Monofermentation of Nutritional Waste in Biogas Plants

Pilot - Biogas Plant

Jan Adolph, Jürgen Beck and **Thomas Jungbluth**
Hohenheim University, Institute of Agricultural Engineering, Stuttgart, Germany

In a joint project of the partners Ing. Friedrich Bauer GmbH (Kemmelbach, Austria), Enersys GmbH (Donaueschingen, Germany) as general planner, the Biogas - Systemtechnik Deutschland (BST - D company) as constructor and the Institutes of Agricultural Engineering as well as Environmental and Animal Hygiene with Veterinary Clinic (head: Prof. Dr. R. Böhm) at Hohenheim University a process engineering technique was developed and tested for the anaerobic monofermentation of nutritional wastes with high energy concentrations and low contents of structural components. The research project started with systematic investigations in the biogas laboratory of the Institute of Agricultural Engineering at Hohenheim University about monofermentation of nutritional waste to obtain information about the fermentation behaviour and the performance of the substrate (compare long version, LANDTECHNIK-NET, volume 01/2004). In a second step intensive process engineering and hygienic investigations followed at the pilot biogas plant being erected by Biogas Systemtechnik Deutschland GmbH at Donaueschingen. The general planning was done by Enersys GmbH, Donaueschingen.

The trials included two phases in a period of in total 192 days. In phase I the fermentation process was started and the tube fermenters of the plant got filled at first exclusively with inoculant material and afterwards they were fed with slowly increasing amounts of nutritional waste. After 130 days phase I finished by the end of November 2002. During that time in the tube fermenters 0.971 $m^3\ CH_4\ m^{-3}\ RV\ d^{-1}$, was produced in average, and in the second fermenter stage 0.431 $m^3\ CH_4\ m^{-3}\ RV^{-1}$ were generated under a hydraulic loading rate of 3.18 kg odm $m^{-3}\ RV\ d^{-1}$ and with a theoretical retention time of the fermentation substrate in both fermenter stages of about 118 d. The gas quality from both fermenter stages reached in average 56.3% CH_4 and 36.1% CO_2. Due to a defective temperature measurement device in combination with malfunction of the gas counter whose signals were basis for the determination of the specific input mass of fresh substrate, the horizontal fermenters got overloaded in the beginning of October. Subsequently the concentration of volatile fatty acids increased rapidly up to 16500 ppm, whereby especially the concentration of propionic acid strongly increased up to 4690 ppm. As a result the pH - value in the horizontal fermenters dropped down to values of 6.4. By re-inoculating with fermented material from the second fermentation stage methane generation was restarted again. In phase II over a duration of 62 days and after having stabilized the process conditions there were generated in average 0.95 $m^3\ CH_4\ m^{-3}\ RV\ d^{-1}$ in the tube fermenters and 0.64 $m^3\ CH_4\ m^{-3}\ RV\ d^{-1}$ in the second fermentation stage with 58.7 % CH_4 and 36.6 % CO_2 in the mixed gas. The concentration of volatile fatty acids was at a level of in average 5070 ppm of acidic acid and 3680 ppm of propionic acid. It can be followed that the process has been overloaded due to the high contents of volatile fatty acids. The results from the lab scale investigations and from the pilot plant confirmed that a monofermentation of nutritional waste is feasible but that there are several starting points to optimize the process and the strategies as well concerning aspects of process engineering and fermentation biology.

Keywords
Biogas, monofermentation, nutritional waste, cogeneration, methane

Introduction

From comunal feeding facilities like gastronomy, hospitals, canteens, student restaurants and barracks every year about two million tons of nutritional wastes accumulate in Germany. Additionally considerable waste masses are produced in the nutritional industry or occur from food marketing. The disposal of these materials for example brewery by - products, residues from soft drink and animal feed production, refuse of the gelatine-fabrication, fibre-, meat production, leather industry and pharmaceutical production is controlled in Germany by the "Biowaste Ordinance - Bioabfallverordnung - BioAbfVO" [1]. Correct disposal according to § 5 Abs. 3 KrW-/AbfG] means that the utilization of these waste has to be in accordance with other public laws e.g. Federal Immision Protection Act (Bundes-Immissionsschutzgesetz -BImSchG), chemical law, hazardous material law, soil protection law). These substrates were collected by specialised companies up to now. A considerable share was used by specially equipped farms for pig feeding after having been sanitised in a boiler at high temperatures for a certain retention time. With this procedure it was possible to recycle valuable nutrients of these wastes. The new EU-directive 1774/2002 (1), which has to be applied since April 2003, prohibits the processing of these materials to animal feedstuff. This results in a severe waste problem with high costs for the utilisation respectively final treatment of these substrates, because established processing techniques like composting or combustion are not appropriate because of high water concentrations.

Material and Methods

In the frame of the research project a pilot biogas plant has been constructed and is operated by the companies Biogas Systemtechnik Deutschland GmbH (BST-D GmbH, Donaueschingen, Germany) in

close cooperation with the company Ing. Friedrich Bauer GmbH (Kemmelbach, Austria) in Donaueschingen, which is shown schematically in **figure 1**.

Description of the Pilot - Biogas Plant

Black - Area

The „black area“ of the pilot plant is the impure part of the unit, where the not yet sanitized delivery is processed and stored until sanitation. By a strict segregation from the „white area“ (compare “White-area”) ents the pure and clean part of the unit after the sanitation step, possible re-contaminations of the already pasteurized substrate are steadily prevented.

