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Detailed monitoring of two biogas plants and mechanical solid–liquid separation of fermentation residues

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ABSTRACT

The Austrian "green electricity act" (Ökostromgesetz) has led to an increase in biogas power plant size and consequently to an increased use of biomass. A biogas power plant with a generating capacity of 500 kW_{el} consumes up to 38,000 kg of biomass per day. 260 ha of cropland is required to produce this mass. The high water content of biomass necessitates a high transport volume for energy crops and fermentation residues. The transport and application of fermentation residues to farmland is the last step in this logistic chain. The use of fermentation residues as fertilizer closes the nutrient cycle and is a central element in the efficient use of biomass for power production. Treatment of fermentation residues by separation into liquid and solid phases may be a solution to the transport problem.

This paper presents detailed results from the monitoring of two biogas plants and from the analysis of the separation of fermentation residues. Furthermore, two different separator technologies for the separation of fermentation residues of biogas plants were analyzed.

The examined biogas plants correspond to the current technological state of the art and have designs developed specifically for the utilization of energy crops. The hydraulic retention time ranged between 45.0 and 83.7 days. The specific methane yields were 0.40–0.43 m^3 N CH_4 per kg VS. The volume loads ranged between 3.69 and 4.00 kg VS/m^3. The degree of degradation was between 77.3% and 82.14%.

The screw extractor separator was better suited for biogas slurry separation than the rotary screen separator. The screw extractor separator exhibited a high throughput and good separation efficiency. The efficiency of slurry separation depended on the dry matter content of the fermentation residue. The higher the dry matter content, the higher the proportion of solid phase after separation. In this project, we found that the fermentation residues could be divided into 79.2% fluid phase with a dry matter content of 4.5% and 20.8% solid phase with a dry matter content of 19.3%. Dry matter, volatile solids and carbon, raw ash and phosphate – in relation to the mass – accumulated strongly in the solid phase. Nitrogen and ammonia nitrogen were slightly enriched in the solid phase. Only the potassium content decreased slightly in the solid phase.

1. Introduction

The intensified development of biogas plants in Austria has brought with it an increased utilization of energy crops, technological changes, and a tendency towards higher electrical generating capacities. For biogas plants beginning operation between 2003 and 2005, the average generating capacity is approx. 320 kW_{el} (Hopfner-Sixt et al., 2007).

The procurement of feedstock for fermentation lies at the beginning of the logistics chain, and is therefore the first operation point in the flow of materials through a biogas plant. Carefully planned energy crop cultivation and rotation, as well as an optimized transportation system, can enable more efficient procurement of feedstock. The economic efficiency of agricultural feedstock supply can also be improved by means of suitable storage, as well as cost and energy-efficient delivery of feedstock to biogas plants. At the end of the logistics chain lays the distribution logistics, which includes the transportation of fermentation residues and their application to croplands.

The operation of large biogas plants consumes a considerable amount of energy, which poses significant logistical challenges to their operators. A biogas plant with a generating capacity of 500 kW_{el} requires a daily substrate throughput of up to 38,000 kg FM (Karpenstein-Machan, 2005). The area of cultivated land necessary to produce this feedstock is approx. 230 ha (Walla and Schneeberger, 2008), resulting in a material transportation radius up to 20 km, which creates enormous logistical demands for the efficient cultivation of large areas of cropland.

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The feedstock used for fermentation generally have a high water content, necessitating the transport of a sizeable mass (per kWh generated) of input feedstock to the biogas plant, appropriate storage facilities there, and eventual removal in the form of fermentation residue. These high throughput requirements put significant pressure on the logistic chain to operate efficiently. Storage capacities suitable for these large quantities must be created, which results in increased capital outlays. Operators of large biogas plants also face the problem of optimally supplying the resulting nutrients for utilization in further energy crop cultivation. The short time frame required for optimal deployment of fermentation residue as fertilizer, the application limit for nitrogenous fertilizer of 210 kg nitrogen per hectare (Commission of the European Communities, 1991), and the yearly prohibition on the use of commercial fertilizers e.g., in Austria from 15 October to 15 February on areas of arable land (15 November to 15 February on permanent grassland) (BMLFUW, 2004, 2008) are all limiting factors on the size of a biogas plant.

NH_3 emission mainly happens after field application of liquid manure and fermentation residues (Amon et al., 2006). After field applications, over 70% of nitrogen can be lost (Pfundtner, 2001). In addition to timing the application and to low trajectory application, reduction of dry matter content is an effective way to reduce NH_3 emissions after liquid manure application. In comparison to untreated liquid manure, fermentation residues are characterized by a much lower content of dry matter. A high risk for increased ammonia losses can be expected as a result of the high pH-value (around 8.0 units) in fermentation residues, which influences the NH_3 volatilisation (Pötsch et al., 2004). Due to the reduction of the dry matter content in the liquid phase by separation, the fertilizer will infiltrate more quickly into the soil than untreated fermentation residues, and the ammonia losses can be reduced (Amon et al., 2006).

