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Anaerobic waste digestion in Germany – Status and recent developments

Peter Weiland
Institute of Technology and Biosystems Engineering, Federal Agricultural Research Centre (FAL), Bundesallee 50, D-38116 Braunschweig, Germany

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Abstract

Anaerobic treatment processes are especially suited for the utilization of wet organic wastes from agriculture and industry as well as for the organic part of source-separated household wastes. Anaerobic degradation is a very cost-effective method for treating biogenic wastes because the formed biogas can be used for heat and electricity production and the digester residues can be recycled to agriculture as a secondary fertilizer. Anaerobic technology will also be used for the common treatment of wastes together with renewable energy crops in order to reduce the CO_2-emissions according the Kyoto protocol. Various process types are applied in Germany which differ in material, reaction conditions and in the form of the used reactor systems. The widespread introduction of anaerobic digestion in Germany has shown that biogenic organic wastes are a valuable source for energy and nutrients. Anaerobic waste treatment is done today in approx. 850 biogas plants on small farm scale as well as on large industrial scale with the best beneficial and economic outcome. Due to some new environmental protection acts which promote the recycling of wastes and their utilization for renewable energy formation it can be expected that several hundreds new biogas plants will be built per year in Germany. In order to use the synergetic effects of a combined fermentation of wastes and energy crops new process types must be developed in order to optimize the substrate combinations and the process conditions for maximum biodegradation.

Introduction

The application of anaerobic digestion processes for the treatment of solid and semi-solid wastes has increased in Germany in recent years because an important goal of the government is to reduce the disposal of organic wastes and to promote their recycling and utilization as a renewable energy source. Therefore, the *Recycling and Treatment of Wastes Act* (Kreislaufwirtschafts- und Abfallgesetz 1994) combined with the *Technical Instructions on Urban Wastes* (TA-Siedlungsabfall 1993) and the *Biowaste Ordinance* (Bioabfallverordnung 1998) were established which have increased the relevance of anaerobic organic waste treatment technologies as one of the most beneficial technologies for wet wastes. The production of biogas as a renewable energy source is also strongly supported by the government in order to decrease the CO_2-emissions according the Kyoto protocol. The aim of the German government is to double the part of the renewable electricity production up to 2010 which means that the energy formation from organic wastes and biomass has to be increased by a factor of 3–4. Therefore on 1 April 2000 the so-called *Renewable Energy Sources Act* (Erneuerbare-Energien-Gesetz 2000) has come into force which supports the production of electricity from biomass by a fixed refund of 0.2 DM/kWh for plants with an installed electricity capacity up to 500 kW_{el} and 0.18 DM/kWh for plants up to 5 MW_{el}. It can be expected that the high refund for the produced electricity will result in the construction of several hundreds new biogas plants per year which are operated mainly with organic wastes but also with the addition of cultivated energy crops, because a new guideline of the European Community makes the utilization of biomass from set

Table 1. Waste sources and waste types used for anaerobic digestion

Waste source	By-products and wastes
Agriculture	Harvesting residues, solid manure, rotten products
Agro- and food-industry	Fruit peels, fruit pulps, spent grain, pressed seeds, pomace, waste bread
Canteens	Food residues, used fat
Paper industry	paper pulps
Pharmaceutical industry	Plant residues, mycelium
Slaughterhouses, carcass plants	Rumen, faeces, animal hair, carcass meal
Municipality	Biowaste, residual refuse, market wastes, grass

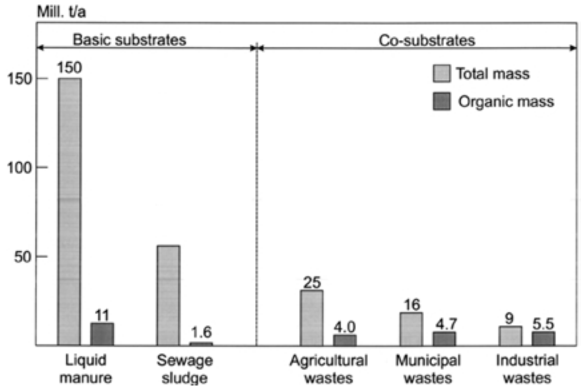

Figure 1. Potential of organic wastes in Germany.

