reactor feed.



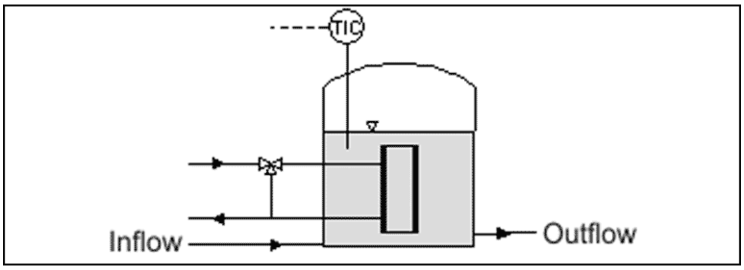


Fig. 6.12: Outer-lying heating pipes (top) and inner-lying pipeline with double coating (bottom) [Fricke et al. 2003]

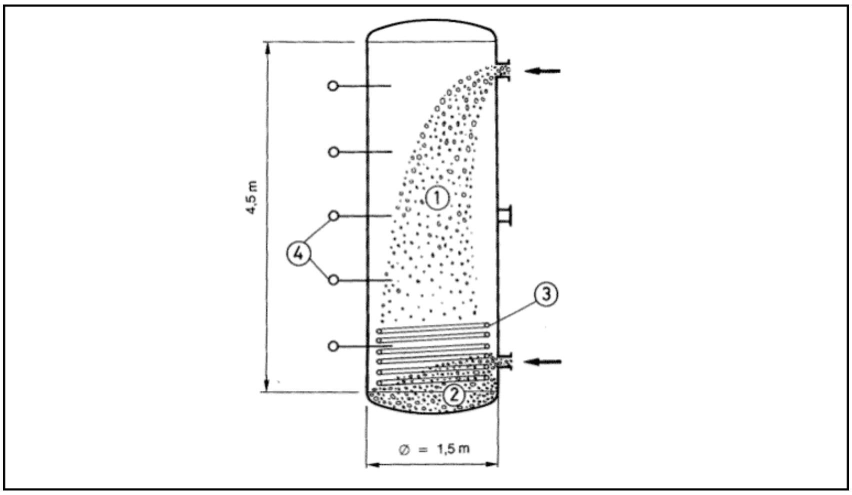
In practice mixed forms of the described systems are generally used. The sole heating of the fermentation substrate in feeding makes overheating the input necessary so that the warmth content balances out the heat loss of the fermentation reactor. The heat conductivity has to be set depending on the cycle dose amount, since due to processing technical reasons a semi-continuous feeding often takes place. The heat conductivity efficiency can be designed as less if the heat conductor is continuously operated in the bypass.

Fig. 6.13: Inner-lying fermenter heating

Heat recovery from the procedure of the fermentation phase is only possible to a limited extent, such that due to the incomplete potential recovery additional heating is necessary for heating the substrate and balancing out the heat loss through the reactor walls. The first heat conductor with added substrate requires thereby more service [Fricke et al. 2003].

Mixing Technology

The substrate in the piping system, storage container and fermenter have to be kept constantly fluid to avoid floating blankets, clogs and sediment accumulation. In the fermenter the substrate has to be as homogeneous as possible in order to offer the degrading organisms as much surface area as possible and a regular supply of nutrients. Fermenters can be actively mixed with the use of stir technology. A passive mixing also takes place along side it due to thermal convection, the introduction of substrate and gas bubbles rising. *Figure 6.14* shows the distribution of the fresh substrate in the fermenter while feeding from the top and from the bottom.



1 substrate

2 excess sludge

3 heating

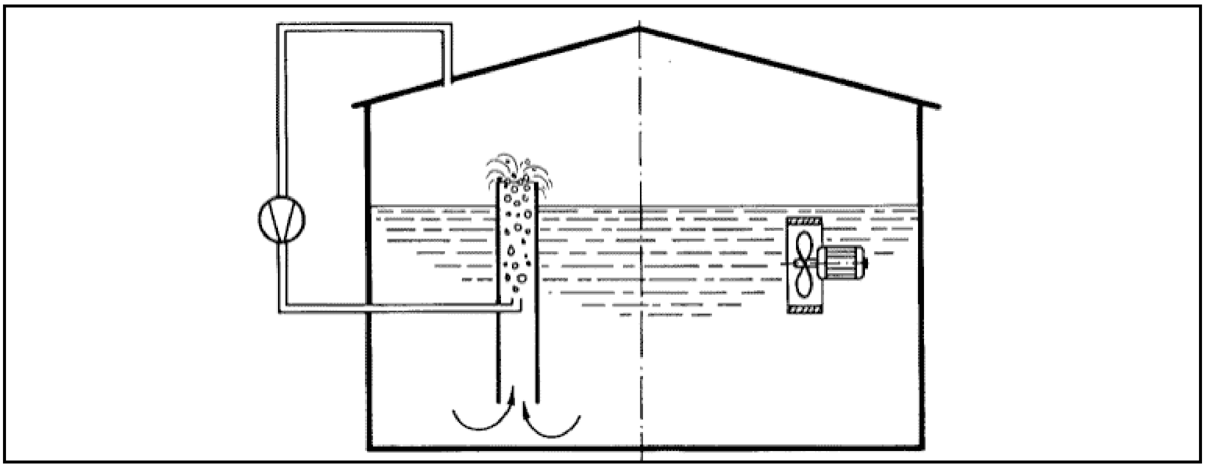
4 biogas injection

Fig. 6.14: Substrate Distribution in the Fermenter [Wellinger et al. 1991]

The mixing in the fermenter has the aim of preventing the formation of a floating blanket and/or executing their destruction. Mixing facilitates the gassing out of the generated biogas. Furthermore the fresh fed substrate has to be mixed with the fermentation residue as quickly as possible. Floating blankets usually can not be destroyed with thermal convection.

Most substrates cause a floating blanket within a few hours due to the floatation of solids on the surface. In order to avoid the disruption of the fermentation process due to the floating blanket the floating particles in the liquid have to be remixed and continuously discharged.

Thorough mixing take place *mechanically* with stirring units, *hydraulically* with externally attached pumps or *pneumatically* with the injection of biogas. As mechanical stirring systems propeller stirrers (in the central pipe or from submerged motor stirrers), winch stirrers and paddle stirring units. An example of pneumatic mixing is the mammoth pump. Principle sketches for a mammoth pump and a submerged motor-propeller stirring unit are shown in *Figure 6.15*.



left Mammoth pump
right Submerged propeller stirrer

Fig. 6.15: Mammoth pump and Submerged Propeller Stirrer [Wellinger et al. 1991]

Mechanical stirring systems can be classified into fast, middle and slow-moving systems. Stirring units are implemented in continuous or interval operation. The type of operation has to be determined individually for each fermentation plant depending on the substrate characteristics, container size and construction type. *Figure 6.16* shows a schematical representation of diverse stirring technology.

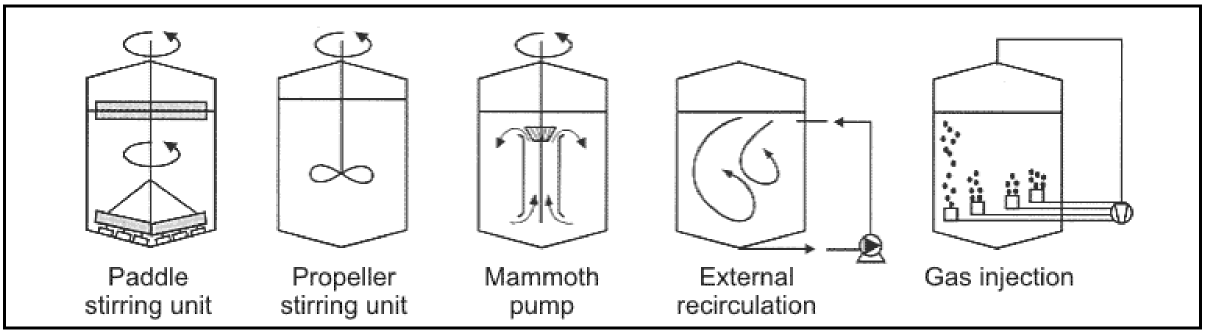


Fig. 6.16: Stirring technology [Edelmann 2001]

Submerged motor stirring units are powered by gearless electronic motors that are pressure water tight and coated for protection against corrosion. These stirring units are completely submerged in the substrate and equipped with geometrically optimised two or three wing propellers. Height, side and tilt settings are carried out by means of a pipeline with gibbets, rope winch and control equipment.

With *lengthwise oriented axle stirring units* the motor is located on the end of a stirring axle that is built into the fermenter at an angle. The axle is routed through the fermenter ceiling or in the case of a film covering through the upper wall area. An additional bearing is possible on the fermenter floor. The stirring units have large surface paddle-formed stirrers.

Axial stirring units are usually axles mounted centrally on the fermenter ceiling. They are especially suited for continuous operation. The powered motor is located outside the fermenter. With the use of gears the speed of the stirrers can be reduced to just a few rotations per minute.

Paddle or winch stirring units are usually used in lying fermenters. Due to the construction type these slow stirrers are generally used in plug-flow fermenters. The paddles are mounted on the horizontal stirring axle. These stirring units are suitable for interval operation. These stirring systems can also be implemented in standing fermenters.

Pneumatic thorough mixing plays only a subordinate role as a part of the technical fermenting process. Thereby biogas is injected through the fermenter floor and the substrate is set into vertical motion by the rising gas. The advantage of this technique is the fact that no mechanical stirring technology is found in the fermenter. This reduces the wear and tear and facilitates the accessibility during repair and service of the mixing technology.

Substrate can be pressed in the fermenter and as a result thoroughly mixed by pumps through vertical and horizontal stir valves. *Hydraulical mixing systems* have the same advantages as pneumatic, although with both it only possible to a certain extent to destroy floating layers, which substantially limits their use.

Sediment Discharge

Sediments and sink layers are formed by the content of heavy materials, such as sand in the fermentation substrate. The heavy materials accumulate on container floor during the course of the fermentation process. Coarse heavy materials can be separated in a collecting container with heavy material separation. Fine heavy materials are sometimes very innerly connected with the organic substances and are first released in the fermentation process. The discharge can be carried out by a floor sweeper or through floor outlets. Massive heavy material accumulation sometimes requires opening the fermenter and subsequently removing the heavy materials either manually or mechanically.

Floor sweepers are used in standing fermenters with round or level ground surface. Floor sweepers should be powered from outside the fermenter in order to make service and repair possible without emptying the fermenter.

Discharge spirals are used in lying and standing fermenters. They have to be mounted (gas-tight and water-tight) through the fermenter wall. Discharge spirals require a pump sump in the fermenter that collects the heavy materials.

In standing fermenters *conical fermenter floors* can also be used for sediment discharge. They are equipped with a sink layer stirrer and removal pump.

The fermenter must be emptied for repair and service of permanently installed systems. Therefore it is advantageous to have aggregates that are located on the outside or removable.

Fermentation Residue Discharge and Post-treatment

Standing fermenters usually have an overflow, from which fermented substrate can be removed through a siphon. Thereby gas emissions are avoided. The use of pumps for the removal of substrates is also possible. In lying fermenters the fermented substrate is removed by means of a plug-flow into an overflow or pumps.

For further recycling and use the collected fermentation residues they have to be treated after the fermentation process. The direct application onto agricultural areas or the aerobic post-treatment for the production of ready compost is understood by recycling the fermentation residues that are generated by the fermentation of biogenous residual materials. Fermentation residues from residual waste treatment are not suitable for agricultural use due to their composition. The treatment of such fermentation residues takes place with the goal of producing waste suitable for landfilling according to AbfAblV (2001) *German waste disposal ordinance* or secondary incineration material for energetic use.

The treatment of the fermentation residues encompasses principally drainage (solid / liquid separation), aerobic post-treatment for hygienisation and production of a ready compost or aerobic stabilisation for the creation of waste suitable for landfilling according to AbfAblV (2001). Depending on the intended use of the fermentation residue a aerobic and/or physical drying for the production of secondary incineration materials and fine confectioning can still be carried out.

5.8.1.1 Drainage

Drainage is the first step of fermentation residue treatment. This procedure step should be allowed for in the dry as well as wet fermentation process. For further recycling the fermentation residues should be drained down to a water content of less than 45-50%. If aerobic post-treatment is planned the input of structure materials with higher water contents is acceptable.

Solid-liquid separation can be economically and technologically sensible in some cases, for example with limited space or limited fermentation residue storage capacity. The accumulated press water can be reintroduced into the process as mashing water. Thereby the additional concentration of potential salts and nutrients should be considered. Spiral separators, sieve belt presses and centrifuges are used for solid

- liquid separation. Spiral separators can produce a product with approximately 40% dry substance (DS) from a fermentation residue with 1 to 20% DS.

Drainage of fermentation residues takes place by means of dry processing due to the high dry substance content of more than 20% in the reactor output, above all through slow-turning sieve spiral presses. The solid material portion in the press material can amount to up to 15%, depending on the input with high fine sand elements into the fermentation plant. The fine sand leads to higher wear and tear in the downstream aggregates so that the fine sand components are usually removed with the aid of a sand removal unit (for example a hydrocyclone) following the press drainage. The waste heat of a CHP (Combined heat and power units) can be used for drying.

Fermentation residues from wet fermentation have smaller particle sized and a lower dry substance content of approximately 5-10% due to the intensive conditioning of the material before the process. Therefore, drainage usually takes place in this process by means of a centrifuge. Drainage using sieve spiral presses is possible with middle and coarse particle sizes of more than 30 mm. However, the use of flocculation additives is necessary. Post-composting of these solids is possible, depending on the circumstances, without the addition of structure material [Fricke et al. 2003].

5.8.1.2 Aerobic Post-treatment

In the long-term management of hygienisation fermentation residues can generally be fed into the recycling process without aerobic post-treatment. As opposed to compost products with a degree of composition between II and III from aerobic treatment the fermentation residues with the same degree of composition exhibit a strong odour emission - caused especially by ammoniac compounds, that are still contained in the product in a large amounts directly after leaving the fermenter. Plant compatible compost products can only be achieved with downstream aerobic treatment.

Diverse technology is available for the aerobic post-treatment of fermentation residues. The choice of the suitable process is influenced by the amount and composition of the waste to be treated, as well as the requirements of the product. Furthermore, the available space, location conditions, especially the requirements of the TA-Luft *Technical Instructions for Air Purification* (Anonymous 2002b) on the level of enclosure play an important role in the choice of the rotting process.

Depending on the targeted degree of maturation and/or degree of decomposition a maturation phase of 2-6 weeks necessary. The post-treatment should be carried out in the first 7 days with active aeration and ventilation since additional methane and strongly odorous ammoniac is emitted as a result of the reductive process. With the throughput capacity of the plant beginning at 10,000 Mg/a the main decomposition should be carried out closed after TA-Luft.

Miscellaneous Plant Technology

For the operation of anaerobic plants further equipment is necessary just as are used in many facilities for biological waste treatment. These include amongst others especially wheel loaders for transporting the material, conveyor belts, pumps, sieves, further feed and discharge aggregates for fermentation substrates etc. Due to the wide range of suppliers and the similarity to the necessary equipment for composting plants or other biological treatment plants this topic will not be addressed in further detail.

5.9 Biogas Use

Gas Composition, Content Materials

The energy yield from the anaerobic bacteria is equivalent to only about 1/20 of the energy yield of aerobic bacteria. The largest part of the energy of the metabolised substrate is retained by the biogas and is therefore available for further use. The biogas composition and quality depends on the applied substrates as well as on the process parameters, such as temperature, retention time and volume load. The methane content of the biogas from thermophilic-operated reactors is less than from the mesophilic-operated reactors due to, for example, the decreasing solubility of carbon dioxide along with increasing temperature. The fundamental components are methane and carbon dioxide. However, traces of hydrogen sulphide, nitrogen and oxygen can be found. Typical average biogas compositions of diverse waste are listed in *Table 6.14*.

The quality of the biogas is determined based on its content of methane, carbon dioxide, hydrogen sulphide ammoniac and further trace gases, such as water vapour. The composition of the biogas is largely dependant on the type of applied raw materials and can only be influenced a limited amount by process direction. The requirements for the gas quality depend on the field of implementation, although drying and desulphurisation are necessary for all uses. For block heat power plants combined heat and power unit and central heating boilers most manufacturers set a limit for hydrogen sulphide at 200 ppm, which should not be exceeded in order to avoid corrosion. Diverse processes are common for gas desulphurisation.

Tab. 6.14: Biogas Composition

Substrate	Biogas component			Source of literature
	CH_4 [Vol.-%]	CO_2 [Vol.-%]	H_2S [Vol. -%]	
Bio waste	57 – 65 62 - 741)	n.g. n.g.	< 0.05 n.g.	Fricke et al. 2002
Liquid manure	53 – 69 (80)[2)]	(15)[2)] 30 - 46	0.05 - 1.0	Hüttner 1997

[1)] Biogas composition of the methanised two-phase process; [2)] High-performance reactor, fed with easily-degradable organic compounds

Gas Piping Systems

The sulphur content in exhaust gas is an important factor in the construction of the piping system since both hydrogen sulphide and organic sulphuric compounds are very corrosive in watery solutions. Consequently the question of adequate desulphurisation of the raw gas is of special interest.

Under general operational conditions the gas piping and accumulation system of the biogas plant a closed system. For safety reasons it is necessary to take precautions to provide a means to discharge pressure, for example with surge tanks, in the case that inadmissible high or low pressure occurs.

With respect to pressure safety (high-pressure) can lead to the risk of explosion and odour problems in the plant surroundings with leaking biogas. By inflow of outside air (low pressure) a mixture capable of exploding is formed in the container. The safety regulation requirements for agricultural biogas plants should also be placed on pressure maintenance. The pressure maintenance concept should be presented clearly in the permit application. If necessary, the concept should be assessed by an expert. Gas pipelines should be planned with a pressure resistance of at least 1.0 bar. Pressure in shafts is not admissible. The biogas should be fed from the fermenter through the gas accumulator to the motors. In such a manner the detention time during desulphurisation with oxygen can be increased and a better balance of the biogas pressure results from feeding it through the gas accumulator. Measures should be taken to prevent the water locks from freezing in winter (for example: anti-freeze)

[N.N. 2004].