Vehicle Scale and Preparation Pit

The nutritional waste is supplied by a company which is specialized on the collection and processing of these substrates in a mashed and pumpable consistence. After having been weighed in the black area of the unit, the substrate is pumped into the reception pit with a capacity of 200 m^3. To be corrosion resistant also under the low pH-values of the delivered substrate, the concrete tank has been protected by a special interior plastic coating. The preparation pit buffers and balances at the same time the eventually occurring strong fluctuations in the nutrient composition of the delivered nutritional waste. In the moment of printing the pilot plant is enlarged by the construction of a reception-station for food refusals with an appropriate processing such as unpacking, comminution and cleaning of the transport containers. The processed material is subsequently pumped to the preparation pit, where it is mixed with the other nutritional waste by a separate agitator with automatic timer.

Sanitation

The mashed and homogenized material is delivered from the preparation pit in loads of approximately 3 m^3 into the sanitation unit, where it is heated up to 70°C. To heat up the substrate efficiently a buffer store of 12 m^3 hot water (90°C) is available which is heated itself by the waste heat of the CHP-unit. The heated substrate is stored for one hour at 70°C which is prescribed by law. During that period it is agitated permanently by a mixer to secure an even heating of every substrate particle. The temperature course during sanitation is automatically and simultaneously registered to create a protocol, because the plant-operator is obliged to prove the function accuracy towards the licensing authority. After the successful sanitation of a substrate load the material is automatically cooled by a heat exchanger in an identical second container, in order to heat up the next substrate load which has to be sanitized in a counter current. Therefore less heat energy is lost due to cooling the sanitized material. This measure secures that the substrate is delivered with a maximum temperature of 35°C into the delivery pit.

White-area

Delivery pit

After sanitation the nutritional waste is delivered with a displacement pump into the so called “white area” of the unit by a pipeline into the delivery pit. This 115 m^3 pit serves as well as the reception pit as an intermediate store. A propeller agitator is homogenising the sanitized nutritional waste every 30 minutes to prevent the segregation of the material. If the plant is run with full load the stored material volume is sufficient for about five days in order to secure a continuous operation also during the weekends with an interrupted material delivery or during maintenance work at the sanitation unit.

Horizontal tube fermenter (first fermenter stage)

From the delivery pit the substrate is discharged with a displacement pump with an integrated flow control unit into the four horizontal tube fermenters (System: Fa. Ing. Friedrich Bauer GmbH, Austria) with a volume of 165 m^3 each. Every fermenter is 25 m long with a diameter of three meters and it is inclined by five degrees to the front end. The centrally located agitator axle serves as well for the homogenisation of the material and for its degassing as well as for the heating of the fermenter content because it is heated in its first third. In the rear part of the tube fermenters the partly fermented substrate flows via the dome area through a siphon system with every delivery charge of

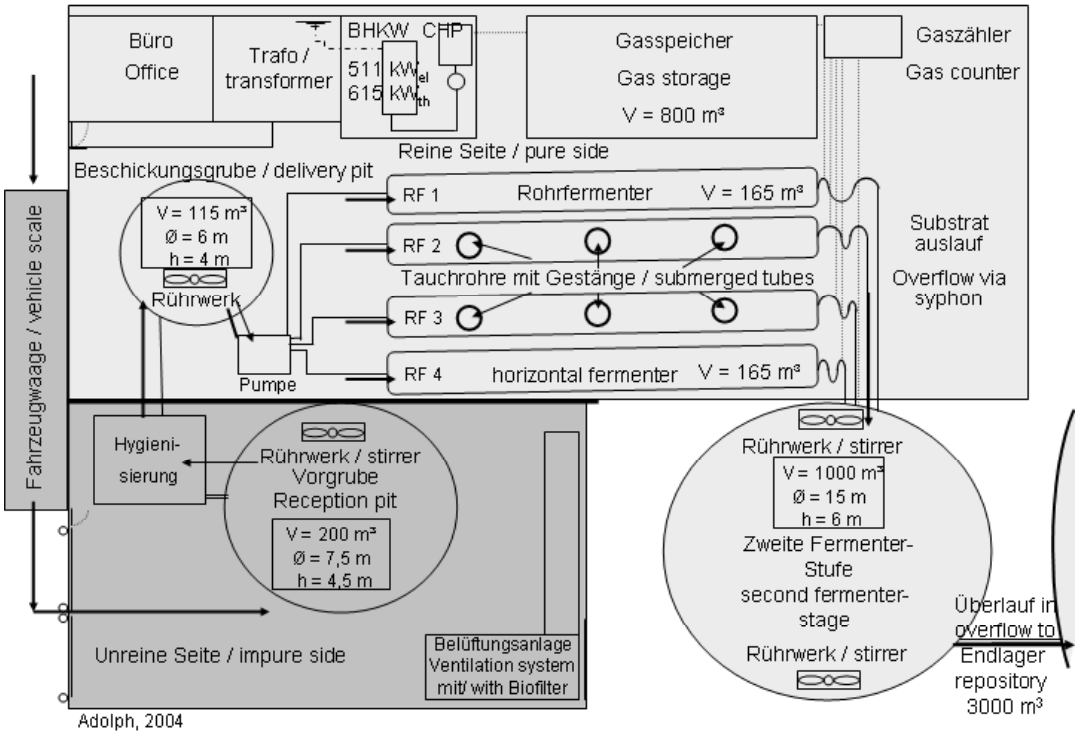

Figure 1: Scheme of the pilot biogas plant, system BST - D, for monofermentation of nutritional waste with four horizontal fer-menters (165 m3 each), one 2nd stage fermenter (vertical cylinder with 1000 m3) and CHP (511 kWel, 615 kWth) for combined heat and power generation from the produced biogas

fresh material in the front part over simple displacement into the second fermenter stage. Above that about four volumetric percent of the produced gas volume is automatically controlled injected into the gas dome area to desulphurise the produced biogas with the help of sulphur reducing bacteria.