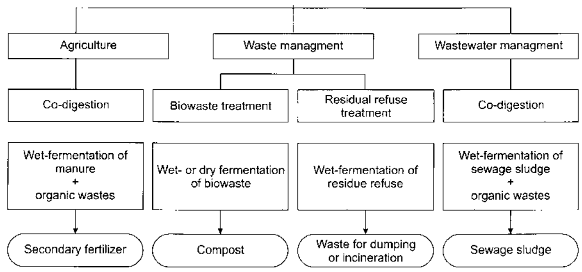

Figure 2. Application of anaerobic solids treatment.

aside areas more easier (EU-decree 2461/99). Various anaerobic technologies find applications which differ in material, reaction conditions and reactor systems. The co-digestion of energy crops together with wastes makes new digestion concepts necessary because the degree of biodegradation has to be enhanced and the synergetic effects of the combined fermentation have to be better utilized.

Waste situation

Solid and semi-solid wastes cover the whole range of materials which are produced in many different branches (Table 1). Most of these wastes are byproducts from agriculture, industry, slaughterhouses and carcass disposal plants. High amounts of organic wastes are also derived from canteens and from the source separated collection of municipal biowastes. Exact mass flow dates for most of these wastes are not available, but Figure 1 shows that agricultural wastes from livestock breeding, sewage treatment and crop production dominate (Weiland 1999a). The potential of wastes from the municipal and the industrial sector is much lower and several industrial wastes are produced only a few months per year.

Therefore, different process types are applied for anaerobic waste treatment (Figure 2). Most of the organic wastes are treated today in co-digestion processes together with manure. In future, also the co-fermentation of wastes together with sewage sludge will find increased application, because the existing sewage sludge treatment plants have over-capacities which can be used for biowaste treatment. Some wastes, e.g., fat wastes from slaughterhouses or canteens, can be treated only together with other substrates because their unbalanced composition inhibits the biological degradation due to the lack of nutrients or trace elements. Other wastes, e.g., residues from vegetable oil refineries, have such a high protein content, that the degradation process can be inhibited by ammonia nitrogen which makes the co-digestion of substrates with low nitrogen content necessary. Mono-digestion processes are applied mainly for biowastes and the organic fraction of residual wastes from households.

Co-digestion in agriculture

The number of agricultural biogas plants increased considerably during the recent years and today more than 850 agricultural biogas plants with reactor volumes between 100 and 4,000 m^3 are in operation and more than 150 plants will be built in the year 2001. Approximately 50% of all plants have reactor sizes lower than 500 m^3, but the trend is going to plant sizes of 1,000 m^3 and more (Weiland 1999b). At present 14 centralized large scale plants with treatment capacities between 16.000 and 126.000 t/a are

Table 2. Centralized co-digestion plants in Germany

Plant	Co-substrate	Capacity (t/a)	Reactor volume (m^3)	Start-up
Barth	Industrial wastes	60,000	4,000	1998
Behringen	Industrial wastes	23,000	2 × 800	1995
Bernstorf	Industrial wastes	43,000	2 × 1,200	1995
Finsterwalde	Industrial wastes	91,000	4 × 900	1995
Fürstenwalde	Biowastes	85,000	2 × 3,300	1998
Göritz	Industrial wastes	33,000	2 × 950	1996*
Großmühlingen	Industrial wastes	40,000	2 × 800	1996
Gröden	Industrial wastes	110,000	2 × 3,100	1995
Neubukow	Industrial wastes	80,000	2 × 2,250	1996
St. Michaelisdonn	Industrial wastes	40,000	1 × 2,250	1997
Pastiz	Sewage sludge	100,000	2 × 2,100	1997
Sagard	Industrial wastes	48,000	3 × 725	1996
Surwold	Industrial wastes	16,000	2 × 500	1996*
Wittmund	Industrial wastes	126,000	2 × 3,500	1996

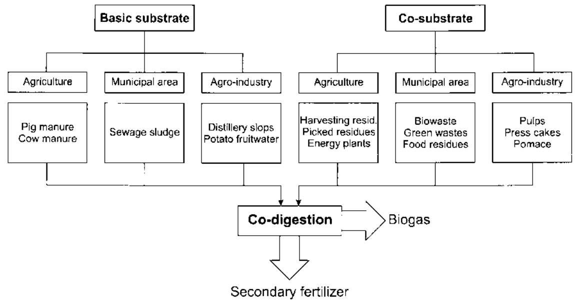

Figure 3. Substrate sources for co-digestion.

