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Manure and biowaste digestion in Germany - history, trends and practical verification -

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Summary

Anaerobic digestion as a natural process enables the re-entering of organic materials into the environmental cycle. As an industrial process it can be helpful to solve problems of environmental pollution and recovery of natural ressources but needs special efforts for stable and efficient operation.
The process design and economic efficiency of biogas plants is primarily related to the possible accuracy in prediction of biogas yields from organic compounds and waste compositions. With the help of experimental results and the analytical description of complex organic compounds it is possible to develop models of energy and mass balances for the digestion of wastes like manures or sewage sludge as well as heterogeneous bulk biowastes.
Process design and plant economy are discussed for the full-scale application of a thermophilic anaerobic digestion system applied for the processing of farm manure and industrial organic wastes as well as agricultural crop residues.
This co-fermentation approach results in enhanced biogas generation which is used for electrical and thermal energy production to meet the plant consumption and in addition enables use of the CHP-waste heat for farm and residential heating at the plant location while surplus of electric power is sold to the public grid.
By the references of numerous plants in operation mainly in Europe full-scale manure digestion is shown to be a proven and reliable technology.

Introduction

The worldwide revival of the anaerobic process for the treatment of biowastes and organic residues has enhanced the general interest especially to find out the capabilities and limits of this technology.
The anaerobic microbial populations are species of a very archaic type of life without oxygen use in their metabolism. That’s why their life-energy generation is rather inefficient and the stepwise incomplete destruction of organic matter causes products of further on high energy content which cannot be used by those microorganisms without the ability of aerobic metabolism based on oxygen as electron acceptor.
This has important consequences for the ecology of the earth because it is the prime guarantee for the permanent recycling of organic matter within the natural succession and results in the following items:

- mineralisation of high amounts of organic matter with only low reproduction of bacterial cells (that means very small generation of new organic matter in opposite to aerobic processes).
- generation of intermediate as well as final products of further on high energetic (caloric) content like methane, alcohol’s, or organic acids, which will be used by aerobic microorganisms as substrate but are also basic compounds of manifold processes helpful for life of mankind.

That’s why anaerobic processes have been used in all times of human history consciously or instinctively, e.g. for

- beer brewery
- wine making
- leaven for dough
- conservation of food like pickled cabbage or annual ensilage
- fermentation of spices
- methane, generated from human sewage for instance at old Chinese fire places
- last but not least development of mystic ideas by observation of will-o’-the wisps on swamps caused by burning methane.

The use of anaerobic processes for the reduction of human organic wastes in an industrial scale only started at the beginning of the twentieth century.
There was a first culmination in anaerobic treatment of municipal sewage sludge in the twenties and thirties. But after World War II the aerobic stabilisation processes dominated because of the more simple process handling and the cheap energy for the aeration technology at that time.
Meanwhile the raise in energy prices as well as the dangerous destruction of global environment have initiated a renaissance of anaerobic digestion again also in the treatment of organic sludge, biowastes and agricultural residues including animal manures.
In this connection it has to be remarked that the composting process which has long been successfully used in practice is now in critical discussion for its industrial scale application because the ecological balance of large composting plants due to their electric power and fuel consumption accounts for a high demand of energy produced from fossil resources. Digestion processes or combined fermentation/composting processes offer clear advantages in this respect because they can cover their own electric power and heat demand on basis of the methane in the biogas without CO_2 generation from the use of fossil fuels and normally a remarkable surplus of energy can be exported .
So besides the recycling of organic matter especially the use of methane as an energy source of a CO_2-neutral process reduces the consumption of fossil fuels like coal, crude oil or natural gas and is said to damp the greenhouse effect.
Last but not least anaerobic processes offer a reduction in annoyance by bad odour during treatment because of the operation in closed reaction tanks compared with the aerobic composting processes, which is always generating a high amount of odour-loaded exhaust air.
Although there has been a drastic reduction in pollution from municipal and industrial point sources a lot of European as well as worldwide waterways still do not meet the goals set for fishing and/or swimming and also groundwater resources are further on more or less contaminated.
One of the leading sources of the remaining pollution is from agricultural operations involving animal

confinement facilities and the land application of manure because these wastes from confined animal operations have the potential to contribute pollutants such as organic matter, sediments, nutrients and pathogens. In addition, confined animal operations may produce objectionable odours.
To limit those pollution problems the European Community is issuing relevant permits. These permits are intended to control pollutants from both discrete sources as well as assure that manure is properly applied for agricultural benefit and does not lead to water quality problems or public health problems.
If the impact of animal manure on the environment can be minimized, the manure is a valuable resource as a fertilizer, soil conditioner and as an energy source. However, due to intensive stock farming technologies, animal manure is no longer obtained in the conventional bulk form with high amounts of chaff and straw, but as a more or less pumpable slurry, the so-called liquid manure. As a consequence special technologies must be employed for storage, transportation and utilisation.
Manure is continuously produced all the year long, whereas its utilisation in grasslands and agricultural fields is regulated and restricted to certain periods of the year. These periods depend on the needs of crop plants, their ability to take up the nutrients, seasonal climate changes, crop rotation and plant ripeness.
To reduce environmental problems linked to manure, like