Second fermenter stage

The substrate leaving the tube fermenters is fermented for further 30 days (under full workload of 8000 t of nutritional waste per year) in a second fermenter stage. This hermetically closed ferroconcrete reactor contains a total volume of 1000 m^3, whereof 800 m^3 serve as substrate volume and 200 m^3 as gas volume. The operation temperature of this fermenter stage is about 38°C. The fermenter is equipped with a wall and floor heating and is protected at its exterior side with a strong 10 cm thick insulation against heat losses. Like in the tube fermenters the desulphurisation of the produced biogas is obtained in the gas volume by air injection.

Repository

After the fermented nutritional waste has left the second fermenter stage by the siphon-overflow they it is guided in a tube to the open repository out of reinforced concrete which contains 1800 m^3. The floor of this reservoir which has been former used in the purification plant has a conic form in order to let the remaining solids in the decomposed material sediment more easily. In the upper part an overflow leads to the regional purification station which is located on the same site.

Gas collection and gas storage

The biogas being produced in the tube fermenters and in the second fermenter stage is collected separately from each fermenter and is transported in inoxydable steel tubes to the foam stripper with upstream gas counters. This elaborate gas collection enables the detailed determination of the gas volumes being produced from every single tube fermenter and to adjust the delivery portion of fresh substrate individually. Furthermore in front of the gas counters a measuring device, ADOS® system, has been installed which determines the CH_4 and H_2S matters automatically by means of non dispersive infrared - spectroscopy (NDIR). Above that this device measures in important parts of the biogas plant like in the fermenter room and in the gas store the gas composition of the ambient air. It is able to activate an alarm in case of exceeded threshold values (25 and 50 of the lower explosion limit). After the volumetric metering and the determination of the content, the biogas is guided via a foam and condensate precipitator to the gas store. There the biogas being produced is collected in a flexible plastic sack with a maximum volume of 800 m^3. In the upside part of it an overpressure safe guard device protects the gas store in the case of a disturbance of the gas utilisation (CHP and stand - by gas boiler) against intolerable high strain. A volume meter determines the fill level of the gas sack and sends a start order to the CHP - unit at a definable filling degree. If the gas level is due to a low gas production not able to secure the permanent operation of the CHP-unit, the gas motor gets from this measuring device a signal to stop operation in order to secure enough biogas to heat up the sanitation - unit and the fermenters with help of the standby gas-boiler.

Gas-flare

In case of a malfunction of the CHP and/or standby gas - boiler the produced biogas cannot or only partly be used. An uncontrolled emission of biogas into the ambient air in a biogas plant of this size is legally prohibited. For these exception cases a gas - flare is installed to ignite the excess biogas under control and to burn it outside the danger zone of the unit.

Activated carbon filter

Although there is a biological desulphurisation unit with air injection into the fermenters, it is possible that the H_2S - content in the biogas is exceeding the tolerable threshold from 150 ppm which is the upper tolerable limit permitted from the CHP-manufacturer. To prevent the expensive parts of the unit like the gas motor and the standby gas-boiler from damages being induced by the deposits in the burner volumes an additional desulphurisation with an activated carbon filter has been integrated which has to be passed by the biogas before utilisation. This is the reason why the H_2S-content can be maintained on a base level of below 150 ppm.

Combined heat and power plant (CHP)

To generate electric energy out of the biogas a Jenbacher gas motor of the type J 212 GS-B/N.L has been installed. It is a V-12 cylinder unit with 24400 cm^3 displacement, intercooling and exhaust-gas turbocharger. It generates under full load an electric power of 511 kW_{el} and a thermal capacity of 615 kW_{th}. The electricity being generated is delivered by 100 % into the public grid and is paid with 10.1 €cent/kWh following EEG (renewable energy law). Under full load the CHP-unit consumes 280 m^3 biogas with a methane content of 60% per operating hour. Thereby the CHP-unit achieves an electrical efficiency of η_{el} = 38.6 % [2]. The waste heat generated in the CHP - unit is transmitted from the cooling water and from the exhaust gases with two heat - exchangers and is delivered to the central heating unit by two 4 m^3 high temperature buffer stores. There it is used for fermenter heating and for operating the sanitation-unit. Above that an emergency cooling system has been installed at the roof to extract excess heat.

Standby gas-boiler

Fluctuation in gas - production may induce that the CHP-unit is not able to run 24 hours per day with full power. Because also during that time especially for the operation of the sanitation unit, sufficient heat has to be provided by a standby gas-boiler operated with biogas as fuel. The net heat capacity of the boiler is sufficient to supply all users of the unit with hot water.

Central Control Technology

The whole biogas plant is controlled by programmable logic controllers (SPS) which allow to monitor online every component at the central computer in the control room by a visualisation software (system: Endress + Hauser GmbH). A modem with remote inquiry enables the manufacturer and the operator of the plant to have a direct remote control of the plant components with adjusting options. In total this system offers the direct information from 267 measuring points and control parameters. This is an enormous advantage in a plant of that dimension to be able to react very fast after disturbances and therefore to prevent costly breakdowns of the unit.

Fermentation substrate

The nutritional waste has been delivered readily in a homogenised condition in a tank truck from an enterprise being specialised on the disposal of nutritional waste. Due to the high number of clients the variation of nutrient contents is quite low and at the same time the material is characterised by high energy content (compare chapter “nput substrate” ong version laboratory investigations Landtechnik-Net.

Inoculation substrate

The fermenters of the pilot plant had been filled first on July 22nd, 2002 with substrate. Half of the total tube fermenters volume (330 m^3) had been filled up with water. Above that 26 m^3 of digested fermentation substrate from a biogas plant in the Allgäu area which is operated in cofermentation with nutritional waste has been divided equally into the four tube fermenters. The remaining volume of 304 m^3 was filled with digested sewage sludge from the purification plant at Donaueschingen [3].