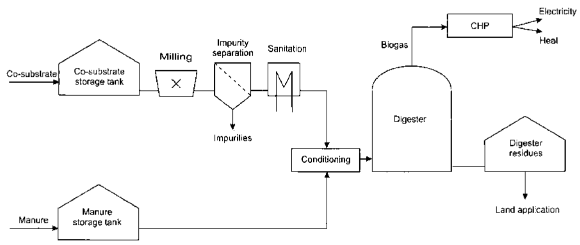

Figure 4. Main components of a co-digestion plant.

in operation (Table 2). The typical treatment capacities of industrial co-digestion plants are much greater than mono-digestion processes for biowaste treatment because the handling and waste management are more easier.

Most of the co-digestion plants use pig manure or cow manure as basic substrate and agro-industrial, municipal and agricultural wastes for co-digestion (Figure 3). Agro-industrial wastes, like pulps, press cakes or pomace from crop and fruit processing but also agricultural residues from harvesting are normally free of contaminants or foreign matter and can be used often without any pretreatment. On the other hand biowastes from households are strongly polluted with plastics, metals, sand and other materials which make a pre-treatment always necessary. Therefore, co-digestion plants have to be equipped with several pre-treatment steps to remove foreign materials, to sanitize hygienic risky wastes and to upgrade the waste for digestion. The typical process steps are shown in Figure 4. A size reduction of solid wastes to particle sizes of 10–40 mm by screw mills or disk mills is necessary to achieve a better biological accessibility, an undisturbed substrate flow within the process and better handling properties for the land application of the treated residues. Impurities like plastics or sand have to be separated by means of flotation and sedimentation techniques in order to avoid process failure and to meet the legislative regulations for the utilization of the residues as a secondary fertilizer. For the co-digestion of hygienic risky materials, like restaurant wastes, grease remover residues or paunch manure a controlled sanitation of the waste is claimed by the *Biowaste Ordinance*. The sanitation is carried out normally in mixed tanks which are operated discontinuously at a pasteurization temperature of 70 °C and a retention time of 1 h. Manure and co-substrates must be intensively mixed within the conditioning tank in order to avoid scum or bottom layers within the digester. The total solid content of the mixture should not exceed a total solids content (TS) of more than 12% because otherwise special reactors and special mixers and pumps have to be applied.

Different reactor systems with mechanical or pneumatic mixing can be used for co-digestion (Figure 5). Very simple are storage tank reactors, where the entire gas tight manure storage tank is insulated, heated and mixed to serve as biogas plant and gas storage. Due to the instationary operation conditions of the reactor the biogas productivity is not constant which makes the utilization of the biogas in a block type power station difficult. Therefore, mainly storage-continuous-flow reactors are applied on farms. Two tanks of similar size are coupled and the first tank is operated like a continuous flow reactor and the second gas tight tank serves as a biogas reactor and storage tank for the treated wastes and biogas. This system results in a constant gas flow and a high biogas yield. For co-digestion plants of industrial size mainly vertical tank reactors with continuous flow are applied which are built with one or two chambers. One chamber systems are mixed

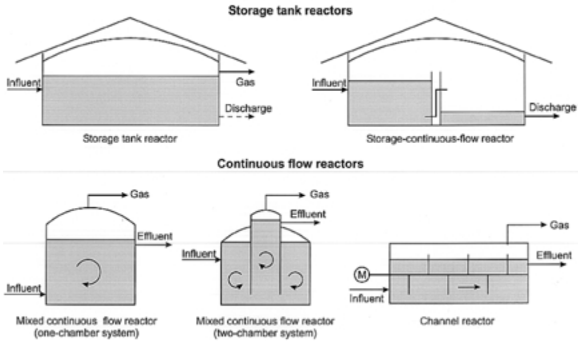

Figure 5. Reactor systems for co-digestion processes.