Detailed descriptions of the safety regulations can be found in "Sicherheitsregeln für landwirtschaftliche Biogasanlagen" *Safety Regulations for Agricultural Biogas Plants* from the Bundesverbandes der landwirtschaftlichen Berufsgenossenschaften *Federal Association of Agricultural Safety Organisations* [N.N. 2002].

Gas Accumulation

Biogas production is nearly constant when the plant is continuously fed. Temporary interruptions in the feeding, however, have an effect on the biogas production and lead to a reduction of the amount of biogas. Buffer storage of the biogas for extensive use is usually necessary for irregularly-fed plants and for bridging operational down-times due to maintenance and repair work. The size of the accumulator can only be set up for balancing short-term as a result of the low energy density of biogas. The bridging of long-term interruptions in biogas use is usually not possible and, therefore, an emergency torch should be included in the design for the environmentally-friendly disposal of the biogas.

Storage of biogas can take place in low-pressure and pressurised storage containers. Low-pressure storage is used in systems with pressure of merely a few millibars and are therefore usually used in biogas plants. The biogas is fed into the storage by its own pressure. The necessity for cost reduction has recently led to the gas space above the fermented material surface being used as a storage for bridging the gap between short-term operational disruptions. One example is the foil gas storage shown in *Figure 6.17*. The foil is weighted down with a concrete ring and is guided along the fermenter wall on a system of rollers.

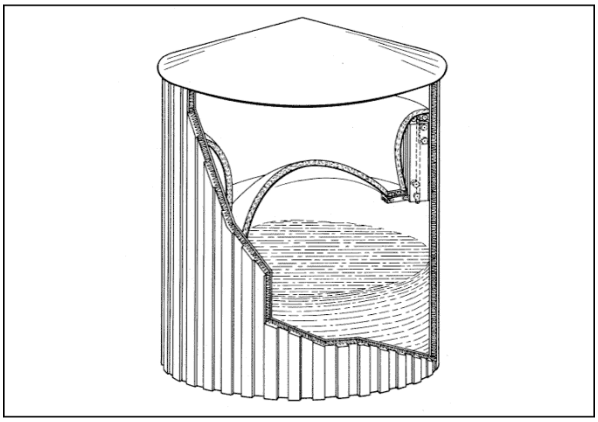


Fig. 6.17: Foil gas storage [Wellinger et al. 1991]

The use of pressurised storages leads to a significant volume reduction due to the increased density. The investment costs for pressurised storage are substantially higher due to the necessary apparative costs and the operation of a pressurised storage is subject to a approval and testing requirement. The installation of a pressurised storage is usually only justifiable in conjunction with the use of the biogas as fuel for vehicles.

Gas Purification

Depending on the recycling procedure different requirements are placed on the biogas conditioning. Approval legal requirements also have an influence. Biogas purification is made up of a combination of the following conditioning procedures depending on the recycling process:

- Demoisturification /particle separation,
- Draining/drying,
- Desulphurisation,
- Selective separation of biogas components

Thereby one can differ between physical, chemical and biological processes as shown in *Figure 6.18*.

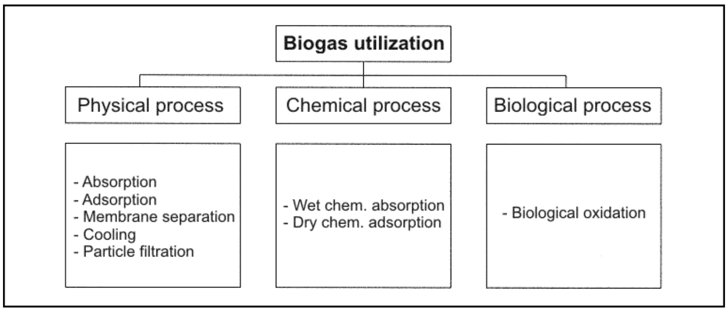


Fig. 6.18: Possibilities for biogas conditioning [Weiland 2003]

Particles in biogas can lead to mechanical damage of the incineration motors and furnace equipment. The separation of particles swept along and foam residues from the reactor usually take place in gravel filters (coarse filter). Thereby a pre-separation of condensate is intended. Further dust removal is carried out mostly directly at the aggregates.

The biogas leaves the reactor completely saturated with steam. The *water content of the biogas* depends on the fermentation temperature in the reactor and is usually 4% for mesophilic operated plants and 12% for thermophilic operated plants. Condense water occurs in the pipeline as a result of exceeding the condensation point and can lead to corrosion in connection with hydrogen sulphide. The condense water accumulated in the pipeline is collected in condense water latches and removed through outlet equipment. The accumulated amounts are marginal and can be fed back into the process.

The use of the biogas in incineration cells, as well as a substitute for natural gas and fuel requires the complete demoisturification of the biogas. Due to cooling of the gas down to temperatures of approximately 4°C a nearly complete drying can be achieved. After the condensate removal the biogas is warmed to a temperature of 15-20°C.

Hydrogen sulphide and *sulphur dioxide* (resulting from the incineration) have a very corrosive effect in conjunction with condensate. The hydrogen sulphide content is determined by the implemented substrate. Tolerable hydrogen sulphide concentrations differ substantially depending on the recycling process. The use of biogas in CHP and steam and heat boilers does not require desulphurisation until a hydrogen sulphide concentration of 0.1-0.15 Vol.-%. Desulphurisation of biogas from the use of biowaste is usually not necessary due to the minimal hydrogen sulphide concentration of less than 0.05 Vol.-%. In contrast, a complete desulphurisation is essential for use of the biogas in incineration cells, as well as a substitute for natural gas or fuel. Different procedures are available for sulphur reduction, such as

- Sorption of iron hydroxide or activated carbon,
- Insertion of iron sludges or iron-(II)-chloride and/or iron-(III)-chloride in the reactor inflow,
- Biological desulphurisation using special bacteria and
- Air dosage in the reactor space

The adsorptive removal of the hydrogen sulphide is carried out on solid cleansing mass. Thereby cleansing mass containing, above all, iron hydroxide or colons filled with activated carbon is used. The removal of he hydrogen sulphide with iron hydroxide takes place through the formation of iron sulphide. The regeneration of the cleansing mass is to a certain extent possible during the process with the addition of oxygen. The regeneration leads to an accumulation of elementary sulphur on the cleansing mass so that a periodical exchange of the cleansing mass is unavoidable for complete regeneration. The regeneration, in particular, as an exothermal reaction leads to a significant heat development that should be considered in the design process of the plant.

The dosing of metal salts can itself cause a reduction of the hydrogen sulphide concentration in the reactor. Thereby iron sludges, iron-(II)-chloride or iron-(III)-chloride is dosed in the plant input. The hydrogen sulphide formed in the fermentation process is then already reduced in the reactor to iron sulphide and remains in the liquid.

Metal salts are implemented as precipitation or flocculation agents in waste water technology so that the actual consumption lies above the stoichiometric necessary requirement due to competing reactions, such as the formation of iron phosphate.

The microbial desulphurisation of biogas is a relatively new process. Hydrogen sulphide is transformed by bacteria into elementary sulphur or sulphate. The micro-organisms are omnipresent and, therefore, do not have to be artificially added. Aside from nutrients and trace elements the bacteria require oxygen for the decomposition of hydrogen sulphide [Fricke et al. 2003].

The dosage of oxygen is carried out in agricultural plants by injecting a small amount of air directly above the surface of the fermenting material in the reactor space. The stoichiometric air requirement lies between approx. 4-6% air in the biogas. The necessary surface for purifying approx. 20 m^3/d of biogas is approx. 1 m^2 [Köberle 1999]. An air rate is therefore set that is equivalent to 3-8 % of the amount of biogas produced daily. Under these conditions hydrogen sulphide is oxidised from sulphur bacteria into elementary sulphur and sulphate, which can then be removed with in the liquid phase. The purification of the biogas in industrial and municipal fermentation plants usually takes place in separate packed colons with growth areas for the bacteria. *Figure 6.19* shows an example of a biological washer. Concentrations of less than 200 ppm can be reliably achieved with this method.

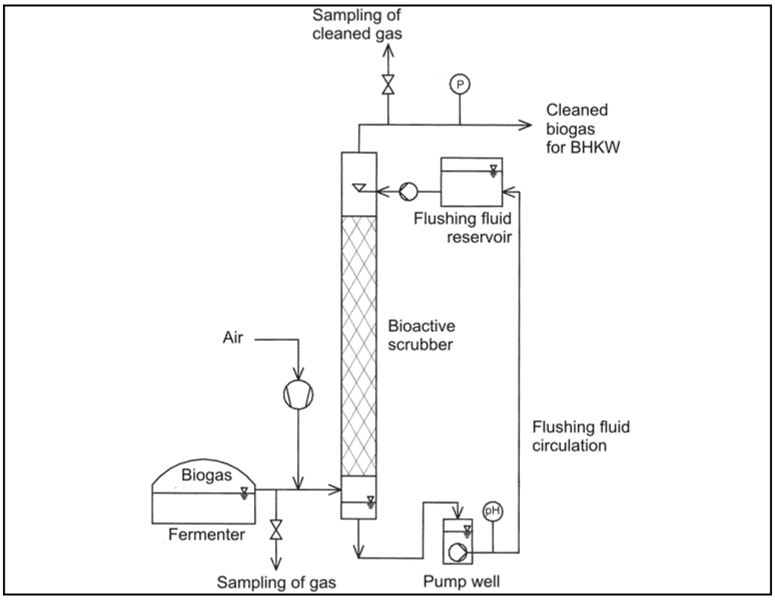


Fig. 6.19: Biological washer [Prechtl et al. 2003]

The separation of hydrogen sulphide removal offers, along with the avoidance of disruptions of the methane production, the advantage that the sulphur does not remain in the reactor and can not be converted once again to hydrogen sulphide. The formed sulphuric acid is then discharged from the packed colons along with the cycle guided wash water [Fricke et al. 2003].

However, practice shows that neither the concentration peak of hydrogen sulphide nor the limit value of the TA Luft could be kept constant since the biology can not adjust quickly enough to the altered concentration of hydrogen sulphide and the remaining hydrogen sulphide concentration hampers or even prohibits the use of emission gas catalysers.

Molecular sieves are made up of zeolite (crystaline aluminium silicate) with continuous structure. A sieve is produced in the cavities, in which different gases are separated according to their molecular diameter and their polarity. By adapting the molecular sieves different gases, such as carbon dioxide and hydrogen sulphide, can be separated in a colon [Wellinger et al. 1991]. *Figure 6.20* shows the schematical representation of a molecular sieve.

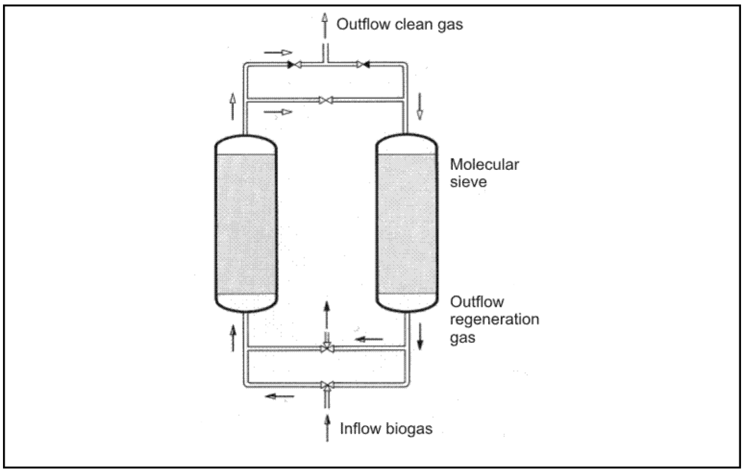


Fig. 6.20: Molecular sieve absorber [Wellinger et al. 1991]

Gas Use and Recycling

The energetic potential of biogas is used for the provision of thermal and electrical process energy. The provision of energy usually exceeds the energy necessity of the plant so that electrical and thermal energy for other uses is available. Surplus electrical energy can be supplied to the public network. The use of the surplus thermal energy is only possible to a certain extent due to the limited possibilities for use on site. Usable energy can be made available as *thermal energy* in the form of *cold, hot water or steam and electrical energy*.

The most common form of biogas use is the flow as heat-power combination in motors conceived or modified especially for this purpose. Aside from the conditioning of the biogas to the quality of natural gas, which was already attempted in the beginning of the nineties, the implementation of incineration cells for increasing the electrical energy yield is still in the development phase. The potentials of biogas use are shown in *Figure 6.21*.

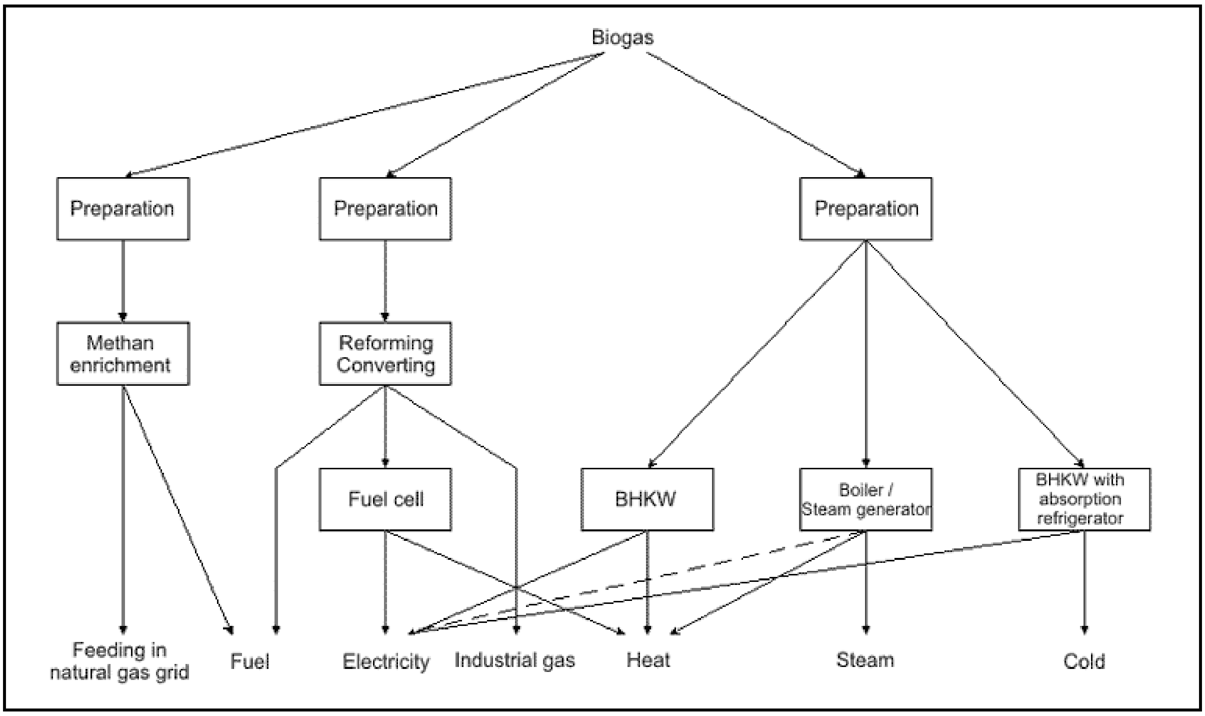


Fig. 6.21: Potential uses of biogas [Fricke et al. 2003]

Standard heat boilers can be used for the *thermal use* of biogas, which can be operated with both biogas and natural gas. Adapted burners are necessary for operation with biogas due to the reduced spark speed compared to natural gas. Small plants with a capacity of up to 30kw can manage with burners that operate with atmospheric pressure. Larger plants nearly all operate with blower burners. The use of a densifier with pressure regulation is usually necessary since the low pressure from, for example, foil storage is not sufficient for the operation of heat boilers.

Motor heat-power combination: Different aggregates and processes are used for the feed-in of biogas and connected waste heat use depending on the size of the plant. These differ substantially according to degree of effectiveness, serviceable life and investment costs.

Gas spark ignition motors are converted automobile motors that are only used in very small plants. The motor's high number of rotations causes a low life expectancy and a high need for service. These aggregates react sensitively to fluctuations of the methane content in the biogas and require a defined air to biogas mixture for efficient operation.

Pilot injection diesel motors are converted production model diesel motors. Through the injection nozzle 7-10 % spark oil is mixed in order to spark the biogas by densification. Heating oil usually serves as spark oil. In order to retain a 100% regenerative energy production newly developed aggregates can also use pure vegetable oil. Due to the high serviceable life of from 30,000 to 40,000 operational hours and the good electrical degree of efficiency of on an average 35 % pilot injection diesel motors are currently the most common. In CHP with an installed electrical capacity of more than 150kw diesel motors are sometimes converted for gas spark ignition operation. These aggregates require an external spark and gas mixer. They can achieve up to 80,000 hours of operation and have an electrical grade of efficiency of up to 37%.

Other motors, such as the *Stirling motors*, are currently being developed, but are not yet ready for practical use. The cooling water, as well as the hot waste heat usually serves for use of the motor waste heat. While the cooling water temperature is limited to 85-90°C hot water of up to 100°C can be made available with the use of the waste heat. Generally, dual circuit systems are used that are connected to a common heat reservoir. Asychronical generators that are characterised by a robust construction are most commonly used for the production of electricity. Due to the network strength no additional aggregates are necessary for the rotation regulation of the engine.

Small, quick-paced turbines with low incineration temperatures and pressures are called *micro gas turbines*. The biogas is incinerated along with highly-densified air. The resulting expansion of the incineration gas emission is used in a turbine in order to cause rotation. The capacity range of micro gas turbines is up to 200 kW. Biogas and incineration air have to be led through a densifier. Gas turbines require a very high purity of the biogas. Therefore, gas purification and drying have to be carried out. Micro gas turbines emit substantially less hazardous gas emissions, compared to motors, as a result of the continuous incineration with air surplus. The waste heat can be transferred to a network more easily and therefore more cheaply than from incineration motors since it only occurs with gas emissions. The service intervals are estimated to be larger than with motors, but micro gas turbines have only as of recently been used in practice and therefore no exact numbers are available. The electrical degree of efficiency lies at approximately 28% and is thereby lower than with conventional incineration motors. The investment costs are approx. 15 to 20% higher than an equivalent motor system.