Measuring parameters and sensor technology

Gas yield

The gas yield from the tube fermenters and from the second fermenter stage was registered by five rotary - piston gas meters. Counter impulses being registered from the measuring devices (each 0.1 m^3) are subsequently delivered to the central control unit. These meters were read off once daily.

Composition of the gases

In the experimental design it was scheduled that the gas quality should be continuously monitored by the ADOS® - analysing device being already installed at the unit. But until the end of the investigations this analyser could not be commissioned due to technical problems. This was the reason why gas quality was determined on the same way as it was done in the laboratory investigations by use of the Siemens - Ultramat 22® at the beginning in a weekly schedule. Later on the data from a gas chromatograph (Perkin - Elmer, Sigma 300®) were available in the frame of cooperation with the University of Applied Sciences Furtwangen [4].

pH-value and fermentation temperature

In addition to the six submerged tubes (picture 3) being welded in the two centre tube fermenters leverages has been constructed which could be immersed totally in the submerged control tubes. Connected to this installation temperature and pH -sensors from the company Endress + Hauser have been flexibly fixed on different levels. They were connected with a wire to a central data logger. So it was possible to obtain additional online information at an interval of two minutes about temperature and pH - course in the fermenter.

Dry matter / organic dry matter and decomposition rate

The German standard - process [5] provided the theoretical guidelines for the determination of dry matter and organic dry matter content of the input and output substrates. The dry matter content had been determined by drying a substrate sample of about 100 grams until mass constancy in a drying chamber at 105 °C for 24 hours. The organic dry matter content had been calculated after having the ash content of the sample determined in a box - type furnace at 450 °C. Subsequently the glow loss could be calculated as follows:

$$\text{odm - content} = \frac{\text{mass (dm) - mass (ash)}}{\text{mass (dm)}} \cdot 100 \ [\%]$$

Because during anaerobic fermentation organic dry mass is not completely digested to biogas it is important to know the digestion rate as an additional parameter in order to be able to evaluate the efficiency of the process. The decomposition efficiency is mainly depending on the chemical composition (energy and nutrient contents) of the initial input material, the reactive conditions in the fermenter (e.g. temperature) and the retention time of the substrate in the biogas fermenter. The decomposition grade can be calculated as follows: Difference between concentration of organic dry matter in fresh substrate (C_{zu}) and fermented substrate (C_{ab}) proportional to fresh substrate.

$$\text{decomposition grade} = \frac{C_{zu} - C_{ab}}{C_{zu}} \ [\%]$$

Fatty acids

The fatty acids being produced in the biogas process are important criteria for the stability of the anaerobic fermentation process. For quantitative and qualitative determination the CP - 3800 GC® - system of Varian Analytical Instruments ash been utilised for the laboratory experiments as well as for the investigations at the pilot plant. This measuring system is segregating the fatty acids by gas chromatography [6, 7]. The samples get delivered into the device by split - injection in relation of 1 : 50 by the hot - needle technology into the vaporiser (insert) with 1 µl of injection volume. To segregate and detect the single fatty acids a capillary-segregation column with 25 meters of length and a diameter of 0.32 mm with 0.25 µm film cover was used.

The used measuring system enables the analysis of C_2 - C_8 fatty acids among them are C_2 and C_3 of special importance for fermentation biology with anaerobic digestion because they are used as parameters for the efficiency and stability of the fermentation process.

Remaining biogas potential

For the operator of a biogas plant it is important that the gas yield from the input material is maximised. If the output material which leaves the digestion plant has still a high gas production potential it could be under certain circumstances economically feasible to build an additional fermenter. Therefore the Hohenheim biogas yield test (HBT) which had been developed at Hohenheim University has been utilised to determine the final gas potential for nutritional waste substrate used at the pilot biogas plant "Biokraft Donaueschingen" [8].

Calculated data

To be able to compare the data from the laboratory experiments as well as those from the pilot biogas plant under different fermentation conditions it was important to calculate important parameters. In **Table 1** these parameters are summarized for a better overview.

Sampling of Substrate

In total substrate samples had been taken with a special developed sampler at the following seven sampling locations. The samples had been analysed for the decomposition rates and for the nutrient contents and fatty acids:

- Reception pit
- Delivery pit
- Tube fermenter front part
- Tube fermenter middle
- Tube fermenter rear part
- Tube fermenter outlet
- Second fermenter stage

In the two central tube fermenters 2 and 4 three submerged tubes were installed in the front, middle and rear part of the reactors. With the sampler (**figure 2**) it was possible to take substrate samples from different levels in the fermenter. The submerged tubes (**figure 3**) were constructed in a way that they had the largest possible openings to let the substrate flow unobstructed through it and to enable representative sampling of the fermenter content.

Results

Starting of the pilot plant, stabilizing of operation conditions - phase I

The substrate portions being daily delivered into the tube fermenters had been increased slowly to have a slow adaption of the microbial population and in order to

Table 1: Calculated process engineering parameters at the monofermentation of nutritional waste at the pilot - biogas plant

Parameter		Formula	Unit
loading rate	(B_R)	$B_r = \frac{S_{zu} \cdot C_{zu}}{V_R}$	g odm/l RV•d (1) kg odm/ m³ RV•d (2)
Retention time	(HRT)	$HRT = \frac{V_R}{S_{zu}}$	d
reactorspecific biogas yield	(G_R)	$G_r = \frac{G}{V_R}$	l/l•d (1) m³/m³•d (2)
reactorspecific methane yield	(M_R)	$M_r = \frac{M}{V_R}$	l/l•d (1) m³/m³•d (2)
substratspecific biogas yield	($G\ oTS_z$)	$G\ oTS_z = \frac{G}{oTS_z}$	l/g oTS (1) m³/kg oTS (2)
substratspecific methane yield	($M\ oTS_z$)	$M\ oTS_z = \frac{M}{oTS_z}$	l/ g oTS (1) m³/kg oTS (2)
decomposition grade	(R)	$R = \frac{C_{zu} - C_{ab}}{C_{zu}} \cdot 100$	%