- the annoying smell
- pathogens, which might be contained in the manure and can be spread over huge areas together with the manure to be distributed finally with wind driven aerosols
- the organic load of manure, which can have a negative influence on the soil if applied in too high amounts
- the high amount of nutrients which are contained in manure and can be a risk for the environment if not spread correctly (wrong timing, concentration too high, losses by gluing of high viscous manure on plants)

In an economical way, during the last decades the anaerobic fermentation process has gained great importance for the treatment of agricultural wastes in Europe. As mentioned before it is the concept to combine the treatment of manure with the production of renewable energy in the form of methane. Existing installations range from smaller plants mainly built by the users themselves to large industrial-scale co-digestion complexes.
Lately some digestion plants are purely designed for the production of renewable energy. For those installations, the major input material is formed by energy-rich plants, which are specifically cultivated to be fed to the digester.
While inquiries in the middle of the eighties detected in the European Community and Switzerland about 550 biogas plants with 420 of them in the agricultural area including about 60 plants for manure treatment within the German territory [1], similar observations in the year 2000 registered in Germany ca. 1000 biogas plants in agriculture with at least 30 of them in industrial scale (digestion volume over 1000 m³), the others smaller individual farm types between 50 m³ to 500 m³ reactor volume.
At the moment there is a strange situation in Europe; while governments in Germany and other members of the EC support by law energy production from renewable sources [2] (including biogas) in kind of guaranteed revenues for the power sold to the public grid, on the other hand BSE, MFD as well as scandals because of illegal use of antibiotics etc. bring intensive stock farming into the twilight of low acceptance. By that it is not clear at the moment if animal life stocks will be limited in heads in future. That for instance would hinder the present trend to industrial scale plants. The typical Danish concept to install centralized plants with manure collection and distribution of digested effluent to several smaller farms is not everywhere accepted by European farmers. Indeed there is sorrow maybe to contaminate the own farmyard with unknown matter or germs from a central plant which is not under individual check and control.

Basic principles of manure digestion

The microbiological process, which is described as „fermentation“ or „anaerobic digestion“ in „black box“ terms, is a sequence of complicated metabolic procedures of a great number of populations of microorganisms living more or less in symbiosis (Fig.1).
There can be distinguished the steps of

- decomposition of solid organic matter into water-soluble compounds by extra cellular bacterial enzymes (so-called hydrolysis)
- utilizing of that soluble high molecular substrate by different species of microorganisms with set free of intermediates like alcohols, sugars, and primarily C_3- to C_5-organic acids (acidogenic species)
- production of mainly acetic acid, H_2, and CO_2 (acetogenic species)
- use of these intermediates by the end-of-metabolic-chain methanogenes with the gaseous end products of CH_4 and CO_2.

Especially acetogenes and methanogenes are living in strong symbiosis because the acetogenic process will be depressed by the enrichment of H_2, which has to be utilized by the methanogenes simultaneously with its production.
It is clearly to understand that the first steps in this metabolic chain would operate strictly in the acidic range of pH if the methanogenes are absent which neutralize the local habitat by utilizing the acetic acid [8].
So the whole process runs in a labile pH-equilibrium and disturbances will cause a non-reversible gliding towards acidification with often finally total failure of the system.
This risk is raised by the low growth