The use of *incineration cells* is currently in the testing phase, but has substantial potential since the electrical degree of efficiency is higher and incineration cells only cause a minimal amount of gas and noise emissions. Since incineration cells can be operated only with hydrogen biogas has to be converted to hydrogen in a reformer. The purity requirements for the implemented biogas are generally very high and different for different incineration cell types.

The *feeding-in of biogas into the natural gas network* can also be an alternative. Whereby legal problems have to be settled and technical problems solved. Biogas, which should be fed into the natural gas network, has to be equivalent to natural gas with respect to purity, fuel value, etc. That means that drying, a nearly complete desulphurisation and a separation of carbon dioxide. This potential for use is currently in its testing phase in Germany.

The use of biogas as *fuel for vehicles* requires that allows for the use in normal automobile motors. Since gas-powered vehicles (such as public transportation buses) are usually operated with natural gas biogas has to be brought up to the quality standards of natural gas. Furthermore, compression is necessary.

5.10 Emissions

Fermentation plants cause emissions in the form of odour, waste air (from ventilation systems) and in the form of waste water. In this framework emissions and their prevention should not be addressed.

5.11 Energetic Considerations

As part of the mechanical conditioning the delivered waste are confectioned for the downstream processes according to their material specific characteristics in different treatment steps - generally chopping, sieving, and metal removal. If the biological treatment takes place through a combination of fermentation and a subsequent maturation phase additional conditioning steps are usually necessary, such as advanced chopping, as well as mixing and pumping procedures with the appropriate electrical energy necessity.

During aerobic post-treatment the windrow ventilation, windrow rotation, as well as the ventilation of the composting hall are all, in particular, the main electricity consumers. In the fermentation process work is done in different temperature areas and according to different heat requirements depending on the process. In mesophilic processes the fermenter temperature lies at approx. 30-37°C, while the anaerobic process in thermophilic plant operation is approx. 50-60°C. In this context is the heat requirement for the fermentation process within a range of 20-60 kWh/Mg bio-waste input, whereby the lower area is allotted for mesophilic and the upper for thermophilic processes. Aside from thermal energy, electrical energy is also needed during fermentation and/or in the subsequent conditioning before the maturation phase. The drainage of the fermentation residue, which is necessary in order to set the water content with respect to the requirements of the subsequent maturation phase, should also be considered as a major energy consumer. Water content in the fermenter output of approx. 88-95% (wet processing) or 65-82% (dry processing) should be reduced to around 55-60% in order to achieve ideal moisture conditions for the maturation phase. The drainage usually occurs in a multiple phases, whereby different aggregates, such as spiral presses, sieve belt presses, centrifuges, decanters and cyclones, are used. The ventilation of the drainage hall is carried out by an electrically-powered blowers. In addition, electricity is needed for the operation of recirculation pumps during fermentation that ensure continuous thorough mixing of the fermentation material in the fermenter. In several processes the addition of heat takes place with the injection of pre-heated air (hot steam). Electrical energy is also necessary for the operation of the blowers [Fricke et al. 2003].

5.12 Hygienisiation and Use of Fermentation Residues

The German Biological Waste Ordinance [BioAbfV, 1998] formulated the requirements for hygiene in detail. The monitoring of hygiene is classified into *direct process testing* (introduction of test or indicator organisms) and *indirect process testing* (temperature measurements). Furthermore, a product inspection is carried out (end product control). In *direct process testing*: Compost from fermentation residual materials can be implemented in agriculture and gardening according to the BioAbfV (1998). This requires special attention of the phytohygiene. The proof of no salmonellae in 50 g material is judged as sufficient for human and pestilence needs. The direct process testing should be judged critically since the existing method of adding test bodies does not consider actual rheological conditions in the fermentation reactor thoroughly enough. In new plants attention should be given to the insertion possibilities of testing bodies. Whereby the temperature sensors (at least 3) should be located immediately near to the area of the inserted test bodies.

Exceptions can be made by the responsible authorities in individual cases "as long as no detraction of the pestilence and phythohygienical needs can be expected based on the composition and origin of the biowaste". This is also true for agricultural small plants, with which the direct process testing could be disproportional and the could be limited to the material testing before and after fermentation - after detailed examination.

Indirect process testing is relatively easy to carry out based on temperature measurements. Whereby the temperature sensors should be located in the immediate vicinity of the inserted test bodies with the test germs. Although moist solids are present in composting, which are substantially more difficult to mix than in wet or dry fermentation, it is noticeable that in composting two weeks in the window core at 55°C is necessary, while in fermentation temperatures of 55°C and a hydraulic retention time of 20 days is demanded (in some cases 10 days at 60°C). The mesophilic fermentation of food residues, catering waste, fat skimmers, among others (not biowaste and green cuttings) requires pre-heating of an hour at 70°C for hygienisation.

Subsequent recontamination of the hygienically safe ready compost with potential pestilence viruses from the input material should be avoided. "Black - white areas" are helpful along with the usual water cleaning of the wheel loader, for catering waste it is essential. For ecological reasons only non-toxic disinfecting agents should be used for cleaning (if possible DVG *German Testing Institute* -tested and free of chlorine), such as inorganic lyes, organic acids (for example antacids) or aldehyde. Furthermore, the use of hot steam spray lances could be sufficient since disinfecting is only targeted at reducing the germs thoroughly, but not complete eradication (sterilisation) [Fricke et al. 2003].

5.13 Process control

The measuring techniques used for the control of the process in the fermentation reactor is manifold. The measurement of the gas production rate and the control of the pressure within the gas zone and the temperature of the substrate is typical. In part pH-values, redox potential, methane and H_2S-content are regularly measured. The measuring techniques in the immediate gas area should be carried out with explosion protection.

The goal of every operator is ensuring an ideal loading of the fermentation reactor. Certain substrates or too much organic loading lead to excessive acidification ("overturn") or to a strong hydrolysis of the reactor contents since the formation of pH-neutral methane can not take place. The disposal of the acidified substrate and reloading can lead to long down time. This reduces the efficiency of the plant. The same true for the case of underloading of the plant. Marginal yields due to reduced biogas production and receipt of substrates results in a sub-optimised efficiency. Therefore the control of process stability is of substantial relevance for the economical success of the entire fermentation plant.

One can not merely fall back on rules of thumb or table values, especially with interchangeable compositions of the input material. The aim of every operator is to achieve the maximum amount of throughput with the given substrate and highest degradation rate so that the maximal efficiency attained.

Many times only the temperature of the substrate in the fermentation reactor is measured to control the biological process due to economical reasons. This is not sufficient for the control of process stability during plant operation.

A sensible measuring technique for controlling process stability depends partially on the process technology. Typically the process stability can be controlled by measuring the gas production and composition. It can generally be assumed that a decrease in the specific gas amount and an increase in CH_4 concentrations means an increased loading of the process.

It should be pointed out that after the feeding of fresh substrate that an increase of gas production and CO_2 concentration is usual. The more often the feeding with less fresh substrate is, the more marginal the deflections are and the less the shock loading of the process is.

If excessively acidified substrate is inserted into a stale operating fermentation reactor a sudden outgassing of CO_2 is caused due to pH-value reactions. This does not necessarily mean a reduction in process stability. However, a continuous increase in CO_2 concentrations over a period of several days or weeks indicates a successively decreasing process stability.

Measuring parameters, such as pH-value and redox potential give supplemental points of reference for the control of process stability. They are not sufficient on their own for secure process control.

The measurement of the concentration of organic acids is a good indication for process stability along with a stable buffer capacity and content of ammoniac or H_2S that is not too high. The measurement and examination of the buffer capacity with nitrate ions as a preventative measure is also useful. The relation of volatile fatty acids to buffer capacity or alkalinity can also be especially significant for the evaluation of process stability through the liquid phase. The designation of the concentration of organic acids and/or the acid spectrum alone can be used with a constant substrate composition. These measurements are not routine and are therefore only possible in specially-equipped laboratories [Fricke et al. 2003].

5.14 Plants and Work Safety

Just as in nearly all large technical plants biogas plants involve a certain potential for danger. The spectrum ranges from the bursting of a pipeline to the danger of explosion. The awareness of potential sources of danger are the requirement for safe operation of the plant.

Every biogas plant should create a safety concept. This contains the instructions for operation and maintenance of the plant and the constructive measures of the manufacturer. Safety concepts should be outlined according to the following schema:

- Construction
- Normal operation
- Disruptions in process procedure
- Service and maintenance of the plant

In plants that produce biogas there is the danger of explosion. The *danger of explosion* can be prevented by constructive measures with high security. A methane-air mixture is capable of exploding with a methane content of 5 - 15 Vol.-%, in a mixture with 35 Vol.-% carbon dioxide only at methane contents of between 5 and 12 Vol.-%. The self-sparking temperature lies at 600 C. Pure biogas is therefore not explosive, just as little does the light insertion of air, for example as a part of the biological desulphurisation, to a danger of explosion. Explosive air-biogas mixtures are formed mainly with the outflow of biogas in more or less closed spaces due to leaks or misguidance. Sources of sparks can be open fires, lightening, hot surfaces and mechanically or statically-caused sparks.

Bursting of plant parts is caused by over or under pressure or by corrosion or age-related weaknesses of the corresponding parts of the plant. Causes of which could be ripped or otherwise clogged pipelines, sliders or shut-off switches. Further causes can be a lack of expansion and contraction possibilities, as well as mismanipulation of the plant.

The leaking of substrate can cause a danger to ground and surface water. Causes can be the bursting of plant parts, as well as the activation of security vents.

Possible *dangers due to electricity* should be considered with electricity guided plant parts and electricity generating aggregates.

The *danger of poisoning and suffocation* might need to be considered in the case of service work, such as someone having to work inside the fermenter.

Danger of falling exists with highly built plant parts or on containers. It should be minimised with constructive measures.

Further detailed information can be found in Wellinger et al. 1991 "Biogas Handbook", and N.N. 2002: "Security Regulations for Agricultural Biogas Plants".

5.15 Description of Selected Plants

In this chapter selected fermentation processes are described. *Table 6.15* gives an overview of current plant concepts on the market.

Tab. 6.15: Fermentation Plants in Germany in 2002 [Fricke et al. 2003]

Process	Manufacturer	Process characteristics						Plant location	Through-put [Mg/a]
		1-phase	2-phase	mesophilic	thermophilic	wet	dry		
3A	Steffen-Ing.		x[1)]	x			x	Delitzsch	1,800
AN	AN Maschinenbau		x[2)]		x	x		Ganderkesee	6,000
Biocomp	T.B.W.		x	x[3)]	x	x		Kehl-heim/Teugn	13,000
Biostab	Roediger	x			x	x		Münster	18,000
		x			x	x		Boden (Wester-wald-Kreis)	25,000
Biopercolat	Wehrle-Werke		x[4)]	x		x		Kahlenberg[5)]	25,000
BRV	Linde-BRV	x			x		x	Heppenheim	33,000
		x			x		x	Lemgo	38,000
		x			x		x	Hoppstädten-Weiersbach	23,000
BTA	BTA/MAT	x		x		x		Baden-Baden	5,000
			x	x		x		Erkheim	11,500
		x		x		x		Flörsheim-Wicker	20,000
		x		x		x		Karlsruhe	8,000
		x			x	x		Kaufbeuren	3,000
		x		x		x		Kehl-heim/Volken-schwand	13,000
			x	x		x		Munich	20,000
		x		x		x		Wadern-Lock-weiler	20,000
		x		x		x		Mühlheim	22,000
Dranco	Organic Waste Systems	x			x		x	Kaiserslautern[5)]	25,000
		x			x		x	Bassum[5)]	15,000
D.U.T.	Dywidag[9)]		x		x	x		Singen	87,000
			x		x	x		Peine/Mehrum	10,000
GÄR TEC	GärTec Vergärungsanlagen		x	x	x	x		Brilon	2,500
IMK	BioEnergie		x[4)]	x		x		Herten	18,000
ISKA®	ISKA®		x[4)]	x		x		Buchen	25,000[10)]
KCA	Linde-KCA				x	x		Radeberg[6)]	55,000
KOPOGAS	Bühler/ KOGAS	x			x		x	Kempten	10,000
		x			x		x	Munich/Eitting	20,000
		x			x		x	Braunschweig	20,000

		x			x		x	Simmern	10,000
		x			x		x	Alzey-Worms	24,000
		x			x		x	Frankfurt	15,000
		x			x		x	Weißenfels[7)]	12,000
Methacomp	Mannesmann -Lentjes (ML)		x	x		x		Mögglingen	2,000[8)]
Valorga	Steinmüller-Rompf Was-sertechnik	x		x			x	Engel-skirchen/Leppe	35,000
		x			x		x	Freiburg	36,000
WABIO	Babcock[9)]	x		x		x		Bottrop	6,500

1) 3-phase process

2) 1st phase mesophilic hydrolysis as percolation

3) 1st phase mesophilic, 2nd phase thermophilic

4) 1st phase mesophilic hydrolysis as percolation

5) Organic fraction out of total waste, no separate collection of biowaste

6) Common recycling of biowaste and sewage sludge

7) Plant being planned

8) Extension of the plant planned for 10,000 Mg/a

9) Marketing taken over by Lizenzgeber Outokumpu EcoEnergy

10) Plant extension planned for 150,000 Mg/a by 2004

Selected Fermentation Processes

The *VALORGA process* exhibits similarities with the DRANCO process in the conditioning of waste. The waste are first chopped, sieved to a particle size of <40mm and the fine fraction fed into the reactor with a solids pump after mashing to a DS content of 25 to 35%. Heating of the fermentation substrate takes place through the heating of the process water for mashing, as well as by dosing saturated steam into the reactor.

The reactors are executed as standing cylindrical concrete containers. *Figure 6.22* shows a principle schema of the process.

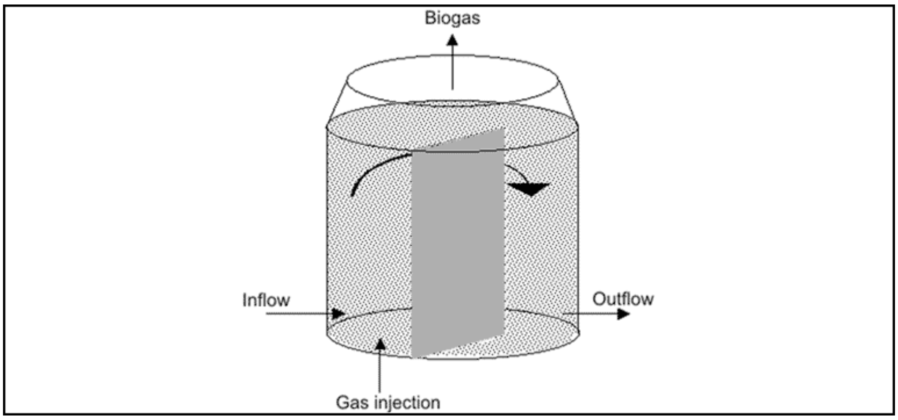


Fig. 6.22: Schema of a VALORGA fermenter [Fricke et al. 2003]

A special characteristic of the reactor is the middle wall in the reactor, which is located along approx. 2/3 of the diameter of the reactor. It separates the input and output area of the fermentation material, in which case bypass flow should be avoided. The fermentation material is as such forced into a horizontal circular feeding unit so that the system could be seen as a plug-flow process. The thorough mixing of the reactor content is carried out without mechanical fixtures with a pneumatic system. Periodically, biogas is vertically pressed into the cycle under a pressure of up to approx. 10 bar through nozzles on the floor of the reactor and in such a manner an effective thorough mixing is striven for. The method of operation is sometimes selectively mesophilic or thermophilic, with hydraulic retention times between around 14 and 28 days. Without the use of mechanical feed fixtures the fermentation materials are distributed by means of gravity. The drainage is two-phase and is mostly made up of sieve spirals and belt filter presses. If need a separation of fine inert materials from the process water is carried out by hydrocyclones (sand separation) and centrifuges [Fricke et al. 2003].

In the *DRANCO process* (Organic Waste Systems - OWS) the conditioning of biowaste is conducted initially with the manual foreign material separation. Subsequently chopping and sieving to the particle size of <40mm are carried out (*Figure 6.23*).

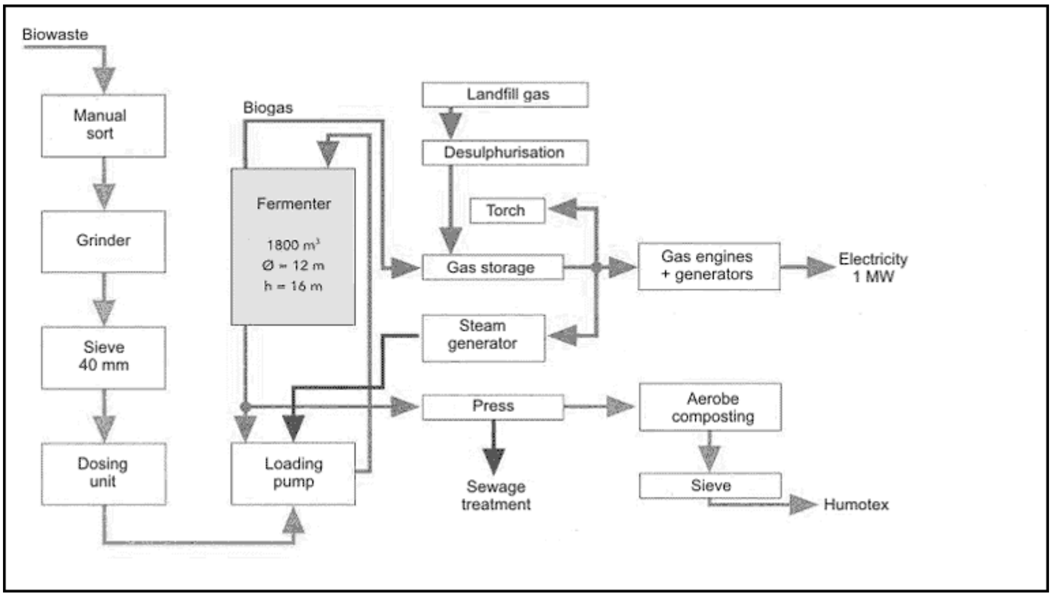


Fig. 6.23: Schema of the DRANCO process [Fricke et al. 2003]

A ball mill can be placed before the fermentation phase, with which the residual waste to be fermented can be conditioned. The sieve underflow makes its way into a dosing unit after Fe separation, with the help of which delivery fluctuations can be compensated. Systematic aerobic hydrolysis does not take place. The material is mashed to a dry substance content of around 25-35% in a mixer and fed into the reactor with the help of piston pumps with pre-pressing fixtures. The fermentation takes place solely in the thermophilic temperature area, in which the heating of the material is carried out by the injection of saturated steam.