(1) = unit: laboratory investigations
(2) = unit: investigations at pilot biogas plant „Biokraft Donaueschingen"

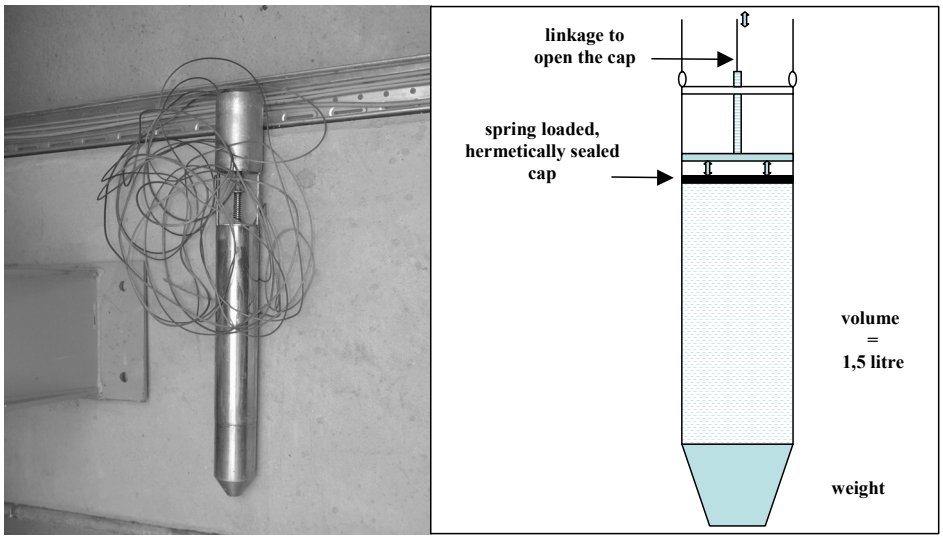

Figure 2: Substrate Sampler

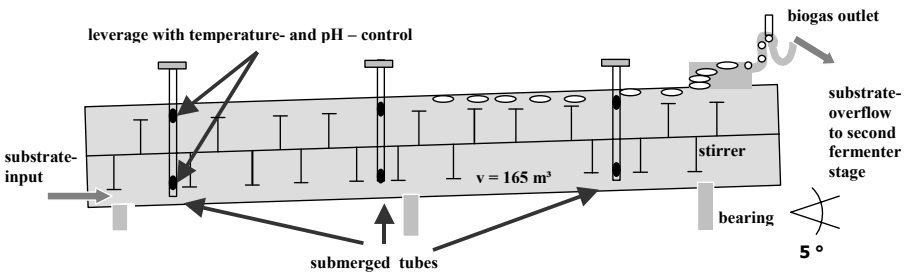

Figure 3: Transverse section of an experimental horizontal - fermenter at the pilot -biogas plant with tube - inserts for temperature-, pH - measurement and for fixing germ - carriers for the Institute for Environmental and Animal Health

continuously increase gas production. Until mid of September the input volume was controlled manually. The target was to obtain the value of 2.5 m^3 biogas m^{-3} RV d^{-1} which has been guaranteed by the plant manufacturer. This value was achieved by the end of August in all tube fermenters and was even exceeded (**figure 4**).

For about 20 days further on biogas generation remained constant. Due to a defective temperature measurement device in combination with malfunction of the gas counter whose signals were basis for the determination of the specific input mass of fresh substrate, the horizontal fermenters got overloaded in the beginning of October. In consequence the fatty acid concentrations increased up to 16500 ppm quite fast. This resulted in a rapid pH - decrease in the tube fermenters and therefore the delivery of fresh input material into the fermenters was reduced down to zero. The biogas generation could be re - established and stabilized again until the end of the initial phase by slowly increasing the daily input portions and by re - integrating fermented material from the second fermenter stage into the tube fermenters for re - inoculation. After this problematic phase the initially similar daily biogas generation rates were different because the input portions were adapted to the actual pH-values in the single fermenters. The reactor specific methane yields reached in the middle of phase I in all tube fermenters about 1.0 m^3 CH_4 m^{-3} RV d^{-1}. In the second fermenter stage 0.35 m^3 CH_4 m^{-3} RV d^{-1} were produced. In the phase of constant gas production everyday about 12 m^3 of fresh material with 17 % odm were delivered thus resulting in a hydraulic loading rate of 3.1 kg odm m^{-3} RV d^{-1} related to in total 660 m^3 of tube fermenter volume. The values of 0.8 - 1.25 m^3 CH_4 m^{-3} RV d^{-1} which had been obtained in the laboratory experiments under a hydraulic loading rate of 3.5 kg odm m^{-3} RV d^{-1} showed in the thermophilic temperature range, that the reactor specific gas production of the tube fermenters in the pilot biogas plant corresponded at that time to those of the laboratory reactors. During this period 108 m^3 CH_4 t^{-1} odm had been produced in the tube fermenters compared to in average 245 m^3 CH_4 t^{-1} odm under a hydraulic loading rate of 3.5 kg odm m^{-3} RV d^{-1} in the laboratory experiment. To have the laboratory experiments comparable, the gas generation from the second fermenter stage has not been taken into account.