rates of acetogenes and methanogenes compared with those of the other species, which can cause enrichments of acidic intermediates.
Main factors of possible disturbances are instabilities in process temperature, destruction of bacterial flocks by shear stress, overloading in organic input easy to hydrolyse, enrichment of bio toxic intermediate compounds (NH_3, H_2S, heavy metal ions), and intolerable intake of oxygen, as well.
Therefore, this process as an industrial procedure oriented fully on performance makes great demands on strict control.
For manure digestion just ammonia toxicity is a relevant problem because in dependence of pH and temperature a defined fraction of the naturally high ammonium content is present as undissociated ammonia (Fig.2). That results first in hindered bacterial growth beyond NH_3-concentrations about 700 mg/l and finally causes complete failure of the microbiological process at higher values.
As shown in Fig.2 bacterial growth at thermophilic conditions is more sensitive to NH_3-toxicity and at higher concentrations the principally faster growing but hindered thermophilic flora needs the same hydraulic retention time for digestion like the undisturbed mesophiles.
That´s why pig and poultry manure for better process stability should be digested preferably at mesophilic temperatures.
Because of the content of intestinal anaerobic bacteria cow manure is a well-operating natural inoculum for digestion. On the other hand the manure just from dairy cattle contains a lot of fibre in the organic fraction, which is difficult to utilize by the anaerobic flora.
That means low reduction efficiencies of the organic fraction (Fig.3) and results in low biogas yield.
But those discussed attributes make cow manure to be the ideal basic substrate for co-fermentation with other organics from energy crops or biowaste fractions of the food processing industry.

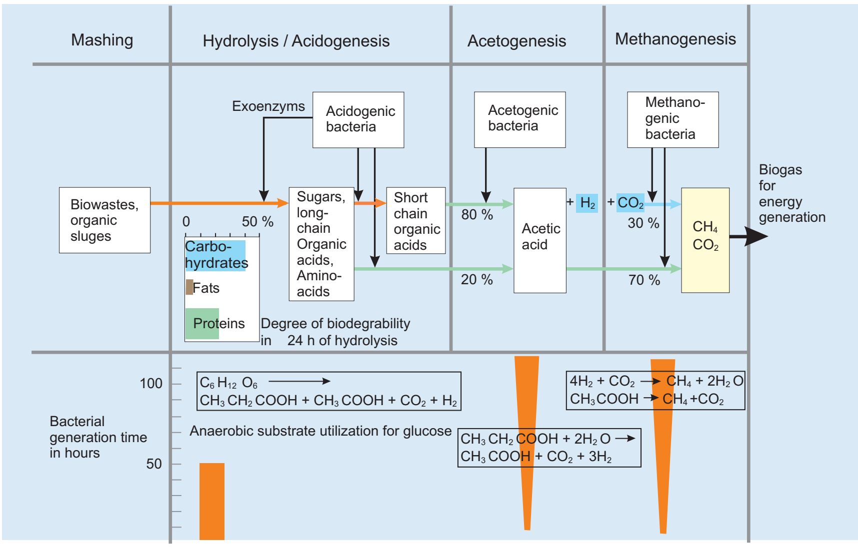

Figure 1: Metabolic chain of anaerobic microorganisms [5]