The reactors are executed as standing cylindrical containers in concrete construction. The removal of material takes place at the conically-formed floor of the reactor, while the mashed waste and recirculated material are fed into the head of the reactor so that the material flows downwards through the reactor. The hydraulic retention time is about 20-30 days. Due to the large circulation flow from the substrate introduction the reactor content is circulated within two work days and signifies as such a semi-continuous mixed operation. The drainage of the fermentation residue takes place with sieve spiral presses with the addition of flocculation agents

[Fricke et al. 2003].

Biowaste is pre-chopped in the *KOMPOGAS process* and/or sieved to a particle size of < approx. 80mm, undergone Fe separation and confectioned to a particle size of <40mm in a second chopping phase with a cutting slide mill and finally stored in an interim bunker, as shown in *Figure 6.24*.

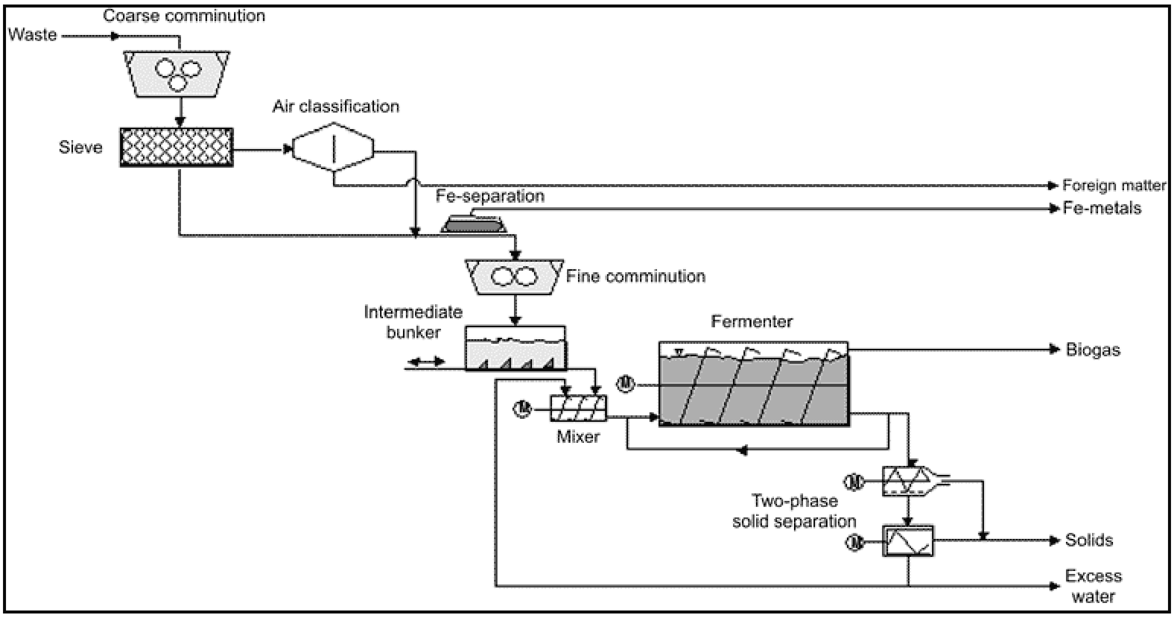


Fig. 6.24: Schema of the KOMPOGAS process [Fricke et al. 2003]

The storage capacity is laid out over a period of 3 days and enables the continuous feeding of the fermentation even over the weekend. Specific aerobic hydrolysis is not undertaken. The conditioned biowaste are mashed with process water to a dry substance content between around 25 and 30% and fed semi-continuously into the reactor by means of solids pumps. The lying reactor operates according to the plug-flow principle. The anaerobic treatment of the substrate takes place solely at thermophilic temperatures of between approx. 55 and 58°C. The reactor input is heated in double pipeline heat conductors, while the radiation losses are compensated for by reactor heating. The retention time in the reactor is approximately 15-20 days. The reactor outflow is partially refed for inoculation of the input material with active biomass. The surplus material is treated in a two-phase drainage using sieve spiral presses and decanters The decanter outflow is then in part used for mashing the waste.

The advanced purification of the process water generally takes place utilisation of flocculation agents, whereby the dry substance content of the waste water is reduced to less than 2%. Experience is available for bio and residual waste [Fricke et al. 2003].

Percolation processing is consisted of aerobic pre-treatment, percolation and downstream fermentation. The processing concept of percolation dates back to 1978 to a two-stage, two-phase described biological processing by Gosch for quicker degradation of organic substances in reactor disposals. In the first stage the solid waste undergoes anaerobic hydrolysis. The resulting diluted waste products are absorbed by the added watery phase and finally fed into a fermenter. In 1997 the first mobile demonstration plant with a yearly capacity of 500 Mg was installed in Ravensburg, Germany. As examples of percolation processing the ISKA® percolation process and the IMK process are illustrated.

In the demonstration plant erected at the landfill in Sansenhecken, Neckar-Oden-waldkreis, *ISKA®-percolation processing* deals with a two-phase plant with upstream mechanical conditioning. The plant, which is at the moment laid out for a treatment capacity of 25,000 Mg/a, is currently being expanded for a processing amount of 150,000 Mg/a. The waste input consists of total waste, a separate biowaste collection does not take place in Neckar-Odenwald county, Germany. In the mechanical conditioning the waste packaging is opened with sack openers and subsequently separated into a coarse fraction with high heating value and a degradable organically-enriched fine fraction by a drum sieve (sieve size 140mm). The fraction <140mm is guided into a metal remover and makes its way finally directly into the percolation reactor.

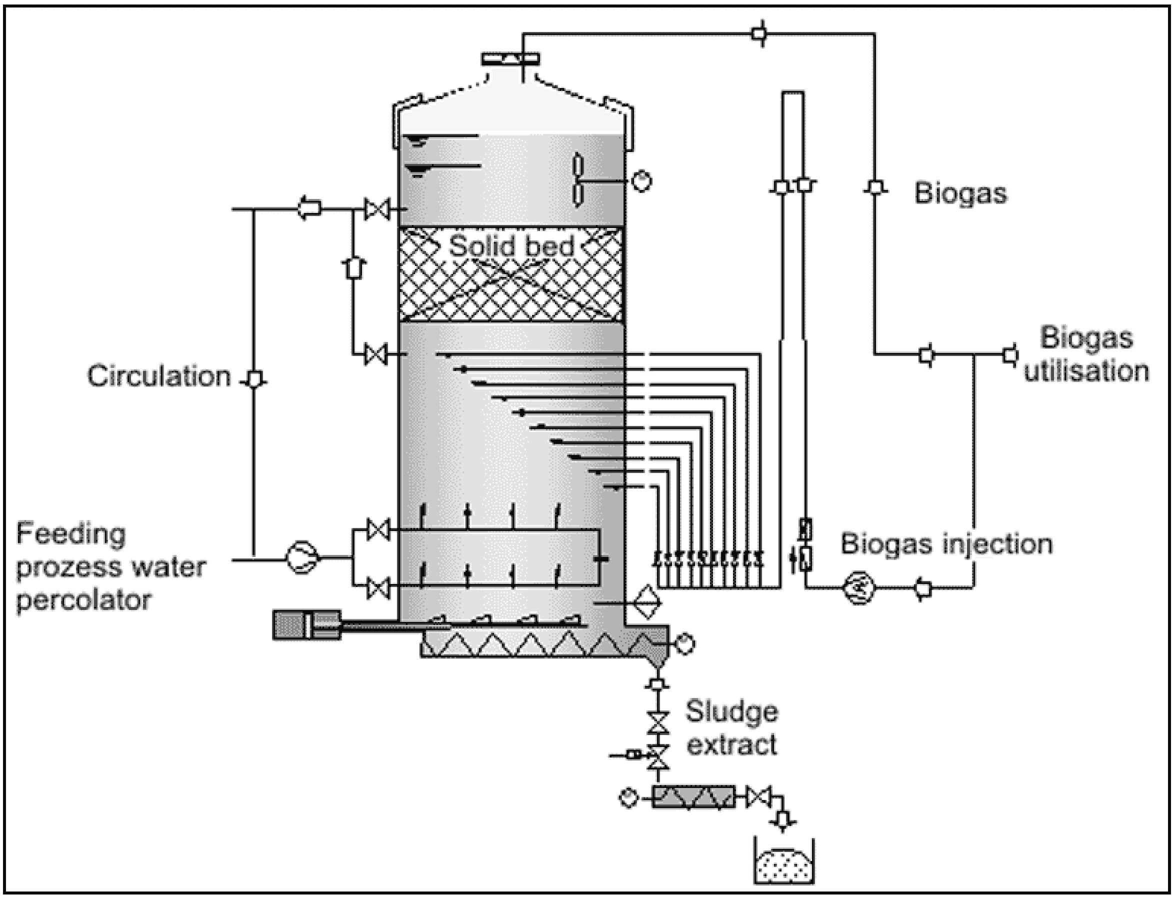


Fig. 6.25: Schema of the ISKA process [Fricke et al. 2003]

In the percolator the material is circulated through a axial located stirring unit and transported through the reactor. Due to periodic injection of air from the reactor floor the material is aerobically hydrolysed in the mesophilic temperature area, in order to increasingly carry over organic substances into the dilution phase. Semi-continuously added wash water flows through the material and causes a washing out of the diluted organic substances or a carry-over of the organic substance from the waste into the fluid phase. After a passing through the percolator (retention time 2-4 days) the solids are removed and drained by means of a spiral press. The process water is guided by the sieve bottom of the percolators, together with the press water from drainage and undergoes a sand wash and fibre separation and is finally fed into a high-capacity reactor operating based on the UASB principle. The co-called hybrid reactor is a standing container, in which the process water is injected at the reactor floor and removed at the head of the reactor. The reactor is a combination of a sludge and fixed bed reactor. The lower portion is operated as a sludge bed, while the upper portion is equipped with a fixed bed. The fixed bed is comprised of a loose packing fill. The thorough mixing of the reactor takes place hydraulically as a result of the circulation of the partial flow of the fermented process water. The reactor content can also be mixed pneumatically by the injection of biogas. The injection of biogas is generally used to wash out the surplus bacteria mass in the fixed bed. Solid still present in the process water are held back in the reactor so that a de-coupling of the liquid and solid material phases takes place. The inert solid materials are, therefore periodically removed form the system. The ideal spatial loading of the reactor lies between 8 and 12 kg CSB/m³ d. The reactor is operated mesophilically, the retention time is 2-6 days.

Partial currents of the treated process water are used directly as wash water in the percolation stage. To prevent an accumulation of nitrogen in the process water cycle partial amounts of the process water have to undergo denitrification before being reused.

As an example of a two-phase wet process without separation of solids after the hydrolysis the *Linde-KCA process* is shown. The conditioned waste undergoes a wet processing in a material dilution/ pulper. The heavy and light materials exhibit a dry substance content of approx. 9% after being freed of suspension and is fed into a hydrolysis basin. This is where the acidification and hydrolysis take place under mesophilic operational conditions in a time period of 1-3 days. Depending on the substrate aerobic circumstances (intermittent hydrolysis) can be set optionally by ventilation. The hydrolysis basin is equipped with stirring units for the purpose of homogenisation. The pre-acidified substrate is finally chopped to a particle size of 5 mm using a self-cutting pump and fed into the methane reactor semi-continuously.

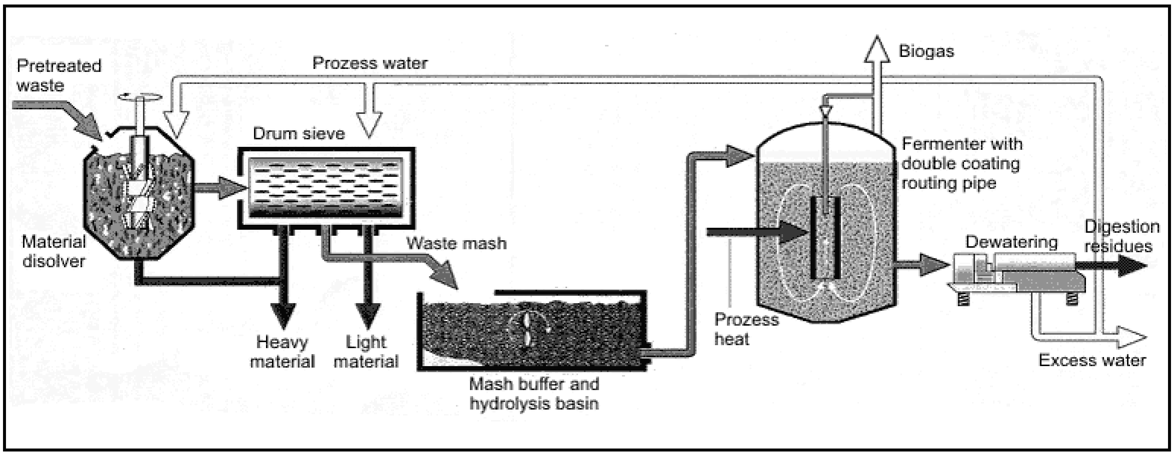


Fig. 6.26: Schema of the Linde KCA process [Fricke et al. 2003]

The reactor is equipped with a pipeline (loop reactor) that is executed as a double-coating pipe and is used as a heat conductor. The thorough mixing of the reactor content takes places pneumatically by injecting biogas into the pipeline. The biogas that is injected into the middle of the pipeline rises and pulls substrate from the inner space of the pipe upwards so that a complete mixing of the reactor content is ensured. The insertion of the suspension is carried out at the reactor head, the fermentation residue removal at the reactor floor. Below the pipeline the mineralised components of the suspension sink due to the lower flow speed and can be removed there. The reactor floor is equipped with a floor surface that has a slant of approximately 10° so that the "tea cup effect" pushes the sediment to the centre. Thereby significant sediment layers can be avoided. The fermentation is operated mesophilically and thermophilically depending on the substrate with hydraulical retention times of around 16 days.

The conditioned waste is also stored in an interim buffer and continuously fed to the fermentation after a fine calibration in to the particle size of <30mm in the *LINDE-BRV process*. The retention time in the interim bunker is approx. 2-4 days. The interim buffer is selectively ventilated and used for aerobic hydrolysis of the material. The aerobic digestion leads additionally to a self-heating of the material do that heating of the reactor input by means of heat conductor is not used. The feeding of the reactor is carried out with a fermenter dosing spiral, which ensures a comparatively gentle material input into the reactor without causing much wear and tear. The setting of the dry substance content at about 30% is achieved by dosing the process water in the input area. The dosing spiral feeds the mashed substrate into the reactor. The sealing of the reactor is guaranteed by the plug remaining constantly in the feed pipe [Fricke et al 2003].

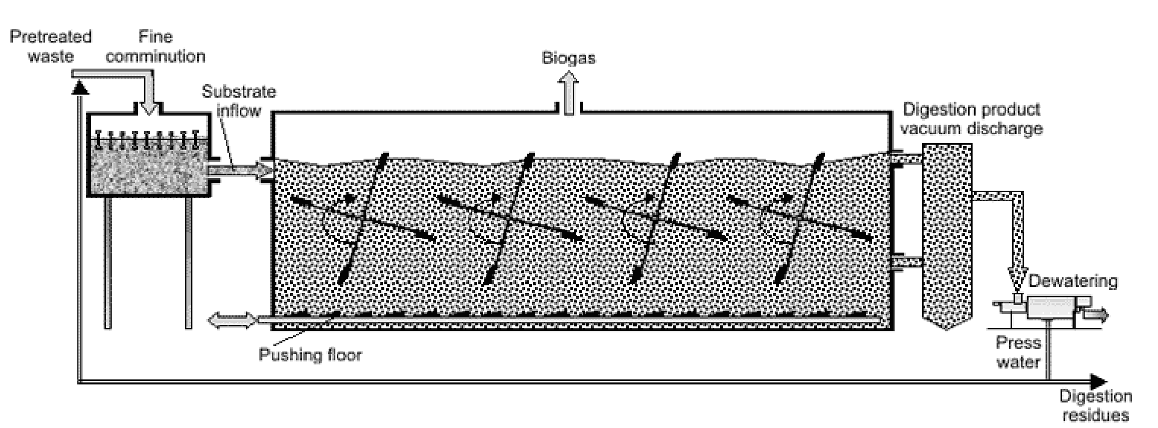


Fig. 6.27: Schema of the Linde BRV process [Fricke et al. 2003]

The reactors are generally executed in a concrete method of construction as a lying fermentation reactor (*Figure 6.27*). The substrate flows through the lying reactor lengthwise as a semi-continuous plug-flow similar to the KOMPOGAS process. The middle hydraulical retention time is around 21 days. The reactor is equipped with several transversely located stirring units with stirring paddles. Aside from improving the gas emission, the formation of floating layers should be avoided as such. The rotational directions of the stirring units are in opposite directions to prevent feeding and is changed periodically. During fermentation of the waste the accumulated inert materials such as stones, sand and glass can be deposited in the reactor and fed into the reactor removal using a drawer floor and extracted. The fermentation substrate is removed at the reactor outflow through several vacuum pipes. The pipes on the reactor floor are used for the removal of sediments that are fed into the drawer. The fermentation residues are drained and post-composted.

BTA processing can condition pre-chopped biowaste from separate collection and residual waste in a one-step wet process. In the subsequential wet processing in a material dilution (BTA-waste-Pulper) coarse and light materials are discharged. Along with the injection of process water a pumpable masher is produced with approx. 10-12% DS and removed through a sieve bottom (openings 8mm). The light materials are extracted by a rake, while the heavy materials have to be removed from the material dilution with the aid of sluices. In order to protect following aggregate from high abrasion, sedimentation and clogging, the suspension is fed into a so-called BTA grit remover (hydrocyclone) - here the small-particle inert materials are removed [Fricke et al 2003].