The use of fermentation residues as fertilizer for the cultivation of further feedstock closes the material and energy cycles for biogas production, and represents a central element of the energy production chain. In addition to the specific nutritional requirements of various cultivated plants, and the regulatory fertilization guidelines, the optimal choice of transportation and distribution systems also plays a vital role. Treatment of fermentation residue by phase separation has positive effects on the distribution logistics. The separation of fermentation residue helps to put the residue into a form that is easily transported, stored, and handled so that it can be used for nutrient export at a competitive price (Dosch, 1996). Transport costs can be reduced when fermentation residues are separated into a solid phase, with a high proportion of nutrient-rich volatile solids, and a liquid phase. Concentration of nutrients in the solid phase can lead to a reduction in the amount of residue transported over high distances, in addition to the benefit of this concentration to agricultural yields (Møller et al., 2000).

Various work (Hepherd and Douglas, 1973; Poelma, 1985; Mukhtar et al., 1999; Møller et al., 2000,2002; Ford and Fleming, 2002; Wright and Graf, 2003; Ruiz et al., 2006; Kaparaju and Rintala, 2008) has shown that the treatment of liquid manure from livestock using various separator designs, when tested in commercial applications and optimized for specific parameters (size of company, market price of organic solids), can be an economically feasible operation. Study of the various separation techniques shows that the type of organic waste substantially affects the characteristic technical and ecological benefits of the separation. Several separator designs have been applied to the separation of liquid manure. Investigations of the specific benefits of separating the residue of biogas plants are still pending. Since the physicochemical structure of fermented biomass differs in principle from the structure of unfermented liquid manure, the presently available information cannot be directly transferred to assess the technical, ecological and economic benefits of separation technologies for new biogas production technologies. Specific investigations are required.

In current agricultural practice, separation techniques for liquid manure have been established using a combination of filter and press pre-treatments. Rotary screen and screw extractor separators are predominantly used, as well as decantation centrifuges, which play a secondary role due to cost considerations (Dosch, 1996).

This paper presents detailed results from the monitoring of two biogas plants and from the analysis of the separation of fermentation residues. The 7-week experimental period and accompanying sample analyses aimed at giving a precise description of process parameters for the two biogas plants. Determination of characteristic values for the volume load, degree of degradation, retention time and specific methane yield is crucial for understanding the efficiency and productivity of a biogas plant. Furthermore, the two different separators (screw extractor and rotary screen separator) for the separation of fermentation residues of biogas plants were analyzed. Throughput performance, efficiency of separation of organic matter, nutrients, and plant structural components, and energy consumption during the separation were analyzed. The results illustrate the practicality of the two separators, and compositions of the solid and liquid phases from separate residues.

2. Materials and methods

2.1. Basis of the biogas systems

The examined biogas plants correspond to the current technological state of the art and have designs developed specifically for the utilization of energy crops. The both biogas plants are comparable with other plants in Germany and Austria as regards the technical standards (Weiland, 2006; Lindorfer et al., 2007; Hopfner-Sixt and Amon, 2007).

Biogas plant 1 (operating since 2005) incorporates a "ring in ring" design and carries a connected electrical load of 500 kW. "Ring in ring" plants work in two stages, with in this case an initial digester (2000 m^3) and a secondary digester (2300 m^3) downstream. Both stages act as fully mixed vertical digesters. The total utilizable volume of these digesters therefore amounts to 4300 m^3. Fresh feedstock is placed into the initial digester and after a controlled retention time, is delivered into the secondary digester by displacement. This so-called "continuous flow" procedure enables the simultaneous occurrence of the four stages of the anaerobic decomposition in both the initial and the secondary digester.

Mixing in the circular initial digester was accomplished via three long-axis mixers with a daily operation period of 3.3 h, and in the secondary digester with two paddle mixers operating for 1.4 h daily. The outer initial ring of the digester was actively heated, which concomitantly heated the inner secondary digester in order to increase the biological activity of methanogenic bacteria.

Biogas plant 2 (operating since 2006) utilizes a single-step design with a rectangular (27 m × 15 m × 6 m), fully mixed horizontal digester. The usable volume of the digester is 2000 m^3, with a connected electrical load of 500 kW. The input feedstock is inserted in the front of the digester and evacuated on the opposite side. Mixing is accomplished via two horizontal stored paddle mixers, which stir the entire digester volume for 9 h daily. The two digester designs are shown in Fig. 1.

Both examined biogas plants utilize direct feeding systems according to feedstock weight. Automatic feeding takes place in small batches several times daily. Screw extractor separators are also installed at both biogas plants. These were utilized to test residue separation efficiency in the first 7-week experimental period of the experiments. These separators have a 1.0 mm perforated screen. The screw extractors are then exchanged for rotary screen separators for a comparable period.