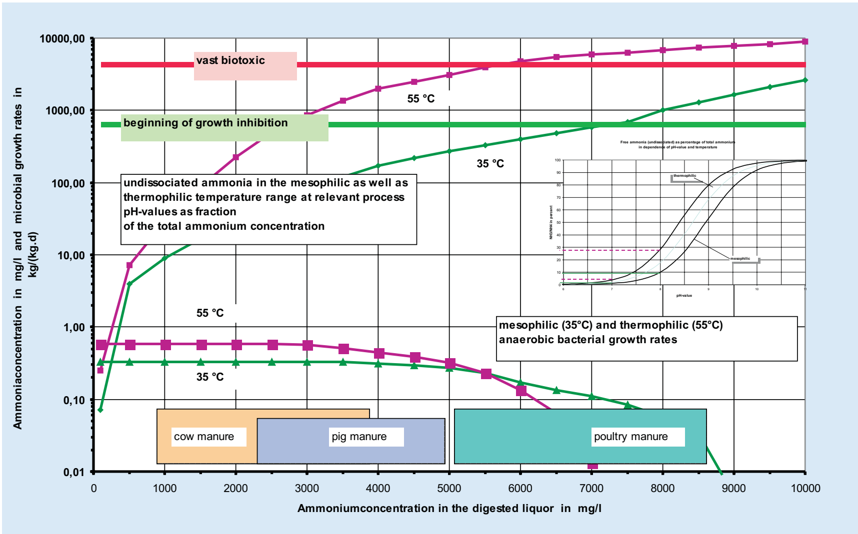

Figure 2: Bio toxicity of undissociated ammonia

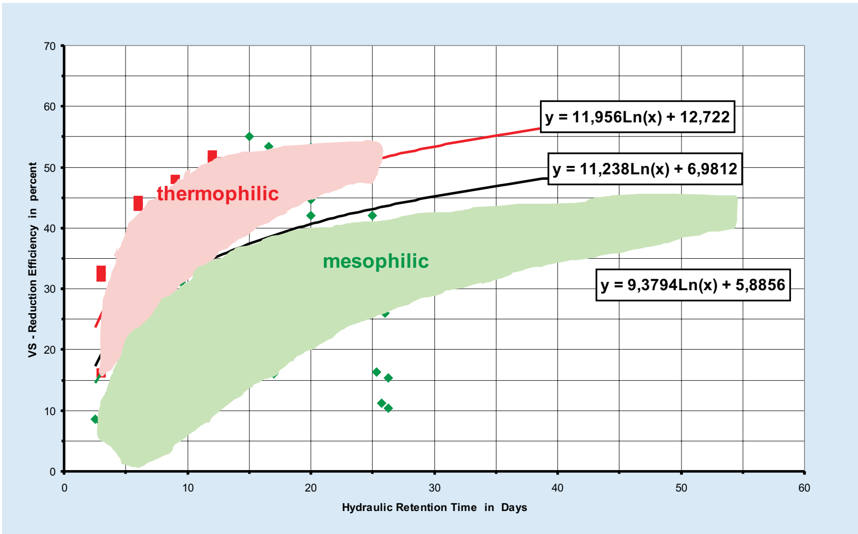

Figure 3: Volatile Solids (VS)- reduction efficiencies for digestion of cattle manure at mesophilic and thermophilic temperatures

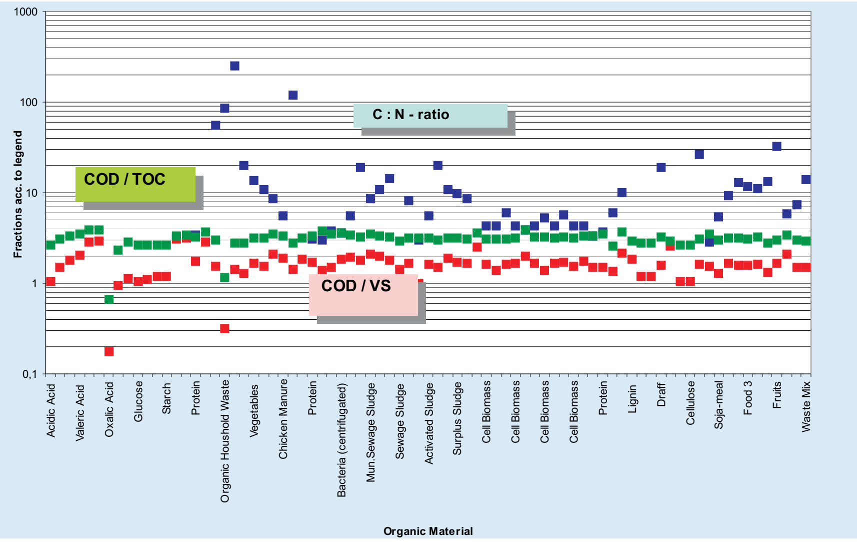

Figure 4: Biochemical parameters of important co-substrates

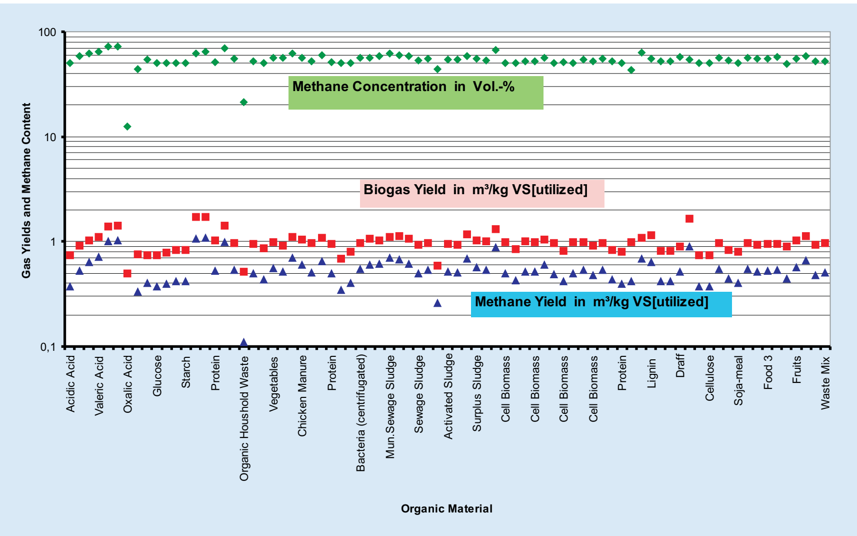

Figure 5: Biogas and methane yield for important co-substrates

Figure 6: General view of the Behringen co-fermentation plant in Germany

There the manure guarantees the pH-buffering of the process due to the nitrogen content and also the delivery of other essential nutrients and prevents the process as a result of the continuous inoculation in a wide range from failures by overloading. The other co-substrates are the necessary carbon sources for high biogas production.