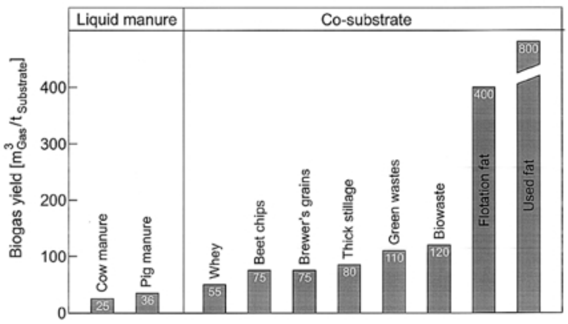

Figure 6. Biogas potential of different organic wastes.

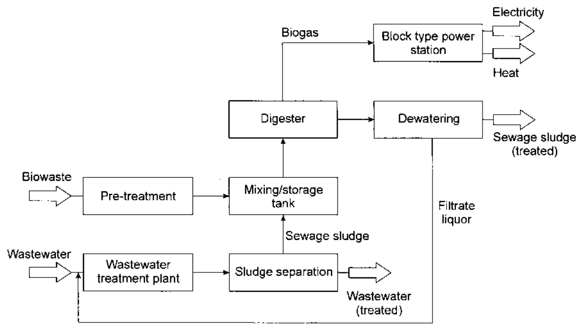

Figure 7. Demonstration plant for co-digestion of forage beets on the monastery farm Dernbach.

mechanically or pneumatically with biogas recycling whereas two chamber systems are mixed by the produced biogas itself. Channel reactors with horizontal stirrers are mainly applied for difficult co-substrates with high fiber or sand content but their size is limited to reactor volumes lower than 300 m^3.

The increased number of agricultural co-digestion plants and their strong competition resulted in a dramatic drop of the gate fee for waste treatment within the last years. Therefore, the increase of the biogas yield per ton of substrate has become the most important economic parameter for co-digestion plants. Figure 6 shows that the gas yield of organic wastes is normally a factor of two or four higher compared to animal manure. The treatment of fat containing wastes, e.g., flotation fat from slaughterhouses or used fat from canteens or food industry, is most economical because gas yields of up to 800 m^3 per ton of waste can be achieved.

Due to the limited availability of organic wastes the co-digestion of agricultural crops will get increasing importance within the next years in Germany for energy production and for a more efficient treatment of organic wastes. Typical crops with high biogas yields per hectare are forage beets, maize, sweet sorghum, ray grass and barley. The biogas yield of these crops lies between 600 and 1,000 m^3 per ton of organic dry mass. Co-digestion of these crops results not only in a strong increase of the biogas productivity but also in a decrease of the trace elements content of the digested residues. Therefore, co-processing of energy crops can be an important aspect in order to fulfil the biowaste ordinance because the utilization of the digester residues as a secondary fertilizer is limited and dependent on the heavy metal content. At present time an interesting demonstration project has been started on a monastery farm which uses forage beets from 30 ha together with pig and cow manure for biogas production. The forage beets are chopped finely using a special mill and the produced mush is ensiled in open tanks according to the *Betavator-Process* of the German Lipp Company (Figure 7). Due to the biological pre-treatment process the beet pulp is stabilized at pH 3.5 and completely liquefied which makes an automatically controlled dosing of the substrate with conventional pumps possible (Erdeljan 1994). Therefore, the biogas formation can be easy adapted to the actual energy demand. Forage beets have the advantage that a high biomass yield of about 100 t/ha beets and 26 t/ha leaves can be achieved with up to 100 m^3 biogas per ton of fresh biomass (Linke 1999).

Co-digestion on sewage sludge treatment plants

Co-treatment of organic wastes together with sewage sludge offers the advantage that existing treatment plants with a complete infrastructure for gas utilization and wastewater treatment can be used. About 1,230 municipal sewage treatment plants in Germany are equipped with a covered digester for sewage sludge treatment (Austermann-Haun et al. 2000). Most of

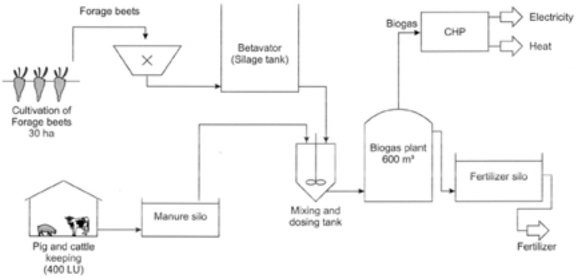

Figure 8. Co-digestion of sewage sludge and biowastes.