Phase I of the investigations documented that the starting of a biogas plant and the subsequent stabilizing of the operation conditions is of special importance. Especially the overload of the tube fermenters with fresh material showed negative effects on the performance. By the means of a detailed analysis of the fatty acid concentration it was possible to testify a long lasting effect of the increased propionic acid concentration in the tube fermenters with losses in performance of gas produc-

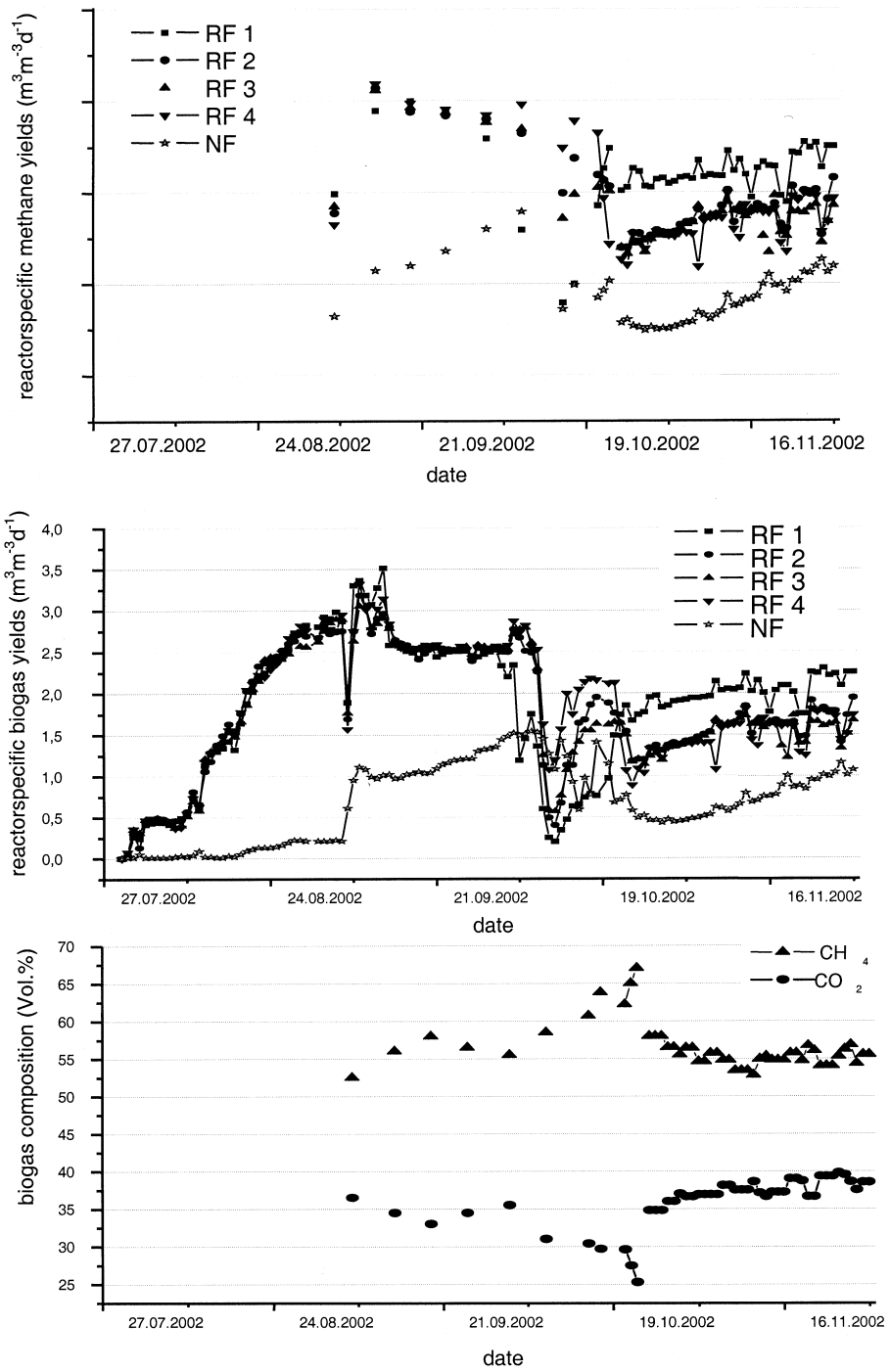

Figure 4: Monofermentation of nutritional waste - reactor specific biogas yields and development of the gas quality during start - up of the plant (phase I, mesophilic temperature)

tion and gas quality. An overload with fresh input material has to be prevented under any circumstances.

Mesophilic continuous operation of the pilot plant - phase II

By the different input portions of sanitised nutritional waste which were adapted to the actual pH-value in the tube fermenters resulted also different reactor specific biogas, respectively methane yields (**figure 5**). Tube fermenter 1 generated in the 62 days in average 1.27 m^3 CH_4 m^{-3} RV d^{-1} with an average pH - value of 7.4 whereas tube fermenter 2 to 4 reached in average only 0.93 m^3 CH_4 m^{-3} RV d^{-1} under nearly similar high pH-values. The reactor specific methane yield of the second fermenter stage generated in this period 0.64 m^3 CH_4 m^{-3} RV d^{-1} and was therefore nearly twice of the one in phase I under an average pH - value of 7.7.

Despite the initial problems with the overload of the tube fermenters in phase I the gas generation stabilised until the end of January 2003. By the means of the automatic pH-registration and the analysis of the fatty acid concentrations it could be testified that viscosity and dry matter content of the fermentation substrate in the tube fermenters in interaction with the agitator and the construction of the fermenter are not sufficient to secure the expected plug-flow in the horizontal tube fermenters. Therefore they have to be characterised as fully stirred fermenters where short-cut flows in the substrate flow could not be excluded. This is the reason why an upstream sanitation unit is indispensable with a clearly defined temperature impact and a certain retention time of the fermentation material before the substrate gets delivered into the tube fermenters. The automatic temperature registration being installed in the central fermenters 2 and 3 allowed detecting a process engineering problem. It is supposed that the temperature sensors of the heating control being located unfavourable in the area of the sediment layer in the tube fermenter caused by differing measuring values in the central control panel a reasonable difference in fermentation temperature. A difference of about ±3 °C can not be tolerated in mesophilic fermentation, although it is known for its insensible temperature behaviour. This measuring mistake can be prevented by changing the position of the temperature sensor into a steadily mixed part of the tube fermenter.