Typical calculated bio-chemical parameters [3], [4], [6], [7] of accepted and often used co-substrates are summarized in Fig. 4 and Fig.5, respectively.

Plant operation in industrial scale

The extraordinary example of a smaller but high efficient industrial-scale co-fermentation plant is presented in the following. The Behringen co-fermentation plant, located in Thuringia County, Germany, processes manure from a confined animal operation of about 1,000 dairy cows together with other industrial and agricultural organic residues. This facility was designed, constructed and commissioned by Linde AG of Germany for BEUG Biogas and Energie GmbH, and started operation during December, 1995.

A general view of the Behringen plant is provided in Figure 6 and a process flow diagram in Figure 7. The overall plant process consists of waste storage and feed composition followed by anaerobic digestion, conversion of biogas to electrical and thermal energy and storage of the stabilized liquid/fibre nutrient product.

The Behringen plant design was based on an anaerobic digestion process that was applied to (a) reduce the odour of the liquid manure, (b) improve the storage stability of the manure, (c) alter the manure nitrogen components to be more easily assimilated by the plants and (d) recover useable energy. Recognizing that dairy cow manure has already undergone a digestive phase in the cow's stomach, and thus has a limited amount of degradable organic available which results in low biogas

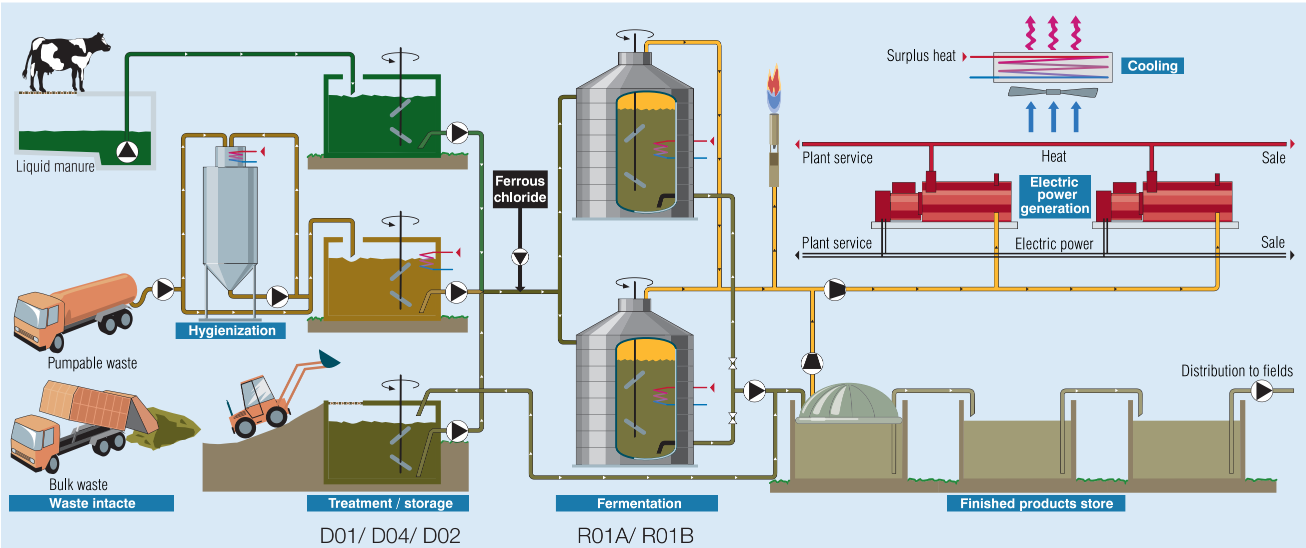

Figure 7: Process flow diagram of the plant

production, the Behringen plant was designed as a co-fermentation plant. In this case the manure was supplemented with organic wastes from the several industrial sources for processing in one-step thermophilic anaerobic digesters with an additional final "anaerobic maturing" of the effluent in a covered storage tank with connection of the gas space to the biogas system. The key waste sources are:

- Liquid manure from a contained animal operation of about 1,000 dairy cows that are housed in closed stables containing slotted floors. The manure is pumped to a storage tank (DO1).
- Fat trap residues and spent cooking oils are delivered to the plant in tank trucks as an emulsion and pumped to a heated storage tank (DO4).
- Bentonite clay that is loaded with fats and oils, derived from the bentonite being used as a filter media in plant-oil refinery, is delivered to the plant in container trucks, stored as bulk and loaded into an under floor storage tank (DO2).
- Solid Fraction of pig manure that has been dewatered with a screw press at the pig farm is delivered to the plant with container trucks, stored as bulk and loaded into a storage tank (DO2). The pig residue is added as a substitute for the bentonite feed material.
- Brewery sludge's, residues of maize silage, low-grade seed potatoes, and rape press cake as charge wise delivery, stored as bulk and loaded into a storage tank (DO2) to be mixed there with the above mentioned wastes and manure or digester effluent to realize a pumpable slurry. Before mixing the bulk materials, such as the fat- saturated bentonite clay and pig residue, are stored on a concrete base. In addition the bulk products are converted into a pumpable state by using a macerator if necessary and adding other waste components or digester effluent, and then stored (DO2).

Characteristics of feed components together with the typical feed composite resulting from combining of the feeds is provided in Figures 4, 10, and 11, respectively. The Behringen plant was designed to process 13,000 t/a of dairy cow manure and up to 20,000 t/a of other industrial organic wastes and agricultural residues from the own farm production [5], [9].
Taking advantage of the co-fermentation synergistic effects allows the biogas yield to be substantially increased relative to the digestion of only liquid manure (Fig.8).

The anaerobic digesters are charged with the various component feeds in accordance with a metering control concept that was developed specifically for the Behringen co-fermentation plant to ensure maximum biogas production. Prior to the combined feed entering the digesters, ferrous chloride is added to control the level of hydrogen sulphide maintained in the digesters.
The two digesters (RO1A and B) are fabricated of welded steel plate and insulated to minimize heat leak at the 57°C operating temperature. Each digester has a liquid volume of 800 m³ and is equipped with a slow speed mixer mounted on the digester tank top to slowly mix the digester contents. The digester temperature is maintained by using coil-pipe heat exchangers located within each digester. Hot water from the plant hot water systems (CHP cooling water) is utilized in these heat exchangers on an as needed basis. At the design feed capacity the digesters provide an 18 to 22 day retention time (in dependence of the possible industrial waste input and consistency) and have a volumetric organic load of about 5 to 7 kilograms of volatile solids per day per cubic meter of reactor volume.
The biogas generated by the fermentation process is supplied directly from the digesters to two engine-

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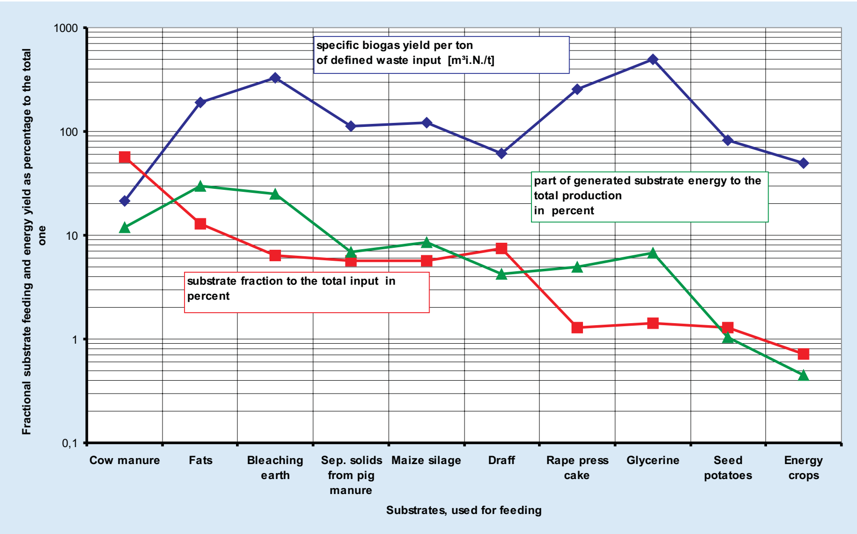