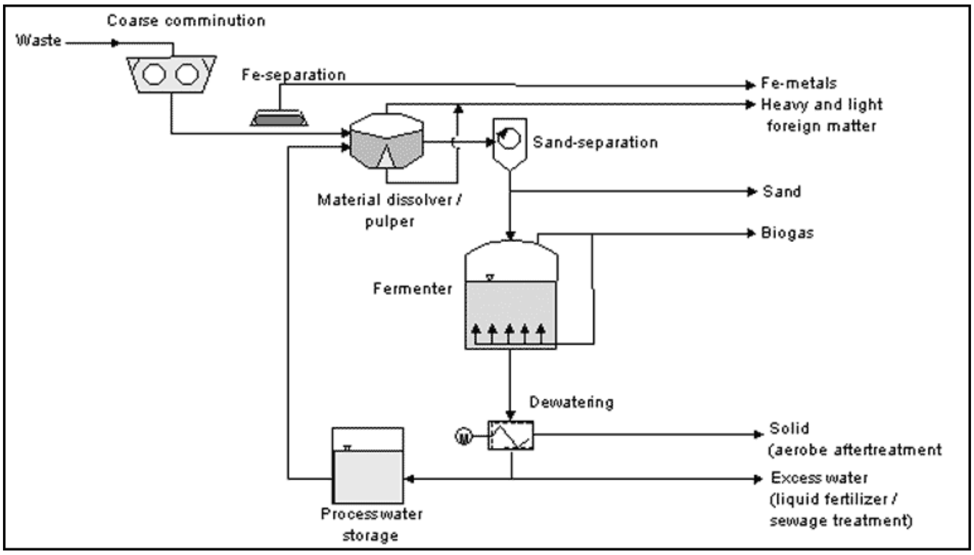


Fig. 6.28: Schema of the one-phase BTA process [Fricke et al. 2003]

An interim storage of the suspension for continuous feeding of the reactor shall be conducted if needed. The reactor is an example of a completely mixed system that is preferably mixed by the injection of biogas through gas lances in a loop-like manner. The methanisation takes place mainly in the mesophilic temperature area operated with hydraulic retention times between 15 and 20 days.

The BTA process is shown in *Figure 6.29* as an example of a two-phase wet process with solid separation after the hydrolysis phase.

The conditioning occurs in the same manner as in the one-phase process. The interimly stored suspension is drained and the fed into the liquid phase of a methanisation stage, while the solids are offset with fluids and fed into the mesophilic operated hydrolysis reactor. The hydrolysis reactor is a completely mixed reactor that is preferably equipped with a pneumatic mixing system. The suspended solids remain in the hydrolysis phase for around 4 days before they are drained again and removed from the process. The fluid phase, rich in accumulated hydrolysed materials, is fed into an upflow modus operated fixed bed reactor, equipped with a loose packing fill. The methanisation takes place with mesophilic temperatures and a retention time of approx. 2 days. Pneumatic or hydraulic mixing of the system does not occur [Fricke et al 2003].

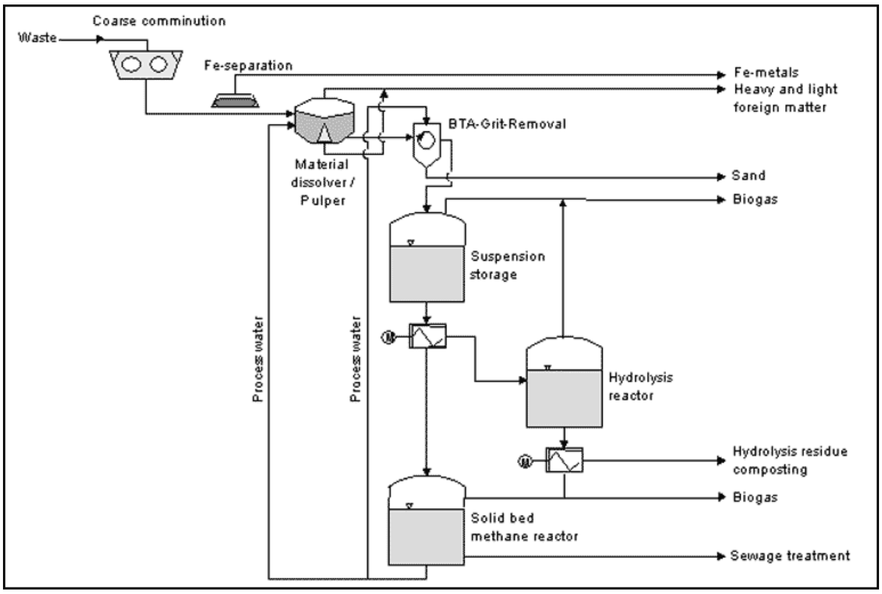


Fig. 6.29: Schema of the two-phase BTA process [Fricke et al. 2003]

The *IMK process* has up to this point only been used in the plant in Herten, Germany for the conditioning of around 18,000 Mg biowaste. The process principle is schematically depicted in *Figure 6.30*. Biowaste is conditioned by chopping, sieving (sieve size 80 mm) and Fe removal and then fed into a hydrolysis reactor. The solids in the batch-engine-powered hydrolysis reactor is mashed to a dry substance content of 25 % with process and used water, circulated through several built-in slanted spirals and then extensively ventilated in order to set the aerobic hydrolysis. After a retention time of around 1 day the material is drained mechanically with sieve spiral presses and once again fed into the hydrolysis reactor. The process of material dilution is repeated twice before the solids are fed to the maturation phase. Before being inserted into the methanisation inert materials from the process water are separated by a hydrocyclone. The reactor in use is a completely mixed reactor that is equipped with propeller stirring units located on the sides of the reactor floor. The retention time in the mesophilic operated reactor is approx. 10-14 days. The bacteria mass is separated using a hydrocyclone after the methanisation in order to increase the process stability and in part fed back into the reactor. Remaining process water is fed back into the hydrolysis for mashing, surplus water can be given to a municipal sewage plant after waste water treatment [Fricke et al 2003].

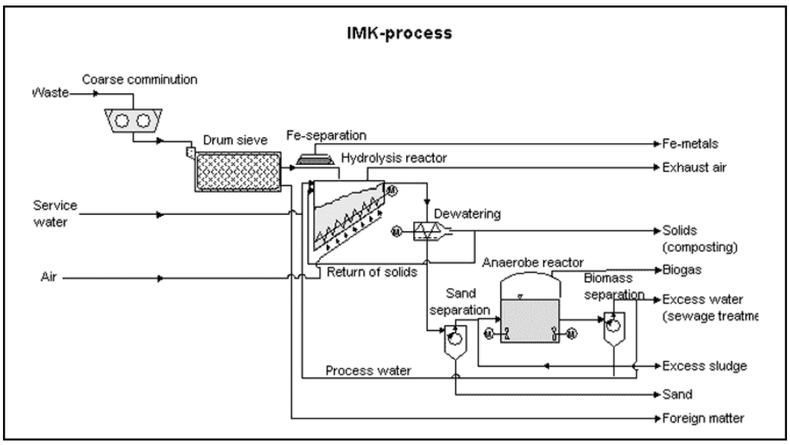


Fig. 6.30: Schema of the IMK process [Fricke et al. 2003]

Coarsely chopped biowaste are first sieved in the *WABIO process* (see *Figure 6.31*). The fine fraction <50mm is then fed into a conditioning container together with a pre-temperised process water collector and homogenised until suspension with a dry substance content of around 15% is achieved.

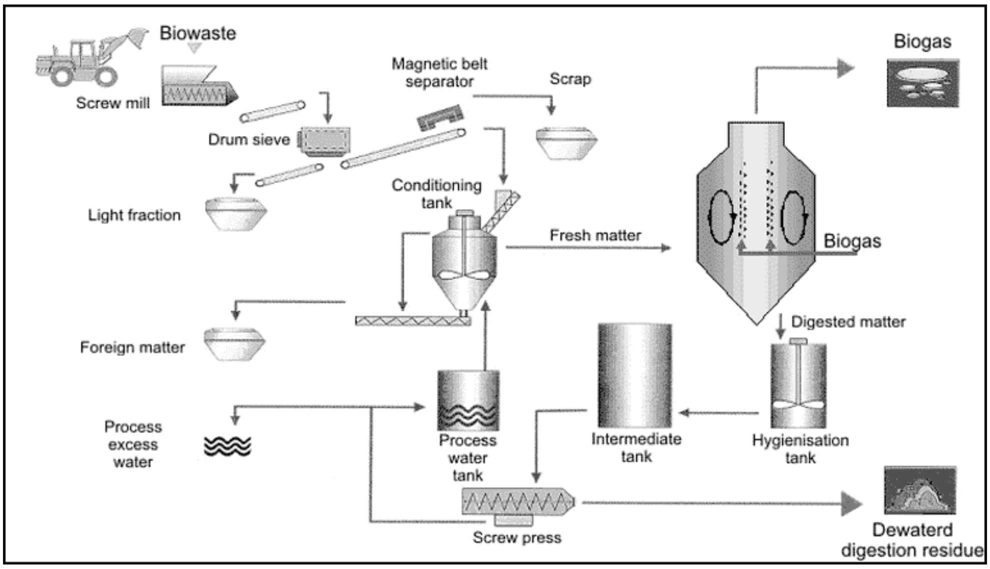


Fig. 6.31: Schema of the WABIO process [Fricke et al. 2003]

Heavy materials are deposited during homogenisation and are removed from the conditioning container, organic adhesions are separated with the aid of cleansing mechanisms and fed back into the process. With the help of paddle mechanisms light materials are siphoned off and removed. The suspension is continuously fed into the fermentation by means of rotating piston engines.

The reactor is operated in mesophilic temperature areas and has a hydraulic retention time of from around 14 to 20 days. The suspension is thoroughly mixed using a pneumatic stirring unit. Thereby a densified biogas is injected at the container floor by a nozzle ring and an elliptical, vertical or loop-like flow is induced. A zone formation of different material compositions that can lead to a acidification of the fermenter content. It should, however, be prohibited by the homogenising effect of the loop-flow.

In a container the fermented suspension - DS approx. 10% at 70°C is hygenised for over an hour and afterwards drained using a sieve spiral presses and the addition of flocculation agents [Fricke et al 2003].

Description of the Selected Fermentation Plants

Figure 6.32 shows the process schema of a *one-phase mesophilic fermentation from the plant manufacturer Entec GmbH*. The plant is comprised of a liquid manure dump and a solid material input, a reactor with 2,500 m³ volume and an external 500m³ gas storage with a water catchment capacity of 10,000 m³.

110 m³ of substrate are treated daily, which is made up of 95% cattle liquid manure, 3% cattle dung and 2% maize silage. The resulting biogas is biologically desulphurised and used in a CHP with a capacity of 373 kW [Weiland et al. 2004].

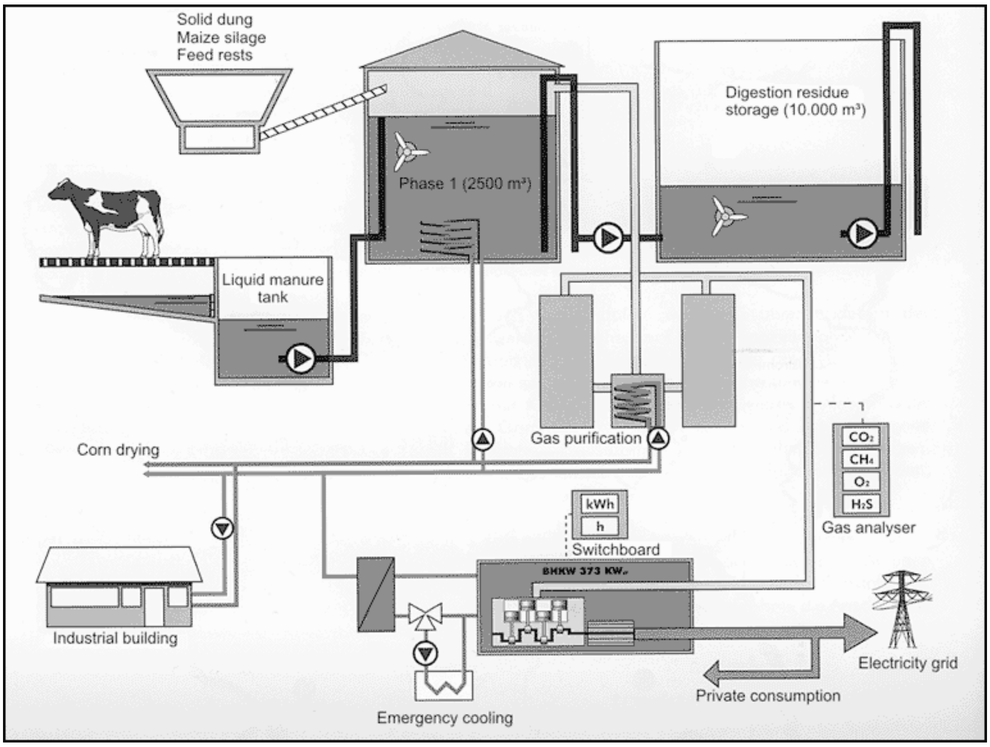


Fig. 6.32: One-phase mesophilic fermentation – Entec GmbH [Weiland et al. 2004]

Further parameters are shown in *Figure 6.33*.

General operating data:

Livestock: 1.150 cattle	AU: 1.150 AU/ha: 1,1 (AU = animal unit) (1ha = 10.000m²)	Area under cultivation:	Farmland: 850,0 ha Grassland: 200,0 ha Renewable resources: 128,0 ha From set aside land: 0 %

Biogas plant (BP): Phases: 1 Manufacturer: Entec GmbH

		DS	oDS	NH_4-N	N_{total}
Average composition of the apllied substrate mix	[kg/t] resp. [% FM]	6,6	5,3	3,6	5,6

Frequency of substrate addition: 6 d^{-1} **Series operation**

		Stufe 1
Operating temperature	[°C]	39
Volume	[m³]	2.500
Reactor system (standing/lying)		s
Added amount of fresh substrate	[t/week]	801
Hydraulic retention time	[d]	20
Volumetric loading	[kg oDS/m³d]	2,5

Digestion residue storage:

Size: 10.000 m³ Cover: none

		DS	oDS	NH_4-N	N_{total}
Composition:	[kg/t] resp. [% FM]	6,2	4,6	2,0	3,8

Gas production:

Biogas production (0° C; 1,013 bar):	17.830	m³/week	resp.	2.547	m³/day
Productivity:	1,02	m³ Biogas/(m³d)		0,61	m³ CH_4/(m³d)
Gas quality before BHKW:	58,5	Vol-% CH_4	Vol-% O_2	103	ppm H_2S

BHKW: Number: 1

	BHKW 1
Type(benzine/ignition/gas):	G
Number of cylinders:	12
Manufacturer:	Seva
Engine:	Deutz

Total specific electric output: 49,1 kWh/t substrate

		BHKW 1
Electric output:		
Electric power rating:	[kW]	373
Average output:	[kW]	244
Power output utilisation:	[%]	65
Utilisation:	[%]	65
Electric yield:	[kWh/week]	40.655
Electric efficiency:	[%]	37,9
Heat output:		
Average output:	[kW]	334
Heat yield:	[kWh/week]	55.435
Thermal efficiency:	[%]	47,8
Total efficiency:	[%]	**85,7**

Substrates	Mass-%
Cattle liquid manure	95,1
Cattle dung	2,8
Silo maize	2,1
Number of substrates:	**3**

Energy balance:

Total power consumption (BP):	0,8	kWh/t substrate	**Total heat consumption (BP):**	43,1	kWh/t substrate
Total power consumption:	687	kWh/week	**Total heat consumption:**	35.617	kWh/week
Share of production:	1,7	%	**Share of production:**	64,3	%

Fig. 6.33: Technical data sheet – Entec GmbH [Weiland et al. 2004]

Figure 6.34 schematically shows a *two-phase mesophilic process with lying fermenter from Schmack Biogas AG*. The system contains a 120 m³ mixing pit, a lying concrete fermenter with the insertion of solids. The post-fermentation takes place in a 1000 m³ container with gas storage.

The plant uses 24 m³ of substrate daily, which is made up of 58% cattle liquid manure, 34%

renewable resources and 8% solid dung.

The biogas desulphurisation occurs through air injection into the post-fermenter. The gas is used by two 55kw pilot injection CHP. An external heat usage does not occur [Weiland et al. 2004].