The very well constructed and dimensioned heat insulation of the tube fermenters can be seen in **figure 6**. Although heating had been stopped, the temperature in the fermentation substrate stayed for more than 10 days above 30°C. In consequence during short term maintenance losses in performance have not to be feared as a consequence of a reduced gas generation.

Residual biogas potential

At the end of the investigations at the pilot biogas plant, the residual biogas potential of the fermented slurry had been determined (compare chapter 2.4). The final dm-content was 1.43 % after a theoretical hydraulic retention time of 94 days in both fermenters. After 50 days of retention time in the Hohenheim Biogas Test at 35 °C still 0.027 m^3 CH_4 kg^{-1} odm had been generated from the fermented material (**table 2**) [9]. The daily input portion at that time was about 15.6 t of fresh matter with about 17 % odm, thus equalling a net hydraulic loading rate in the tube fermenters of 4.16 kg odm m^{-3} RV d^{-1}. Related to the projected total annual treatment capacity of 8000 t of nutritional waste, this resulted in an utilisation ratio of 71%. The decomposition rate of the raw material related to the total system was in average 91% (n = 22). If the pilot plant would work under full load with

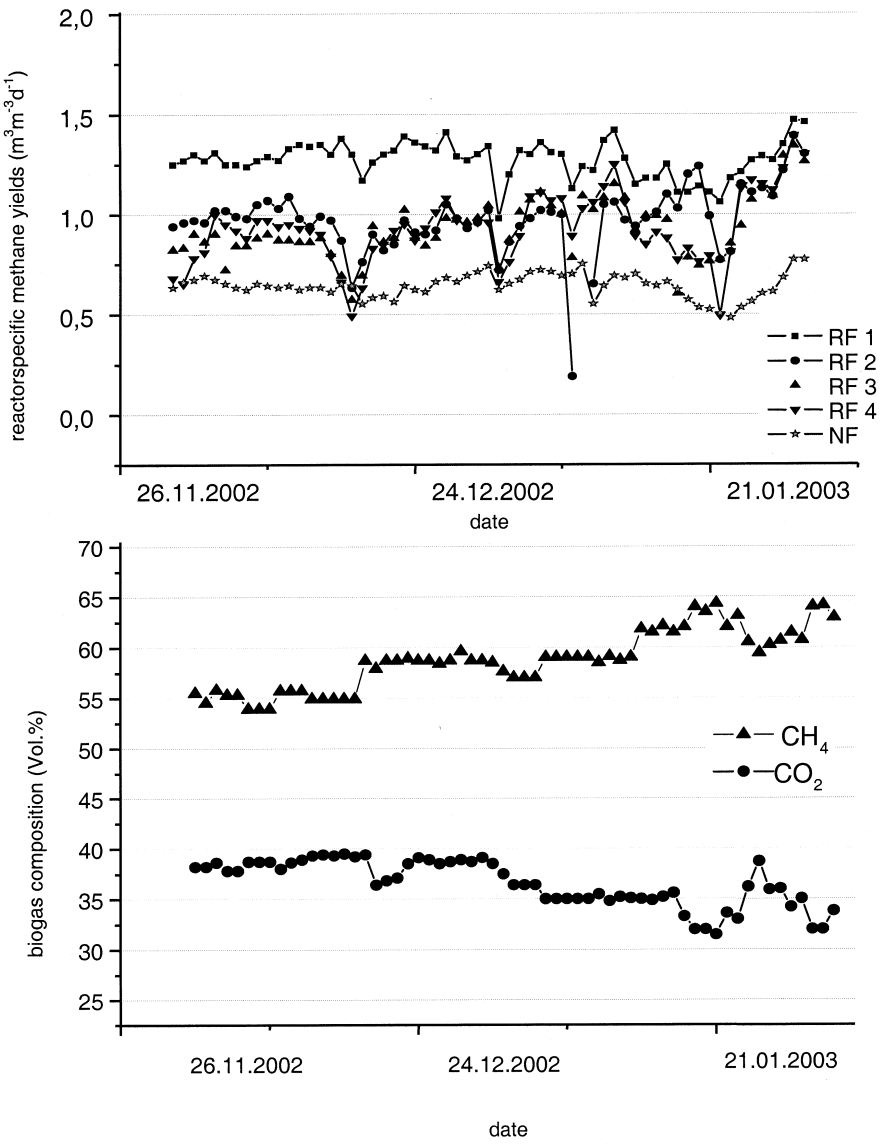

Figure 5: Monofermentation of nutritional waste - reactor specific methane yields and development of the gas quality during continuous mesophilic operation (phase II)

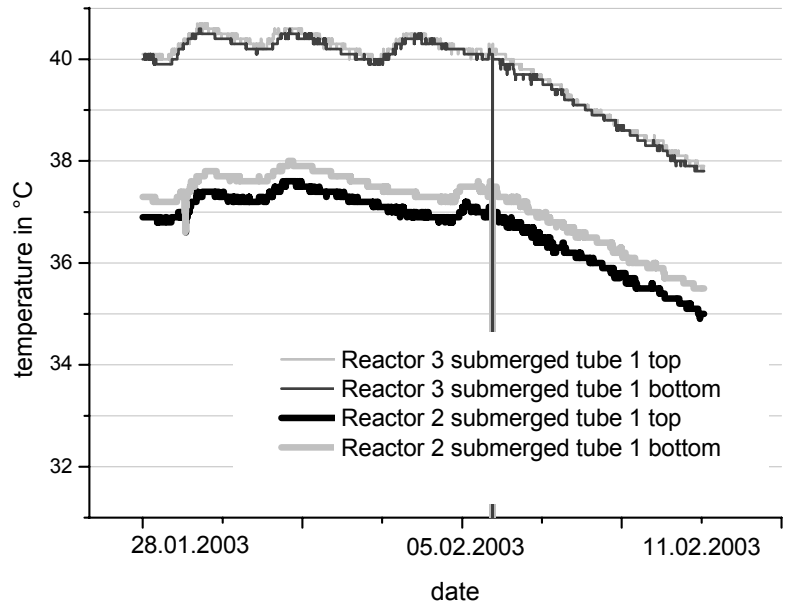

Figure 6: Monofermentation of nutritional wastes - development of fermentation temperature in two tube fermenters in continuous operation and after deactivation of the fermenter - heating system for maintenance at the end of phase II