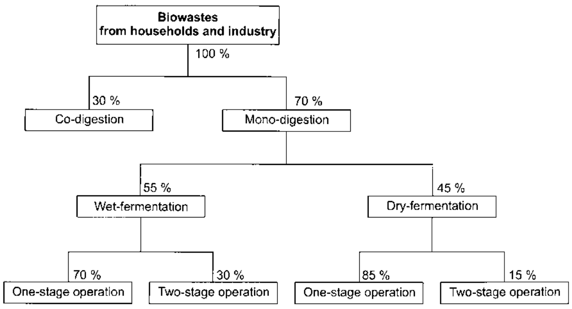

Figure 9. Process types used for municipal biowaste treatment.

these plants have a free treatment capacity between 15 and 30% which can be used for co-fermentation of organic wastes but today only approx. 11% of these plants are operated with co-substrates. Mainly grease trap residues and flotation fats are treated together with sewage sludge but only one full-scale plant is operated with source separated biowaste from households (Gebhardt 1999). The typical process flow of a sewage sludge co-digestion plant is shown schematically in Figure 8.

In order to use the free treatment capacity a lot of pilot-scale experiments are carried out today with food residues, market residues, organic wastes from food- and agro-industry and residual refuses from households. The preliminary results have shown that the common treatment of sewage sludge and biowastes produces a better degradation than when both materials were treated separately and a higher quality of the sewage sludge with respect to pollutants and nutrients is also achieved (Schmelz 1999). The gas production can be enhanced by a factor of 2–3 but the amount of filtrate and its load in COD, BOD and TKN is much higher. In some cases the total nitrogen return load of the wastewater treatment plant by recirculation of the filtrate liquor is enhanced up to 30% and more which can be a limiting factor for the application of co-digestion processes on sewage treatment plants.

Mono-digestion of municipal wastes

In Germany about 8.3 Mill t of biowastes from households and trade are collected per year. The main part (7.1 Mill t/a) is treated by composting and only 1.2 Mill t/a is treated in anaerobic digestion plants. Approximately 28 full-scale anaerobic treatment plants with capacities between 5,000 and 30,000 t/a are in operation. The different treatment technologies and their proportion on the total treatment capacity are shown in Figure 9. About 70% of the separate collected wastes are treated in mono-digestion processes and 30% in co-fermentation plants together with manure. Wet-fermentation and dry-fermentation systems are applied with similar frequency and the waste management market does not indicate any specific preference of one system. The wet digestion systems are operated at TS-contents of 8–12% whereas the dry-fermentation processes are operated at 20–35% TS. Most of the wet-fermentation processes are operated at mesophilic temperatures conditions (30–38 °C) whereas thermophilic temperatures (>55 °C) are preferred mainly for dry-fermentation (Kern et al. 1999). Usually the digested wastes are dewatered after anaerobic treatment in order to produce a solid phase which can be used for compost production. The remaining surplus water is highly loaded in COD (8,000-20,000 mg O_2/l) and BOD (1,000–12,000 mg O_2/l). The total nitrogen content (TKN) is between 1,500 and 3,000 mg TKN/l with more than 80% in the form of ammonia nitrogen (NH_4-N). Normally, the surplus water is indirectly discharged to a municipal wastewater disposal plant. For direct discharging several treatment processes have been tested in pilot-scale that mostly apply an ultra-filtration for pre-treatment and a reverse-osmosis for wastewater polishing (Stegmann & Leikam 1999). With the exception of NH_4-N all relevant parameters for wastewater discharging can be eliminated with more than 95% efficiency. The elimination efficiency of NH_4-N depends on the pH-value and can be enhanced if the pH-value of the reverse osmosis feed is reduced to approximately 5.5 by addition of acids.