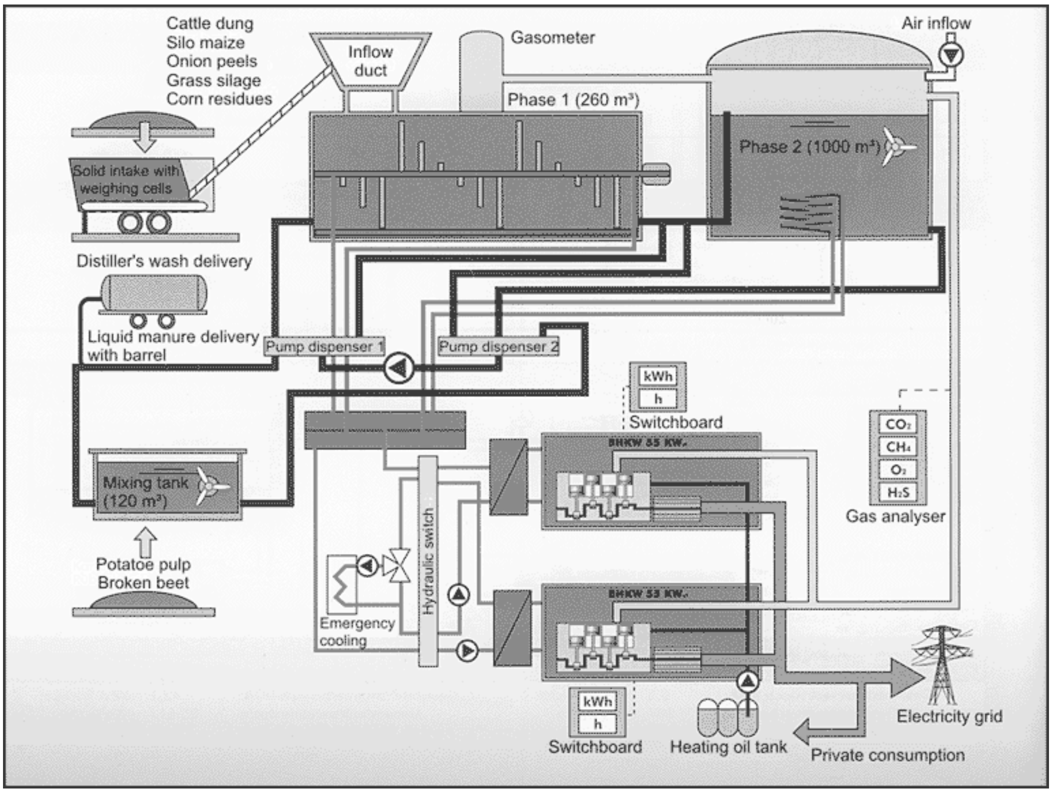


Fig. 6.34: Two-phase mesophilic fermentation – Schmack Biogas AG [Weiland et al. 2004]

General operating data:

Livestock:	100 Dairy cows 100 Cow calf 100 Fattening bulls	AU: 230 AU/ha: 1,5 (AU = animal unit) (1ha = 10.000m²)	Area under cultivation:	Farmland: 80,0 ha Grassland: 70,0 ha Renewable resources: 6,0 ha From set aside land: 11 %

Biogas plant (BP): Phases: 2 Manufacturer: Schmack

		DS	oDS	NH_4-N	N_{total}
Average composition of the apllied substrate mix	[kg/t] resp. [% FM]	14,0	11,9	1,7	4,6

Frequency of substrate addition: 2 d^{-1} **Series operation**

		Phase 1	**Phase 2**	**Total**
Operating temperature	[°C]	39	40	
Volume	[m³]	260	1.000	1.260
Reactor system (standing/lying)		l	s	
Added amount of fresh substrate	[t/week]	61	107	168
Hydraulic retention time	[d]	35	50	85
Volumetric loading	[kg oDS/m³d]	6,4	1,3	

Digestion residue storage:

Size: : 1.500 m³ Cover: none

		DS	oDS	NH_4-N	N_{total}
Composition:	[kg/t] resp. [% FM]	5,1	3,6	2,5	4,2

Gas production:

Biogas production (0° C; 1,013 bar):	6.574 m³/week	resp.	939 m³/day	
Productivity:	0,70 m³ Biogas/(m³d)		0,42 m³ CH_4/(m³d)	
Gas quality before BHKW:	56,8 Vol-% CH_4	0,2 Vol-% O_2		189 ppm H_2S

BHKW: Number: 2

	BHKW 1	BHKW 2
Type(benzine/ignition/gas):	I	I
Number of cylinders:	4	4
Manufacturer:	Schnell	Schnell
Engine:	Perkins	Perkins
Amount of ignition oil [%]:	18,2	11,5

Total specific electric output: 93,0 kWh/t substrate

		BHKW 1	BHKW 2	Total
Electric output:				
Electric power rating:	[kW]	55	55	110
Average output:	[kW]	55	55	110
Power output utilisation:	[%]	100	100	100
Utilisation:	[%]	69	88	79
Electric yield:	[kWh/week]	6.376	8.153	14.529
Electric efficiency:	[%]	31,9	33,9	32,9
Heat output:				
Average output:	[kW]			
Heat yield:	[kWh/week]			
Thermal efficiency:	[%]			
Total efficiency:	[%]			

Substrates	Mass-%
Cattle liquid manure	57,8
Distiller's wash	16,5
Cattle dung	7,7
Silo maize	5,8
Grass silage	5,3
Onion peels	2,4
Potatoe pulp	2,1
Corn residues	2,0
Broken beet	0,4
Number of substrates:	9

Energy balance:

Total power consumption (BP):	9,1	kWh/t substrate	**Total heat consumption (BP):**	k.A.	kWh/t substrate
Total power consumption:	1.536	kWh/week	**Total heat consumption:**	k.A.	kWh/week
Share of production:	10,6	%	**Share of production:**	k.A.	%

Fig. 6.35: Technical data sheet – Schmack Biogas AG [Weiland et al. 2004]

The two-phase mesophilic and thermophilic wet fermentation process from Archea GmbH is comprised of a dung pit, a standing 200m³ steel fermenter with insertion of solids and a standing 350m³ post-fermentation container with gas storage, as illustrated in Figure 6.36. A 250m³ tank serves as fermentation residue storage. The plant is fed 5m³ of substrate daily that is made up of 36% pig liquid manure and 64% renewable resources. A biological desulphurisation takes place in the post-fer-menter by air injection. The biogas is used by a pilot injected CHP with an electrical capacity of 80 kW. Further technical data are listed in *Figure 6.37* [Weiland et a. 2004].

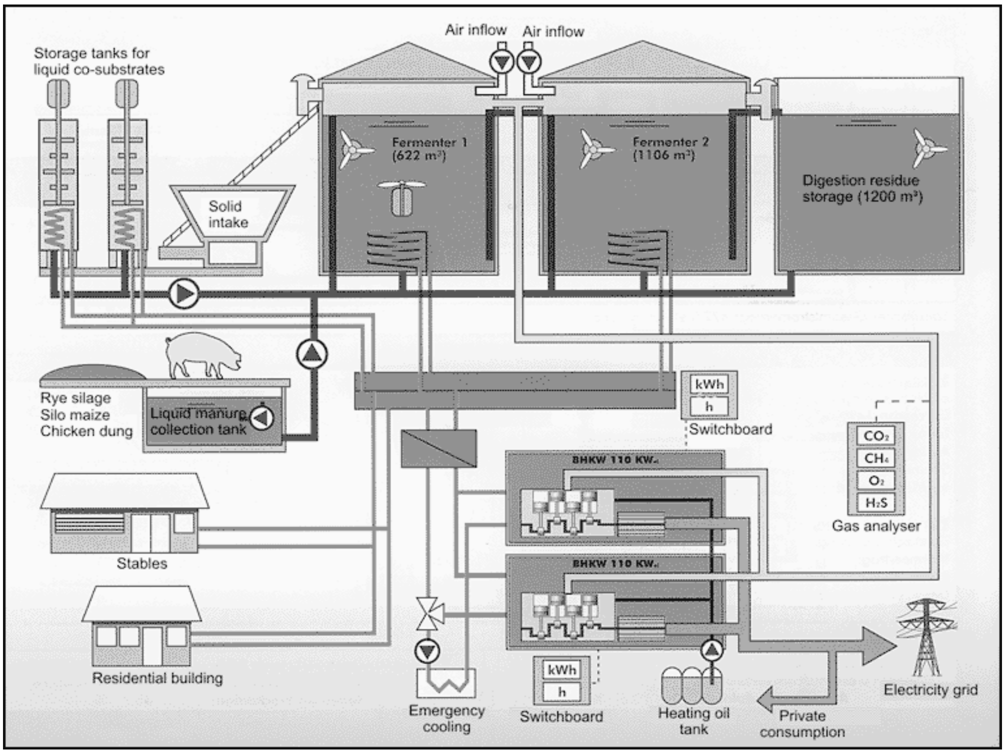


Fig. 6.36: Two-phase mesophilic fermentation – Archea GmbH [Weiland et al. 2004]

General operating data:

Livestock:	70 Mother sows	AU: 73	Area under cultivation:	Farmland:	200,0 ha
	400 Fattening pigs	AU/ha: 0,4		Grassland:	0,0 ha
				Renewable resources:	10,0 ha
		(AU = animal unit) (1ha = 10.000m²)		From set aside land:	100 %

Biogas plant (BP): Phases: 2 Manufacturer: Archea

		DS	oDS	NH_4-N	N_{total}
Average composition of the apllied substrate mix	[kg/t] resp. [% FM]	18,3	16,2	1,9	5,0

Frequency of substrate addition: 20 d^{-1} **Series operation**

		Phase 1	Phase 2		Total
Operating temperature	[°C]	49	27		
Volume	[m³]	200	350		550
Reactor system (standing/lying)		l	s		
Added amount of fresh substrate	[t/week]	37			37
Hydraulic retention time	[d]	30	60		90
Volumetric loading	[kg oDS/m³d]	4,7	0,9		

Digestion residue storage:

Size: 250 m³ Cover: not gas proof

		DS	oDS	NH_4-N	N_{total}
Composition:	[kg/t] resp. [% FM]	6,7	4,8	3,2	5,1

Gas production:

Biogas production (0° C; 1,013 bar):	5.045 m³/week	resp.	721 m³/day	
Productivity:	1,31 m³ Biogas/(m³d)		0,69 m³ CH_4/(m³d)	
Gas quality before BHKW:	52,9 Vol-% CH_4	1,3 Vol-% O_2		244 ppm H_2S

BHKW: Number: 1

	BHKW 1
Type(benzine/ignition/gas):	I
Number of cylinders:	6
Manufacturer:	Schnell
Engine:	Perkins
Amount of ignition oil [%]:	9,1

Total specific electric output: : 292,0 kWh substrate

		BHKW 1
Electric output:		
Electric power rating:	[kW]	80
Average output:	[kW]	79
Power output utilisation:	[%]	99
Utilisation:	[%]	80
Electric yield:	[kWh/week]	10.713
Electric efficiency:	[%]	36,7
Heat output:		
Average output:	[kW]	69
Heat yield:	[kWh/week]	9.252
Thermal efficiency:	[%]	32,0
Total efficiency:	[%]	**68,7**

Substrates	Mass-%
Silo maize	42,4
Pig liquid manure	36,8
Extraction residues	20,7
Number of substrates	**3**

Energy balance:

Total power consumption (BP):	34,3	kWh/t substrate	**Total heat consumption (BP):**	98,8	kWh/t substrate
Total power consumption:	1.133	kWh/week	**Total heat consumption:**	3.583	kWh/week
Share of production:	10,6	%	**Share of production:**	38,7	%

Fig. 6.37: Technical data sheet – Archae GmbH [Weiland et al. 2004]

Biogas Nord designed a mesophilic wet fermentation process that is made up of two steel storage tanks connected in a row, a collection dung pit and a standing 622m³ concrete fermenter with the insertion of solids and a 1106m³ concrete post-fermenter (*Figure 6.38*). An open disposal zone with 1200m³ volume is a part of the system. 9m³ of substrate are fed into the fermenter hourly. The substrate is composed of 37% pig liquid manure, 7% chicken solid dung and 56% co-substrates. The biogas is biologically desulphurised by the addition of air into the reactor and post-fermentation container. The two installed pilot injection CHP each have a capacity of 110 kW [Weiland et a. 2004].

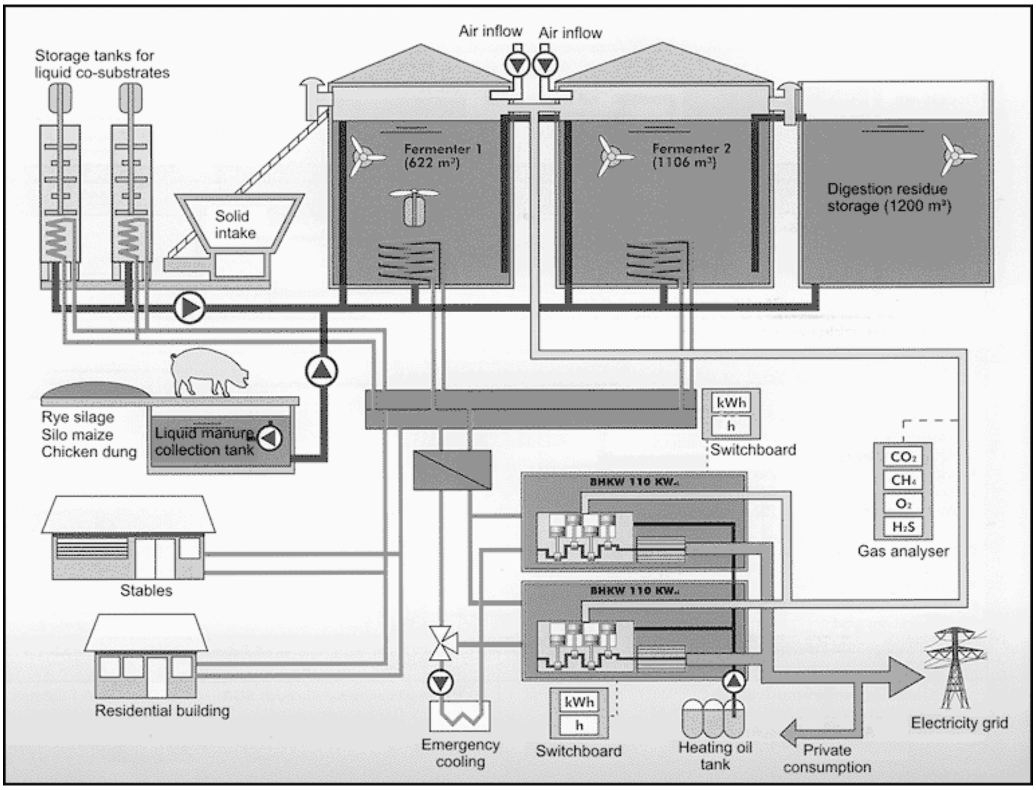


Fig. 6.38: Two-phase mesophilic fermentation – Biogas Nord GmbH [Weiland et al. 2004]

General operating data:

Livestock:	1.200 Fattening pigs	AU: 168	Area under cultivation:	Farmland:	80,0 ha
		AU/ha: 2,1		Grassland:	0,0 ha
		(AU = animal unit)		Renewable resources:	20,0 ha
		(1ha = 10.000m²)		From set aside land:	40 %

Biogas plant (BP): Phases: 2 Manufacturer: Biogas Nord

		DS	oDS	NH_4-N	N_{total}
Average composition of the apllied substrate mix	[kg/t] resp. [% FM]	26,0	23,0	3,2	7,7

Frequency of substrate addition: 24 d^{-1} **Series operation**

		Phase 1	Phase 2	Total
Operating temperature	[°C]	42	40	
Volume	[m³]	622	1.106	1.728
Reactor system (standing/lying)		s	s	
Added amount of fresh substrate	[t/week]	45	20	65
Hydraulic retention time	[d]	125	164	289
Volumetric loading	[kg oDS/m³d]	2,7	0,7	

Digestion residue storage:

Size: : 1.200 m³ Cover: none

		DS	oDS	NH_4-N	N_{total}
Composition:	[kg/t] resp. [% FM]	4,7	2,7	5,5	7,1

Gas production:

Biogas production (0° C; 1,013 bar):	13.297	m³/week	resp.	1.900	m³/day	
Productivity:	1,10	m³ Biogas/(m³d)		0,61	m³ CH_4/(m³d)	
Gas quality before BHKW:	55,7	Vol-% CH_4	1,1	Vol-% O_2	433	ppm H_2S

BHKW: Number: 2

	BHKW 1	BHKW 2
Type(benzine/ignition/gas):	I	I
Number of cylinders:	6	6
Manufacturer:	D&B	D&B
Engine:	Deutz	Deutz
Amount of ignition oil [%]:	11,5	10,0

Total specific electric output: : 472,2 kWh, substrate

		BHKW 1	BHKW 2	Total
Electric output:				
Electric power rating:	[kW]	110	110	220
Average output:	[kW]	101	107	208
Power output utilisation:	[%]	92	97	95
Utilisation:	[%]	68	91	79
Electric yield:	[kWh/week]	12.494	16.811	29.305
Electric efficiency:	[%]	34,7	36,1	35,4
Heat output:				
Average output:	[kW]	93	127	220
Heat yield:	[kWh/week]	11.557	18.716	30.273
Thermal efficiency:	[%]	31,0	42,4	36,7
Total efficiency:	[%]	**65,7**	**78,5**	**72,1**

Substrates	Mass-%
Pig liquid manure	37,1
Fat	18,2
Old food	16,8
Flour residues	8,9
Chicken dung	6,8
Silo maize	6,4
Apple marc	2,0
Whey water	1,0
Corn residues	0,7
Turkey dung	0,5
Flotation fat	0,5
Milk fat	0,2
Number of substrates	**12**

Energy balance:

Total power consumption (BP):	15,4	kWh/t substrate	**Total heat consumption (BP):**	64	kWh/t substrate
Total power consumption:	888	kWh/week	**Total heat consumption:**	3.717	kWh/week
Share of production:	3,0	%	**Share of production:**	12,3	%

Fig. 6.39: Technical data sheet – Biogas Nord GmbH [Weiland et al. 2004]

Biogas Weser-Ems operates a *two-phase mesophilic wet fermentation process*. A schematical illustration can be found in *Figure 6.40*. The plant consists of two 100m³ collection containers, a concrete fermenter with 655m³ content and a standing concrete post-fermenter with a volume of 855m³, as well as an open 770m³ disposal zone. The substrate is made up of 55% flotate fat, 32% cattle and pig liquid manure, 10% silo maize and 3% chicken dung. 22m³ are inserted into the fermenter daily. The biogas is chemically desulphurised in the reactor and used for two pilot injection CHP with an electrical capacity of 160 kW respectively [Weiland et a. 2004].