shorter retention time it is supposed that the remaining gas potential will increase. In this case it is recommended to install a gas tight cover of the final storage tank in combination with a biogas recovery and utilisation in the existing parts of the plant (compare fig. 1)

Analysis of heavy metals in the fermented substrate

At the end of the investigations the heavy metal contents of the input substrate and of the fermented nutritional waste had been analysed by the Landesanstalt für landwirtschaftliche Chemie at Hohenheim University following the requirements of the biowaste ordinance (Bioabfallverordnung - BioAbfVO, [1]) (**table 3**). Due to the fact that heavy metals are not decomposed in biogas plants, they accumulate along the fermentation process in the dry matter of the fermentation residues [10]. This becomes especially critical, if the fermentation residues get spread on agricultural areas in the frame of utilisation cycles or if they get processed for other utilisation e.g. in peat or soil substitutes. Because it is planned for the next extension of the pilot plant to utilise and process the residual fermentation sediment, the sedimentation of the fermentation residue has been simulated in a laboratory cylinder for six weeks. Finally heavy metal analyses are available to compare the fresh nutritional waste with the final fermented substrate. Table 3 shows the increased concentration of heavy metals as a consequence of the decomposition of the organic material. Especially the quicksilver, copper-, and zinc loads of the sediment clearly exceed the thresholds of the bio - waste ordinance (BioAbfVO [1]). Compared to them the results of the fresh substrate and of the liquid supernatant are unobjectionable. The liquid is guided to the waste water processing plant for further treatment.

Outlook

The investigations at the pilot biogas plant in Donaueschingen had been terminated by the end of January 2003 after in total 192 days. Compared to the preceding laboratory investigations higher substrate specific biogas and methane yields had been obtained. This was especially due to the more than 100 days of hydraulic retention time in comparison to the 26 days in the lab experiments. The desired throughput capacity of about 22 t of fresh matter per day, equalling 8000 t annually could not yet be reached. The better proc-

Table 2: Quantification of the residual biogas - potential from monofermentation of nutritional waste after 94 days of retention time in the pilot – biogas plant at the end of the evaluation - period (TS: 2.42 %; odm: 1.43 %; 50 days of fermentation at 35 °C, according to Helffrich and Oechsner [8])

	m^3 Biogas kg^{-1} oTS (n=3)	m^3 CH_4 kg^{-1} oTS (n=3)	Vol.% CH_4 in residual-Biogas (n=6)
Ø	0.0383	0.0266	69.9

Table 3: Analysis of the heavy - metal contents of the fresh and of the fermented material after monofermentation of nutritional waste at the pilot biogas plant in Donaueschingen at the end of the investigation - period

in mg / kg dm	Preparation pit	Second fermenter stage	Liquid supernatand	Sediment	Limit value (BioAbfVO)
mercury	0.02	0.69	0.05	1.33	1
cadmium	< 0.2	0.75	< 0,2	1.41	1.5
copper	14	126	19	243	100
molybdenum	0.54	4.7	2.4	7.7	-
lead	0.51	15	2.6	29	150
chromium	10	42	38	65	100
nickel	3.3	15	20	17	50
zinc	36	318	50	573	400

ess performance with higher fermentation temperatures, having been testified in the lab experiment, could not be proved in the pilot biogas plant, because a thermophilic operation was not possible. As a further development step a second vertical fermenter and a reception and processing chain for packed food waste is built up in the moment. The residual biogas potential of the fermentation residue (output material) having been determined with the help of the Hohenheim Biogas Test was during the investigation period at around 6 m^3 CH_4 d^{-1} with a methane content of 70 Vol.%. Along with the increase of the plant load presumably also the residual biogas potential will increase. Under these circumstances a cover of the final store with biogas collection and an eventual heating could increase the daily gas yield and quality. The additional costs have to be taken into account in relation to the yield. To increase the annual throughput and to stabilise the process, an upstream hydrolytic phase and a thermophilic fermentation are recommended. The investigated process testifies the feasibility of a monofermentation of nutritional waste. It became clear that there are still possibilities to optimise the process under aspects of process engineering and fermentation biology.

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Autoren

Dipl.-Ing.sc.agr. Jan Adolph
Institut für Agrartechnik
Universität Hohenheim
Garbenstrasse 9
70599 Stuttgart
Tel: +49/(0)711/459-3930
Fax: +49/(0)711/459-2519
E-mail: jadolph@uni-hohenheim.de

Dr. Jürgen Beck
Institut für Agrartechnik
Universität Hohenheim
Garbenstrasse 9
70599 Stuttgart
Tel: +49/(0)711/459-2502
Fax: +49/(0)711/459-4307
E-mail: jafbeck@uni-hohenheim.de

Prof. Dr. Thomas Jungbluth
Institut für Agrartechnik
Universität Hohenheim
Garbenstrasse 9
70599 Stuttgart
Tel: +49/(0)711/459-2835
Fax: +49/(0)711/459-4307
E-Mail: jungblut@uni-hohenheim.de