Figure 8: Mass fractions and energy yield of the digested co-substrates

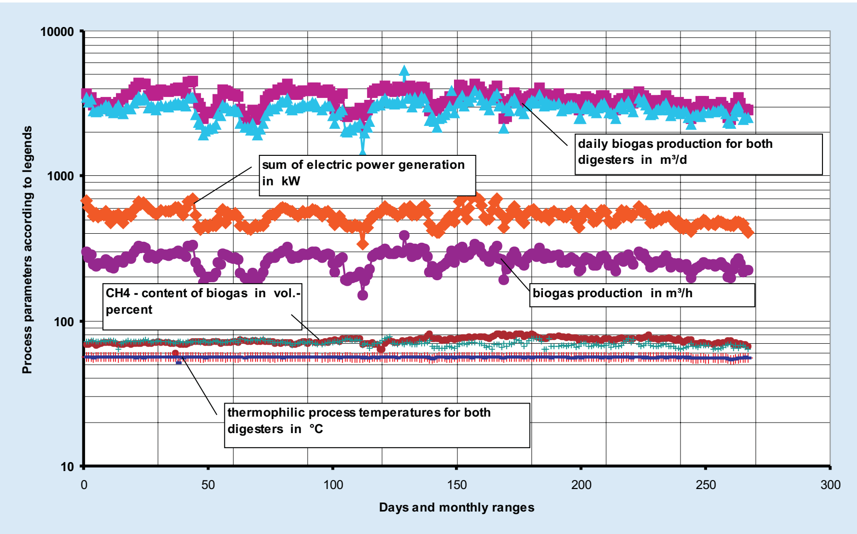

Figure 9: Process parameters and energy production

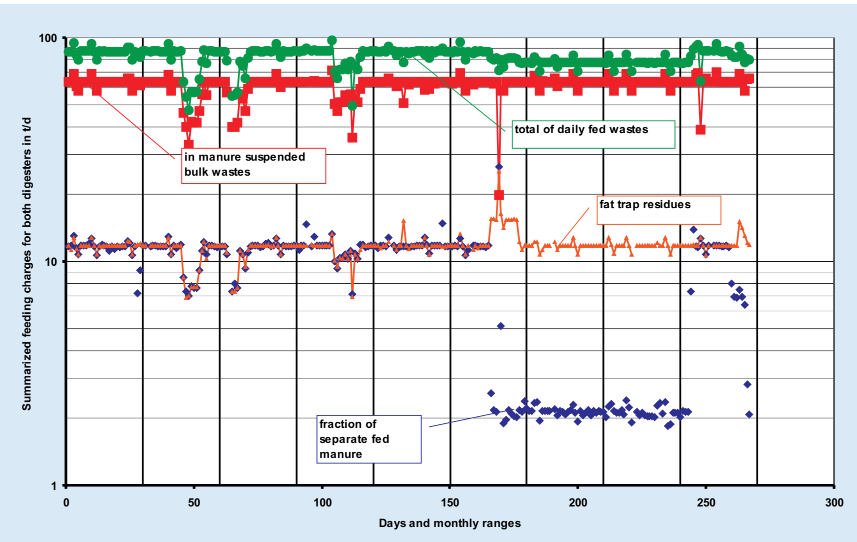

Figure 10: Daily input feeding of the stored substrates

generator sets (CHP) to produce electrical power and thermal energy. Additional biogas for supply to the engine-generators is collected by a membrane gasholder that is installed floating on top of the initial storage tank for the digester effluent. The quantity of biogas collected by the membrane represents about 10 percent of the total biogas produced.
The co-fermentation of the dairy cow manure and the industrial organic residues provides for a biogas yield of about 900 to 950 m³ NTP per ton of converted volatile solids. The methane content of the biogas is about 68 percent. The biogas yield depends upon the composition of the feed material and its biodegradability and can vary over a ten-fold range (Fig.8). Since the Behringen fat/oil feed stream contains a substantially larger quantity of convertible carbon matter then the manure, the co-fermentation approach to waste conversion results in substantially higher biogas yields.
Jenbacher Energiesystem GmbH, Austria supplied the piston engine-generator sets, and each has an electrical capacity of 450 kilowatts and a thermal capacity of 750 kW. Based on the biogas production rate the Behringen power station produced about 600 to 700 kilowatts of electrical energy (Fig.9) with peaks up to 800 kilowatts by the present feeding of glycerine. The heat rejected by the engine-generators is contained by a hot water system and used by both the co-fermentation plant as well as the confined animal facility.
About 30 percent of the electrical energy produced is used to supply the co-fermentation plant and confined animal facilities. The remaining electrical energy is supplied into the local utility energy grid for which Behringen receives about 0.2 DM per kilowatt-hour. This electrical energy purchase price is fixed by the German government by law as the electrical energy price for “green” power from renewable sources.
The energy production is typically limited by the variability of the industrial organic wastes. As previously