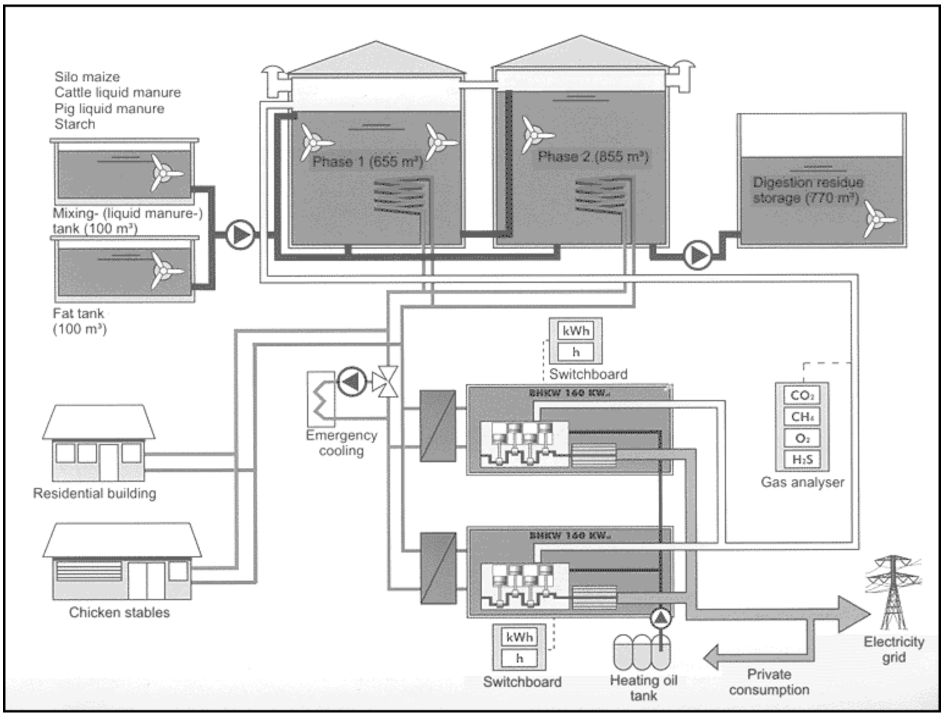


Fig. 6.40: Two-phase mesophilic fermenter – Weser-Ems [Weiland et al. 2004]

General operating data:

Livestock:	80	Fattening bulls	AU:	263
	800	Fattening pigs	AU/ha:	4,0
	42.000	Fattening chicken		
			(AU = animal unit)	
			(1ha = 10.000m²)	

Area under cultivation:		
Farmland:	65,0	ha
Grassland:	0,0	ha
Renewable resources:	0,0	ha
From set aside land:	0	%

Biogas plant (BP): Phases: 2 Manufacturer: Biogas Weser-Ems

		DS	oDS	NH_4-N	N_{total}
Average composition of the apllied substrate mix	[kg/t] resp. [% FM]	12,0	10,4	3,2	7,5

Frequency of substrate addition: 12 d^{-1} **Series operation**

		Phase 1	Phase 2	Total
Operating temperature	[°C]	42	40	
Volume	[m³]	655	855	1.510
Reactor system (standing/lying)		s	s	
Added amount of fresh substrate	[t/week]	116	40	156
Hydraulic retention time	[d]	41	47	88
Volumetric loading	[kg oDS/m³d]	2,3	1,4	

Digestion residue storage:

Size: 770 m³ Cover: none

		DS	oDS	NH_4-N	N_{total}
Composition:	[kg/t] resp. [% FM]	5,4	4,0	5,4	7,4

Gas production:

Biogas production (0° C; 1,013 bar):	14.314	m³/week	resp.	2.045	m³/day
Productivity:	1,35	m³ Biogas/(m³d)		0,87	m³ CH_4/(m³d)
Gas quality before BHKW:	63,9	Vol-% CH_4	0,1 Vol-% O_2	28	ppm H_2S

BHKW: Number: 2

	BHKW 1	BHKW 2
Type(benzine/ignition/gas):	I	I
Number of cylinders:	6	6
Manufacturer:	Seva	Seva
Engine:	Volvo	Volvo
Amount of ignition oil [%]:	11,9	13,6

Total specific electric output: : 256,5 kWh, substrate

		BHKW 1	BHKW 2	Total
Electric output:				
Electric power rating:	[kW]	160	160	320
Average output:	[kW]	140	144	284
Power output utilisation:	[%]	88	90	89
Utilisation:	[%]	86	48	67
Electric yield:	[kWh/week]	23.038	13.004	36.042
Electric efficiency:	[%]	34,4	34,6	34,5
Heat output:				
Average output:	[kW]	129	131	260
Heat yield:	[kWh/week]	21.398	13.494	34.892
Thermal efficiency:	[%]	32,3	31,5	31,9
Total efficiency:	[%]	66,7	66,1	66,4

Substrates	Mass-%
Flotation fat	54,5
Cattle liquid manure	17,5
Pig liquid manure	15,3
Silo maize	9,1
Chicken dung	3,3
Pig dung	0,2
Number of substrates:	6

Energy balance:

Total power consumption (BP):	17,2	kWh/t substrate
Total power consumption:	2.406	kWh/week
Share of production:	6,7	%
Total heat consumption (BP):	83,1	kWh/t substrate
Total heat consumption:	10.813	kWh/week
Share of production:	31,0	%

Fig. 6.41: Technical data sheet – Weser-Ems [Weiland et al. 2004]

Euro-Biogas operates a *three-phase mesophilic and thermophilic wet fermentation process* with chemical desulphurisation. The schematically process procedure is illustrated in *Figure 6.42*. The fermentation plant has three collection pits (120 m³), two standing 708 m³ concrete fermenters (phase 1 mesophilic, phase 2 thermophilic) and a gas-tight post fermenter with a volume of 2000 m², which simultaneously serves as gas storage. In addition, there is a 200 m³ external foil gas storage.

21 m³ of substrate are required daily. This is made up of 15% silo maize, 4% cattle liquid manure and 81% co-substrates. The desulphurisation of the gas takes place chemically with the addition of iron-(II) into one of the collection pits. The gas use occurs through a 320 kW pilot injection CHP [Weiland et a. 2004].

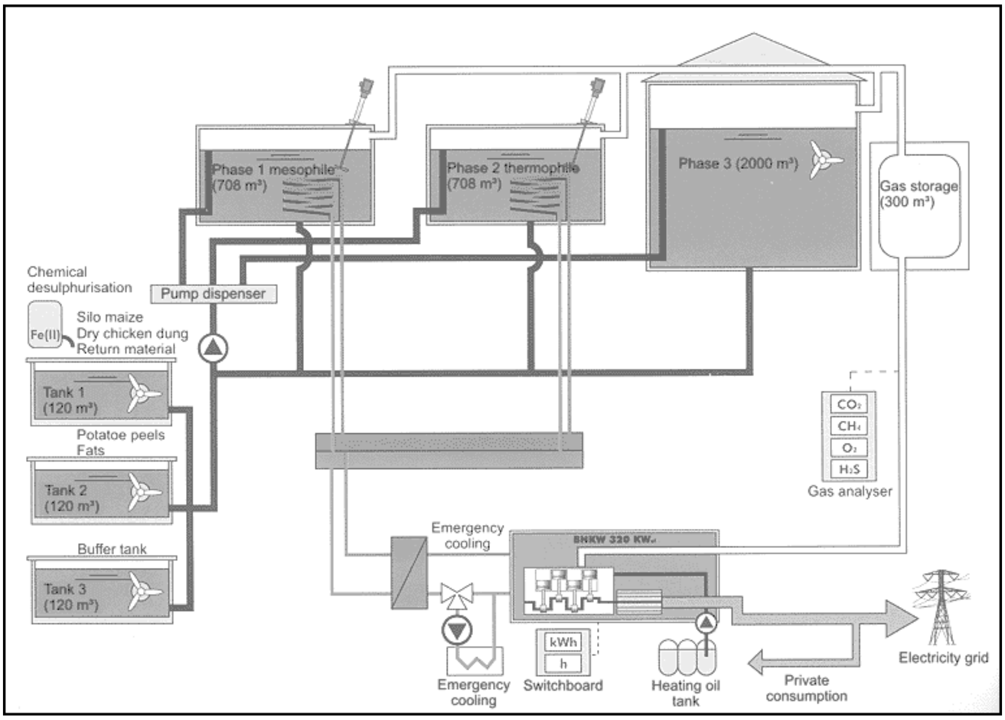


Fig. 6.42: Three-phase mesophilic fermentation – Euro-Biogas [Weiland et al. 2004]

General operating data:

Without livestock	Area under cultivation:	Farmland:	230,0 ha
		Grassland:	0,0 ha
		Renewable resources:	40,0 ha
		From set aside land:	75 %

Biogas plant (BP): Phases: 3 Manufacturer: Euro-Biogas (Soltauer Gruppe)

		DS	oDS	NH_4-N	N_{total}
Average composition of the apllied substrate mix	[kg/t] resp. [% FM]	25,4	22,7	1,1	4,7

Frequency of substrate addition: 12 d^{-1} **Parallel operation**

		Phase 1	Phase 2	Phase 3		Total
Operating temperature	[°C]	40	53	34		
Volume	[m³]	708	708	2.000		3.416
Reactor system (standing/lying)		s	s	s		
Added amount of fresh substrate	[t/week]	62	50	37		149
Hydraulic retention time	[d]	57	190	106		353
Volumetric loading	[kg oDS/m³d]	3,1	2,5	0,9		

Digestion residue storage:

Size: : 2.000 m³ Cover: gas proof

		DS	oDS	NH_4-N	N_{total}
Composition:	[kg/t] resp. [% FM]	3,6	2,4	2,7	3,8

Gas production:

Biogas production (0° C; 1,013 bar):	14.505	m³/week	resp.	2.072	m³/day
Productivity:	0,6	m³ Biogas/(m³d)		0,32	m³ CH_4/(m³d)
Gas quality before BHKW:	55,3	Vol-% CH_4	0,8 Vol-% O_2	257	ppm H_2S

BHKW: Number: 1 BHKW 1

	BHKW 1
Type(benzine/ignition/gas):	I
Number of cylinders:	6
Manufacturer:	Seva
Engine:	Volvo
Amount of ignition oil [%]:	14,8

Total specific electric output: : 274,6 kWh, substrate

		BHKW 1
Electric output:		
Electric power rating:	[kW]	320
Average output:	[kW]	285
Power output utilisation:	[%]	89
Utilisation:	[%]	66
Electric yield:	[kWh/week]	35.559
Electric efficiency:	[%]	37,5
Heat output:		
Average output:	[kW]	260
Heat yield:	[kWh/week]	34.892
Thermal efficiency:	[%]	31,9
Total efficiency:	[%]	**69,4**

Substrates	Mass-%
Potatoe peels	45,7
Fat	18,6
Silo maize	15,3
Chicken dung	6,9
Inoculation sludge	4,3
Cattle liquid manure	3,7
Flour waste	2,9
Biowaste	1,0
Whey	0,9
Corn residues	0,6
Number of substrates:	**10**

Energy balance:

Total power consumption (BP):	26,9	kWh/t substrate	**Total heat consumption (BP):**	94,7	kWh/t substrate
Total power consumption:	3.366	kWh/week	**Total heat consumption:**	11.432	kWh/week
Share of production:	9,5	%	**Share of production:**	32,8	%

Fig. 6.43: Technical data sheet – Euro-Biogas [Weiland et al. 2004]

MT Energie GmbH offers a *thermophilic wet fermentation process* with potential hygienisation phase. A schema is shown in *Figure 6.44*. It consists of a 255m³ hydrolysis mixing container with the insertion of solids, two fermenters connected in a row (volume based on need 1870m³ or

2244m³) and a gas-tight 2400m³ disposal zone.

The amount of substrate fed daily is 43m³. The substrate is made up of silo maize, catering waste, grass silage and other co-substrates, as well as cattle and pig liquid manure. The biogas is desulphurised by the injection of air into the reactors and disposal area. Three pilot injection CHP (two with 250 kW respectively, and one with 55kw) use the biogas [Weiland et a. 2004].

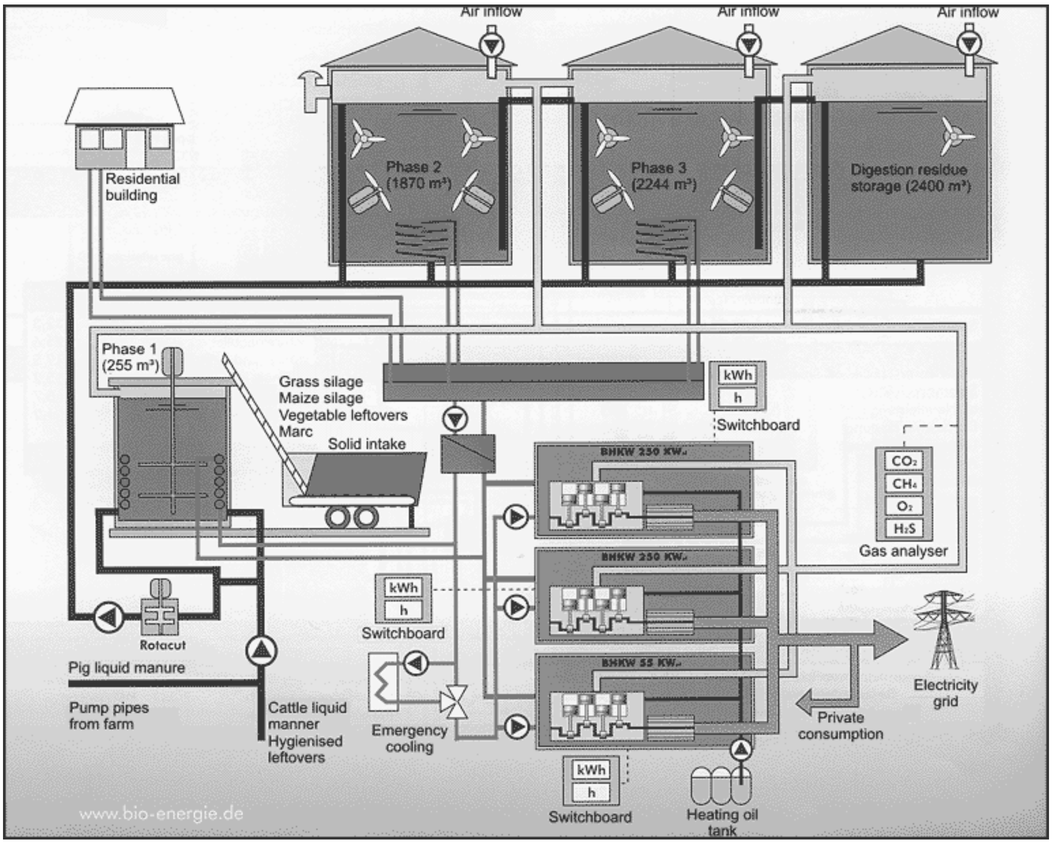


Fig. 6.44: Three-phase thermophilic fermentation – MT Energie GmbH [Weiland et al. 2004]

General operating data:

Livestock:	80 Fattening pigs 1.100 Fattening chicken	AU: 250 AU/ha: 1,8 (AU = animal unit) (1ha = 10.000m²)	Area under cultivation: Farmland: 110,0 ha Grassland: 30,0 ha Renewable resources: 0,0 ha From set aside land: 0 %

Biogas plant (BP): Phases: 3 Manufacturer: MT-Energie

		DS	oDS	NH_4-N	N_{total}
Average composition of the apllied substrate mix	[kg/t] resp. [% FM]	16,8	15,3	1,5	4,7

Frequency of substrate addition: 12 d^{-1} **Series operation**

		Phase 1	Phase 2	Phase 3		Total
Operating temperature	[°C]	54	52	42		
Volume	[m³]	255	1.870	2.244		4.369
Reactor system (standing/lying)		s	s	s		
Added amount of fresh substrate	[t/week]	302				302
Hydraulic retention time	[d]	2	18	31		51
Volumetric loading	[kg oDS/m³d]	35,5	4,7	1,7		

Digestion residue storage:

Size: : 2.400 m³ Cover: gas proof

		DS	oDS	NH_4-N	N_{total}
Composition:	[kg/t] resp. [% FM]	4,4	3,1	3,0	4,2

Gas production:

Biogas production (0° C; 1,013 bar):	39.716 m³/week	resp.	5.674 m³/day	
Productivity:	1,3 m³ Biogas/(m³d)		0,68 m³ CH_4/(m³d)	
Gas quality before BHKW:	51,6 Vol-% CH_4		0,3 Vol-% O_2	72 ppm H_2S

Substrates	Mass-%
Silo maize	34,6
Cattle liquid manure	20,2
Starch- and fat-containing substrates	22,1
Pig liquid manure	18,2
Grass silage	4,8
Corn residues	0,1
Number of substrates	**6**

BHKW: Number: 3

	BHKW 1	BHKW 2	BHKW 3
Type(benzine/ignition/gas):	I	I	I
Number of cylinders:	6	6	4
Manufacturer:	D&B	D&B	Schnell
Engine:	Deutz	Deutz	Perkins
Amount of ignition oil [%]:	9,3	12,3	

Total specific electric output: : 255,3 kWh, substrate

		BHKW 1	BHKW 2	BHKW 3	Total
Electric output:					
Electric power rating:	[kW]	250	250	55	555
Average output:	[kW]	246	236	48	530
Power output utilisation:	[%]	98	94	88	95
Utilisation:	[%]	96	71	77	83
Electric yield:	[kWh/week]	40.265	29.988	7.133	77.386
Electric efficiency:	[%]	34,7	31,8		
Heat output:					
Average output:	[kW]				
Heat yield:	[kWh/week]				
Thermal efficiency:	[%]				
Total efficiency:	[%]				

Energy balance:

Total power consumption (BP):	11,6	kWh/t substrate	**Total heat consumption (BP):**	k.A.	kWh/t substrate
Total power consumption:	3.328	kWh/week	**Total heat consumption:**	k.A.	kWh/week
Share of production:	4,3	%	**Share of production:**	k.A.	%

Fig. 6.45: Technical data sheet – MT Energie GmbH [Weiland et al. 2004]

A *three-phase mesophilic wet fermentation process* is offered by *Novatech GmbH*. A schema is shown in *Figure 6.46*. The plant consists of two lying fermenters with 190 and 205m³ content, a standing 840m³ concrete fermenter and a 1210m³ disposal zone. Biogas can be stored temporarily in an external 240m³ gas storage.

15m³ of substrate are required daily as input. The substrate consists of 40% cattle liquid manure, 34% pig liquid manure, 20% chicken liquid manure and 6% silo maize.

The biogas is biologically desulphurised in the third fermenter by the injection of air and used by a gas CHP with 75 kW electrical capacity [Weiland et a. 2004].