Beside the treatment of source separated biowastes from households the so-called mechanical-biological treatment of the remaining residual refuse will get increasing importance within the next years as a pre-treatment step. The aim of the biological treatment is to decrease the organic content of the waste for

Table 3. Process conditions for residual waste treatment in different anaerobic treatment plants

Plant location		Industrial plant Bassum	Pilot plants Donauwald	Kahlenberg	Münster	Quarzbichl	Ravensburg
Process type		Dry-ferment. One-stage Thermophilic	Wet-ferment. Two-stage Mesophilic	Percolation Two-stage Mesophilic	Wet-ferment. One-stage Mesophilic	Dry-Ferment. One-stage Mesophilic	Dry-Ferment. One-stage Mesophilic
Waste fraction	(mm)	<40	n.i.	<150	<50/<20	<40	<60/<70
Retention time	(d)	21	7	20	n.i.	19	26
Degradation	(%ODM)	37	48	45	55	50	39
Biogas yield	(m^3/t DM)	250	240	115	n.i.	220	200
	(m^3/t ODM)	n.i.	360	n.i.	420	380	320

n.i. – no information.

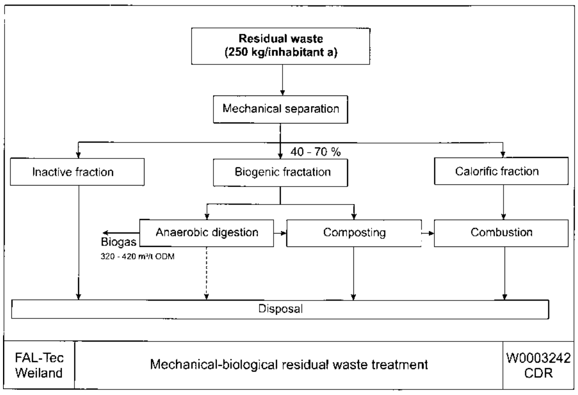

Figure 10. Mechanical-biological treatment of residual wastes.

dumping or to reduce the waste mass for incineration. Per inhabitant about 250 kg of residual wastes are formed per year. Before the residual wastes can be treated anaerobically a mechanical separation is necessary to separate the inactive fraction which can be disposed and the calorific fraction which can be used in combustion plants. After the mechanical pretreatment about 40–70% of the total mass remains in the form of a biogenic fraction. The anaerobic treatment of these fractions results in a considerable biogas formation of up to 250 m^3 per ton of dry mass (Nieweler 1998). This demonstrates that the uncontrolled emission of the climate relevant methane gas which occurs after waste deposition can be eliminated considerably. Normally, the anaerobic treated fraction does not fulfil the conditions for dumping or incineration and has to be post-treated by composting. The different process steps are shown in Figure 10. The organic content for wastes which should be dumped is restricted by the TA-Siedlungsabfall on <5% organic dry matter (ignition loss) which cannot be achieved by biological treatment processes alone. In order to implement the mechanical-biological treatment process as a pre-treatment step for waste management, several equivalence parameters for determining the biological stability are discussed today which can substitute the ignition loss. Suitable parameters which were proposed are the specific gas yield after 21 days ($GB_{21} <$ 20 l gas/kg TS) and the respiration activity in 4 days ($AT_4 < 5$ mg O_2/g TS).

The anaerobic treatment of residual wastes is tested in several pilot-plants but only one full-scale plant with a capacity of 11,000 t/a is in operation (Table 3). Usually, only the fine-fraction of the residual refuses is used for anaerobic digestion because the organic matter is mainly accumulated in the fraction with particle sizes below 60 mm. The results of the different pilot scale studies have shown that depending on the waste origin between 37 and 55% of the organic dry matter can be degraded anaerobically. With respect to the necessary post-treatment by composting dry-fermentation processes are preferred for anaerobic treatment. Laboratory experiments using a multi-step anaerobic digestion process have recently shown that a high degree of degradation can be achieved if the hydrolysis reactor (first stage) is operated at hyperthermophilic conditions (65 °C) and the methanation stage at thermophilic conditions (55 °C). After anaerobic treatment the respiration activity value AT4 of the treated wastes is lower than 5 mg O_2/g TS which demonstrates that a complete waste stabilization is possible without any post-treatment by composting (Scherer & Vollmer 1999). To what extent these results can be achieved in full-scale plants is not known at the present time.

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