discussed, the thermal energy produced from the engine-generators is used for maintaining digester temperature, heat treatment of specific industrial wastes and heating of facilities relating to both the co-fermentation plant and the confined animal operation as well as some residences in the neighbourhood of the plant.
The effluent liquid nutrient stream has a total solids concentration of about 9 percent with about 3.5 percent of the total solids available as total nitrogen. This total nitrogen has a higher ammonia content than the feed, allowing the nitrogen to be assimilated easier by the crops.
The fermentation effluent, rich in nutrients, is pumped to storage tanks and held until applied directly to the local agricultural land. There are four effluent tanks, each having a volume of about 2,000 m^3. Each storage tank contains a mixer, which is normally operated prior to withdrawing the liquid fertiliser for land application. The storage tanks have sufficient volume to hold the liquid fertiliser for over 100 days, which avoids land application during winter and rainy periods. The material is applied to the land using tank trucks equipped with drag-piping systems to avoid aerosols.
A summary of the Behringen co-fermentation plant input balance is provided in Figure 10. The feed composition can vary substantially due to availability and variability of the industrial organic wastes. This results from the majority of the carbon matter being associated with the industrial organic wastes.
The feed composition of the bulk materials (Fig.11) guarantees always the same potential of digestibility independent from the daily or weekly waste delivery.
The time period that was required to complete the Behringen plant, from engineering to mechanical completion, was ten months. In addition, about three months was required to achieve pseudo-steady state operation of the co-fermentation process.
Operation staff consists of two people, mainly organizing unloading and

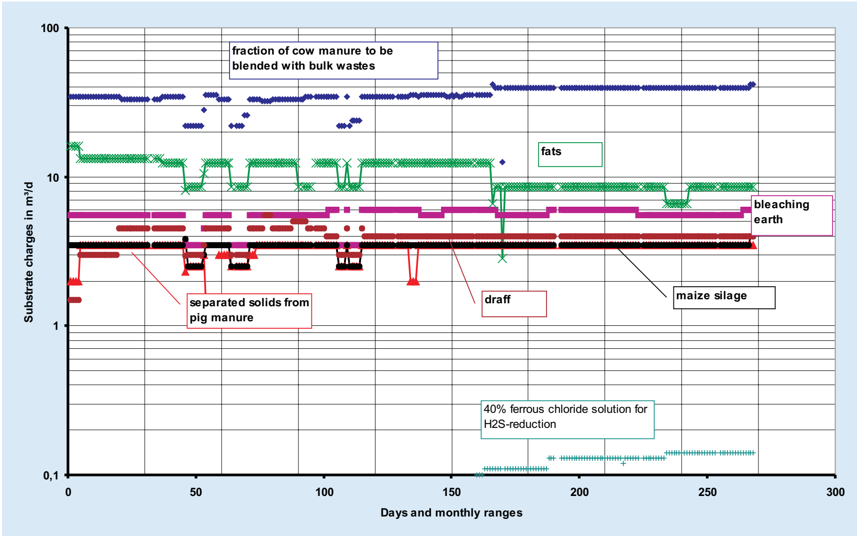

Figure 11: Feed composite of bulk waste fraction, suspended in manure

material specific storage of the incoming industrial waste charges.
Night and weekend operation is fully automatic with included telephone alarm service for significant disturbances or malfunction in main systems of the plant.

Conclusions

The full-scale experience from that farm-owned biogas plant, using a complex manure/biowaste substrate, demonstrates the possibility of high and stable biogas production with technological efforts acceptable also for an agricultural company.
Cost efficiency of such plant depends on the governmental support for the idea of “green” energy production and the peoples´ acceptance to use the digested products in agriculture as fertiliser. To offset the plant annual costs, income is received from the sale of electrical energy and payment for processing of industrial organic wastes. However, whereas the value for electrical energy has been guaranteed now for a longer period by governmental decision, the value for the industrial organic wastes has been steadily decreasing because former industrial organic wastes become more and more the status of a wanted “fuel” for energy production on the European market.
It is evident that a true mass and energy balance based on detailed input specification with due account of the long-term development of the waste situation in the territory should be taken into account at the stage of such a plant design already in order to achieve a high plant efficiency.
The possibility of theoretical calculation of biogas yields, even for complex waste mixtures, enables the modelling of process dependencies on input changes in quantity and quality.
It is an instrument to reduce design failures in the planning phase as well as to enable the plant operator to foresee fluctuations in biogas production and methane content.
Manure treatment on industrial scale and with industrial technology reduces harmful and hazardous impacts on the environment. On the other hand this process safety has its price and makes consequent process optimisation necessary with respect to the individual local conditions.
Integrated treatment/production plants will help to compensate treatment expenses by the receipts for sold products. In addition savings for energy, fertilizer, and so on, will economize the overall efficiency of such a project.
That’s why all possible efforts have to be made not only to realize a “manure treatment” but also to enable directly or indirectly the generation of useful products to be sold on the market.

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