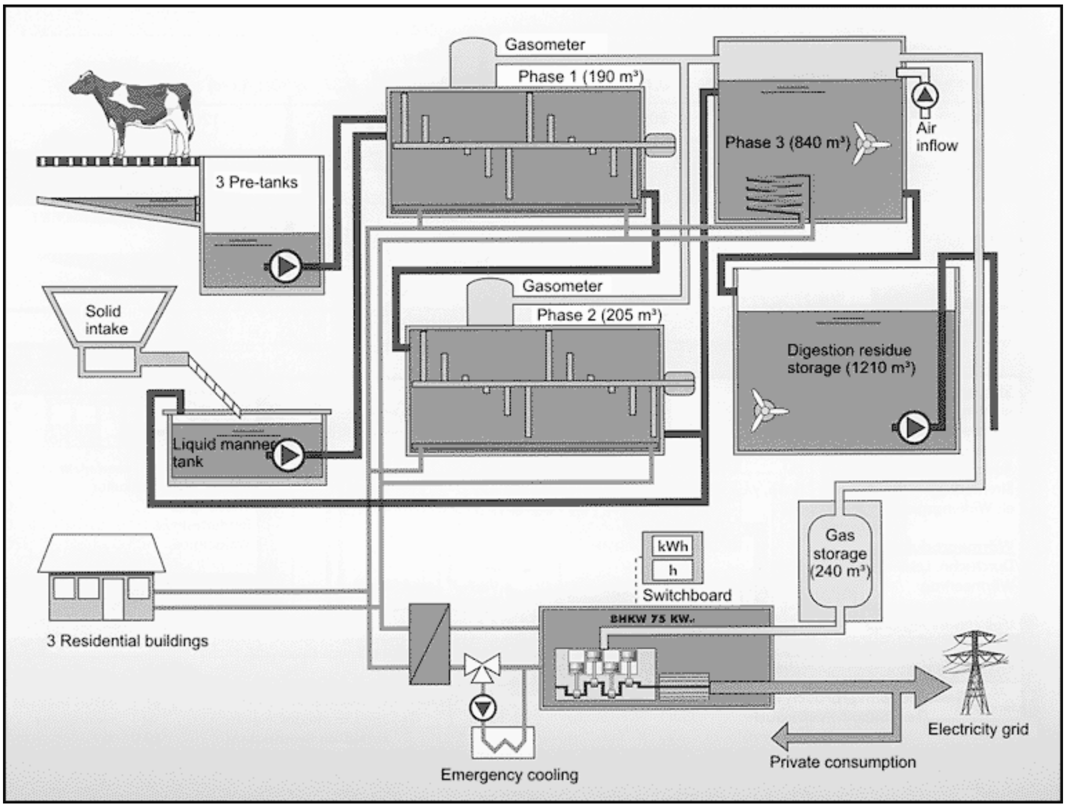


Fig. 6.46: Three-phase mesophilic fermentation – Novatech GmbH [Weiland et al. 2004]

General operating data:

Livestock:	700 Fattening pigs 15.000 Laying hens 50 Dairy cows 50 Cow calves	AU: 225 AU/ha: (AU = animal unit) (1ha = 10.000m²)	Area under cultivation: Farmland: 230,0 ha Grassland: 70,0 ha Renewable resources: 0,0 ha From set aside land: 10 %

Biogas plant (BP): Phases: 3 Manufacturer: Novatech

		DS	oDS	NH_4-N	N_{total}
Average composition of the apllied substrate mix	[kg/t] resp. [% FM]	8,0	6,5	2,4	4,4

Frequency of substrate addition: 4 d^{-1} **Series operation**

		Phase 1	Phase 2	Phase 3		Total
Operating temperature	[°C]	37	39	31		
Volume	[m³]	190	205	840		1.235
Reactor system (standing/lying)		l	l	s		
Added amount of fresh substrate	[t/week]	104				104
Hydraulic retention time	[d]	12	13	58		83
Volumetric loading	[kg oDS/m³d]	5,3				

Digestion residue storage:

Size: : 1.210 m³ Cover: none

		DS	oDS	NH_4-N	N_{total}
Composition:	[kg/t] resp. [% FM]	3,3	2,2	3,3	4,0

Gas production:

Biogas production (0° C; 1,013 bar):	5.614	m³/week	resp. 802	m³/day
Productivity:	0,65	m³ Biogas/(m³d)	0,37	m³ CH_4/(m³d)
Gas quality before BHKW:	53,9	Vol-% CH_4	1,0 Vol-% O_2	176 ppm H_2S

BHKW: Number: 1

	BHKW 1
Type(benzine/ignition/gas):	G
Number of cylinders:	6
Manufacturer:	CES
Engine:	MAN

Total specific electric output: : 75,1 kWh/t substrate

		BHKW 1
Electric output:		
Electric power rating:	[kW]	75
Average output:	[kW]	63
Power output utilisation:	[%]	84
Utilisation:	[%]	63
Electric yield:	[kWh/week]	7.953
Electric efficiency:	[%]	27,5
Heat output:		
Average output:	[kW]	112
Heat yield:	[kWh/week]	13.986
Thermal efficiency:	[%]	52,1
Total efficiency:	[%]	**79,6**

Substrates	Mass-%
Cattle liquid manure	40,4
Pig liquid manure	33,7
Chicken liquid manure	20,2
Silo maize	5,7
Number of substrates:	4

Energy balance:

Total power consumption (BP):	k.A.	kWh/t substrate	**Total heat consumption (BP):**	k.A.	kWh/t substrate
Total power consumption:	k.A.	kWh/week	**Total heat consumption:**	k.A.	kWh/week
Share of production:	k.A.	%	**Share of production:**	k.A.	%

Fig. 6.47: Technical data sheet – Novatech GmbH [Weiland et al. 2004]

Abbreviations

EEG: Erneuerbare-Energien-Gesetz (Renewable Energy Sources Act)

WPS: Whole Plant Silage

Mg: Megagram

ODS: Organic Dry Substance

DS: Dry Substance

MS: Moist Substance

UASB: Upflow Anaerobic Sludge Blanket - Reactor

CHP: Combined Heat and Power Unit eqivalent to BHKW

AbfAblV (2001): German Waste Disposal Ordinance

TA-Luft: Technical Instructions for Air Purification

Literature

AbfAblV (2001): Verordnung über die umweltverträgliche Ablagerung von Siedlungsabfällen (Abfallablagerungsverordnung - AbfAblV), BGBl. I S. 305.

ANS (2003) Status quo der Bioabfallsammlung und Verwertung; Schriftenreihe des ANS 44, Orbit-Verlag, Weimar.

ATV (2003) "Technische Rahmenbedingungen für die Vergärung biogener Abfälle" ATV-DVWK-Merkblatt M 372, Hennef.

BioAbfV (1998): Verordnung über die Verwertung von Bioabfällen auf landwirtschaftlich, forstwirtschaftlich und gärtnerisch genutzten Böden - Bioabfallverordnung vom 21. September 1998, Bundesanzeiger 1998 Teil I Nr. 65, Bonn.

Böhnke B.; Bischhofsberger, W.; Seyfried, C.F. (1993): Anaerobtechnik. Springer-Verlag Berlin.

Edelmann, W. (2001): Biogaserzeugung und Nutzung. In: Energie aus Biomasse - Grundlagen, Techniken, Verfahren. Kaltschmitt, M; Hartmann, H. (Publ.): Springer Verlag Berlin.

EEG (2000): Gesetz für den Vorrang Erneuerbarer Energien (Renewable Energy Sources Act).

EU Verordnung 1774 (2002): Hygienevorschriften für nicht für den menschlichen Verzehr bestimmte tierische Nebenprodukte. Amtsblatt der Europäischen Gemeinschaften. L 273/1-95.

Fachverband Biogas (2002): Anlagenstatistik des Fachverbandes Biogas.

Fricke K.; Müller W.; Bartetzko C.; Einzmann U.; Franke J.; Heckenkamp G, Kellner-Aschenbrenner K.; Kölbl R.; Mellies R.; Niesar M.; Wallmann R.; Zipfel H. (1999): Stabilisierung von Restmüll durch mechanisch-biologische Behandlung und Auswirkungen auf die Deponierung; Endbericht des BMBF-Verbundvorhabens "Biologische Vorbehandlung von zu deponierenden Abfällen", Teilvorhaben der Ingenieurgemeinschaft Witzenhausen (Nr. 1480945), Potsdam.

Fricke, K.; Bidlingmaier, W.; Hüttner, A. (2003): Die Vergärung von Bio- und Restabfällen. Skript für die Lehre. Knoten Weimar, unpublished.

Hüttner, A.; Weiland, P. (1997): Technologische Bewertung von Demonstrationsanlagen zur umweltverträglichen Gülleaufbereitung und -verwertung; Abschlußbericht BMBF-Fördervorhaben, Institut für Technologie der Bundesforschungsanstalt für Landwirtschaft (Völkenrode), Braunschweig

Kaltschmitt 2003

Körberle, E. (1999): Maßnahmen zur Verbesserung der Biogasqualität, Entschwefelung von Biogas in landwirtschaftlichen Biogasanlagen; In: Berichte zur 8. Biogastagung, Fachverband Biogas (Publ.), Weckelweiler.

Köttner, M.; Kaiser, A. (2001): Übersicht über die Verfahren der Trockenvergärung. http://www.graskraft.de/seminar4/feststoff.html.

Kraft, E.; Bidlingmaier, W.; Fricke, K.; Stegmann, R.; Widmann, R. (2004): Großes Potential - Die Zukunftschancen der wiederentdeckten Anaerobtechnologie sind deutlich erkennbar. Müllmagazin Issue 2/2004, S.8-11.

Langhans; G. (2000): Der Wärmehaushalt der Vergärung. Teil 2. EntsorgungsPraxis 9, S. 30-33.

N.N. (2002): Sicherheitsregeln für landwirtschaftliche Biogasanlagen. Bundesverband der landwirtschaftlichen Berufsgenossenschaften e.V., Hauptstelle für Sicherheit und Gesundheitssschutz. Arbeitsunterlage 69, Kassel.

N.N. (2004): Hinweise zum Immissionsschutz bei Biogasanlagen. Anforderungen zur Vermeidung und Verminderung von Gerüchen und sonstigen Emissionen, Niedersachsen, Rd.Erl. d. MU vom 02.06.2004 Az.: 33 3 - 40501/208.13/1, VORIS 28500, Nds. MBl. Nr. 22 vom 14.7. 2004 S. 461.

Prechtl, S.; Schneider, R.; Anzer, T.; Faulstich, M. (2003): Mikrobiologische Enschwefelung von

Biogas. In: Workshop "Aufbereitung von Biogas", Gülzower Fachgespräche, Bd. 23, FNR e.V. (Publ.), Gülzow.

Schattauer, A.; Weiland, P. (2004): Beschreibung ausgewählter Substrate. Handreichung Biogasgewinnung und Nutzung. Fachagentur Nachwachsende Rohstoffe e.V. (Publ.), Leipzig.

Scholwin, F.; Weidele, T.; Gattermann, H.; Schattauer, A.; Weiland, P. (2004) Anlagentechnik zur Biogasbereitstellung. Handreichung Biogasgewinnung und Nutzung. Fachagentur Nachwachsende Rohstoffe e.V. (Publ.), Leipzig.

Schmelz K (2000) Co-Vergärung von Klärschlamm und Bioabfällen, Manuskripte zur Abfallwirtschaft, Rhombos - Verlag, Berlin.

Weiland, P. (2003): Notwendigkeit der Biogasaufbereitung, Ansprüche einzelner Nutzungsrouten und Stand der Technik. In: Workshop "Aufbereitung von Biogas", Gülzower Fachgespräche, Bd. 23, FNR e.V. (Publ.), Gülzow.

Weiland, P. (2004): Stand der Technik bei der Trockenfermentation - Zukunftsperspektiven. In: Trockenfermentation - Evaluierung des FuE-Bedarfs. Gülzower Fachgespräche, Bd. 23, FNR e.V. (Publ.), Gülzow.

Weiland, P.; Rieger, C.; Ehrmann, T. (2004): Biogas-Anlagen. 12 Datenblätter.Fachagentur Nachwachsende Rohstoffe e.V., Gülzow.

Wetter, C.; Brügging, E. (2004): Leitfaden zum Bau einer Biogasanlage – Von der Idee zum konkreten Vorhaben. Bd. I bis IV. FH Münster. Downloaded on 01.12.2004 from http://www.fh-muenster.de/FB4/biogas/biogas.htm.

Literature

AbfAblV (2001): Verordnung über die umweltverträgliche Ablagerung von Siedlungsabfällen (Abfallablagerungsverordnung - AbfAblV), BGBl. I S. 305.

ANS (2003) Status quo der Bioabfallsammlung und Verwertung; Schriftenreihe des ANS 44, Orbit-Verlag, Weimar.

ATV (2003) "Technische Rahmenbedingungen für die Vergärung biogener Abfälle" ATV-DVWK-Merkblatt M 372, Hennef.

BioAbfV (1998): Verordnung über die Verwertung von Bioabfällen auf landwirtschaftlich, forstwirtschaftlich und gärtnerisch genutzten Böden - Bioabfallverordnung vom 21. September 1998, Bundesanzeiger 1998 Teil I Nr. 65, Bonn.

Böhnke B.; Bischhofsberger, W.; Seyfried, C.F. (1993): Anaerobtechnik. Springer-Verlag Berlin.

Edelmann, W. (2001): Biogaserzeugung und Nutzung. In: Energie aus Biomasse - Grundlagen, Techniken, Verfahren. Kaltschmitt, M; Hartmann, H. (Publ.): Springer Verlag Berlin.

EEG (2000): Gesetz für den Vorrang Erneuerbarer Energien (Renewable Energy Sources Act).

EU Verordnung 1774 (2002): Hygienevorschriften für nicht für den menschlichen Verzehr bestimmte tierische Nebenprodukte. Amtsblatt der Europäischen Gemeinschaften. L 273/1-95.

Fachverband Biogas (2002): Anlagenstatistik des Fachverbandes Biogas.

Fricke K.; Müller W.; Bartetzko C.; Einzmann U.; Franke J.; Heckenkamp G, Kellner-Aschenbrenner K.; Kölbl R.; Mellies R.; Niesar M.; Wallmann R.; Zipfel H. (1999): Stabilisierung von Restmüll durch mechanisch-biologische Behandlung und Auswirkungen auf die Deponierung; Endbericht des BMBF-Verbundvorhabens "Biologische Vorbehandlung von zu deponierenden Abfällen", Teilvorhaben der Ingenieurgemeinschaft Witzenhausen (Nr. 1480945), Potsdam.

Fricke, K.; Bidlingmaier, W.; Hüttner, A. (2003): Die Vergärung von Bio- und Restabfällen. Skript für die Lehre. Knoten Weimar, unpublished.

Hüttner, A.; Weiland, P. (1997): Technologische Bewertung von Demonstrationsanlagen zur umweltverträglichen Gülleaufbereitung und -verwertung; Abschlußbericht BMBF-Fördervorhaben, Institut für Technologie der Bundesforschungsanstalt für Landwirtschaft (Völkenrode), Braunschweig

Kaltschmitt 2003

Körberle, E. (1999): Maßnahmen zur Verbesserung der Biogasqualität, Entschwefelung von Biogas in landwirtschaftlichen Biogasanlagen; In: Berichte zur 8. Biogastagung, Fachverband Biogas (Publ.), Weckelweiler.

Köttner, M.; Kaiser, A. (2001): Übersicht über die Verfahren der Trockenvergärung. http://www.graskraft.de/seminar4/feststoff.html.

Kraft, E.; Bidlingmaier, W.; Fricke, K.; Stegmann, R.; Widmann, R. (2004): Großes Potential - Die Zukunftschancen der wiederentdeckten Anaerobtechnologie sind deutlich erkennbar. Müllmagazin Issue 2/2004, S.8-11.

Langhans; G. (2000): Der Wärmehaushalt der Vergärung. Teil 2. EntsorgungsPraxis 9, S. 30-33.

N.N. (2002): Sicherheitsregeln für landwirtschaftliche Biogasanlagen. Bundesverband der landwirtschaftlichen Berufsgenossenschaften e.V., Hauptstelle für Sicherheit und Gesundheitssschutz. Arbeitsunterlage 69, Kassel.

N.N. (2004): Hinweise zum Immissionsschutz bei Biogasanlagen. Anforderungen zur Vermeidung und Verminderung von Gerüchen und sonstigen Emissionen, Niedersachsen, Rd.Erl. d. MU vom 02.06.2004 Az.: 33 3 - 40501/208.13/1, VORIS 28500, Nds. MBl. Nr. 22 vom 14.7. 2004 S. 461.

Prechtl, S.; Schneider, R.; Anzer, T.; Faulstich, M. (2003): Mikrobiologische Enschwefelung von Biogas. In: Workshop "Aufbereitung von Biogas", Gülzower Fachgespräche, Bd. 23, FNR e.V. (Publ.), Gülzow.

Schattauer, A.; Weiland, P. (2004): Beschreibung ausgewählter Substrate. Handreichung Biogasgewinnung und Nutzung. Fachagentur Nachwachsende Rohstoffe e.V. (Publ.), Leipzig.

Scholwin, F.; Weidele, T.; Gattermann, H.; Schattauer, A.; Weiland, P. (2004) Anlagentechnik zur Biogasbereitstellung. Handreichung Biogasgewinnung und Nutzung. Fachagentur Nachwachsende Rohstoffe e.V. (Publ.), Leipzig.

Schmelz K (2000) Co-Vergärung von Klärschlamm und Bioabfällen, Manuskripte zur Abfallwirtschaft, Rhombos - Verlag, Berlin.

Weiland, P. (2003): Notwendigkeit der Biogasaufbereitung, Ansprüche einzelner Nutzungsrouten und Stand der Technik. In: Workshop "Aufbereitung von Biogas", Gülzower Fachgespräche, Bd. 23, FNR e.V. (Publ.), Gülzow.

Weiland, P. (2004): Stand der Technik bei der Trockenfermentation - Zukunftsperspektiven. In: Trockenfermentation - Evaluierung des FuE-Bedarfs. Gülzower Fachgespräche, Bd. 23, FNR e.V. (Publ.), Gülzow.

Weiland, P.; Rieger, C.; Ehrmann, T. (2004): Biogas-Anlagen. 12 Datenblätter. Fachagentur Nachwachsende Rohstoffe e.V., Gülzow.

Wetter, C.; Brügging, E. (2004): Leitfaden zum Bau einer Biogasanlage - Von der Idee zum konkreten Vorhaben. Bd. I bis IV. FH Münster. Downloaded on 01.12.2004 from http://www.fh-muenster.de/FB4/biogas/biogas.htm.