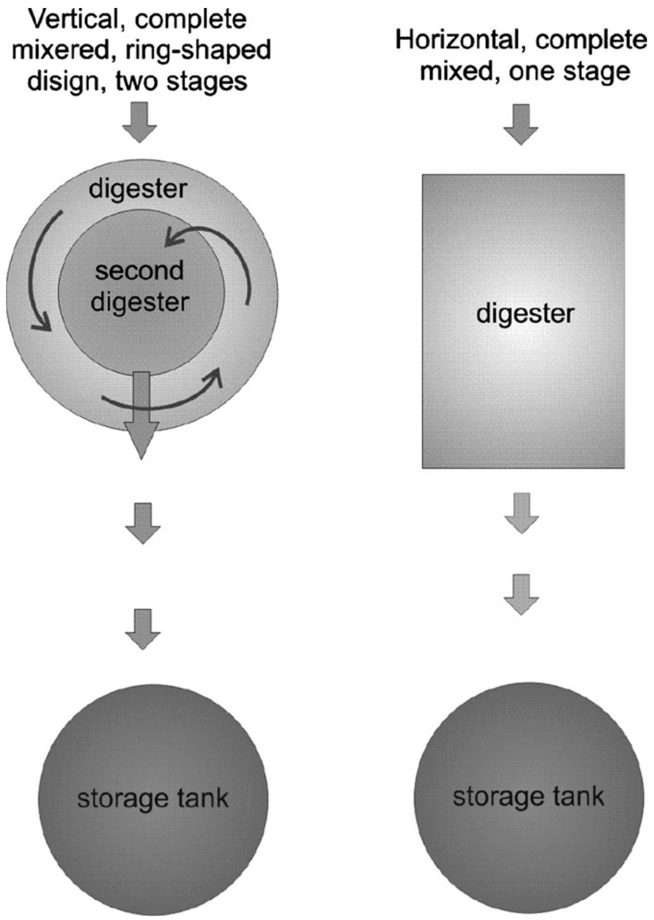

Fig. 1. Schematic representation of the digester systems of the examined biogas facilities.

In Biogas plant 2, the separator was fed from the secondary digester through a 2 m^3 large collection hopper. In Biogas plant 2 the separator was fed directly from the digester by a rotary pump.

The electrical operating loads of the two separators were determined directly with a clamp-on ammeter at the biogas plants. Determination of the degree of separation took place via collection and individual weighing of the liquid and solid phases. The separations required 1 h, and were repeated three times during each experimental period.

2.2. Analysis

Intensive measurements of material and energy flows were performed on the screw extractor and rotary screen separators at both plants over a period of 7 weeks. Samples of the digestion substrate were taken from the input stream and both output streams (solid and liquid phases). Nutrient analysis of samples from the entire process chain revealed the mass distribution and enrichment of fertilizer-relevant nutrients in the liquid and solid phases. Sampling of the input and fermenting substrates was conducted according to the sampling plan shown in Table 1.

In each case, approx. 1 L samples of liquid feedstock and 1–2 kg samples of solid feedstock (silage) were taken. For fermenting substrates at each process stage, and for the output streams, samples of approx. 1 L substrate were taken. Nutrient analyses were performed on the different feedstock, fermenting substrate and fermentation residue samples as detailed in Table 2.

Determination of dry weights took place via different weighing after samples were dried at 105 °C until their weight remained constant. The organic volatile solids (VS) content of the samples was determined by incineration in a box furnace at 550 °C. The organic nitrogen (N_{org}) and carbon (C_{org}) contents of fermenting substrates were determined with an elemental analyzer. Ammonium nitrogen was determined by means of Büchi® steam distillation following titration with 0.01 M H_2SO_4·pH-values were measured with a glass electrode. These analyses were performed according to the VDLUFA (2004) standard procedures.

Table 1
Sampling plan for chemical analysis of substrates for separator testing during the experimental period (EP) (experimental period: 7 weeks).

	Biogas plant 1	Biogas plant 2
Feedstock	4×	4×
Digester	4×	4×
Secondary digester	4×	–
Separator inflow	8×	8×
Liquid phase	8×	8×
Solid phase	8×	8×

In addition to the substrate sample analyses, daily recording of the significant process parameters represented crucial data for the evaluation of the results. The following data were recorded daily from both examined biogas facilities:

- Feedstock input to the main digester (feedstock type and amount in kg)
- Fermentation output (amounts of separator inflow, solid and liquid phase in kg)
- Temperature (in digester, secondary digester)
- Gas production and gas composition (CH_4 and CO_2).

The CH_4 and CO_2 content in the biogas were measured with the fix installed gas analyser “AVITE GA13 (basis system series 03).

2.3. Data analysis

Based on data recordings from the two biogas plants and the results of laboratory analysis of substrate samples, the following process parameters were computed:

- Hydraulic retention time
- Degree of degradation of organic substances
- Volume load
- Specific methane yield

The hydraulic retention time indicates the average period of time that substrates spend in the individual digesters. The hydraulic retention time was determined by the relationship between total digester volume and the volume of fresh substrate introduced daily, and is given in days. The retention time is controlled to insure that no more bacteria are lost to the secondary digester than the initial digester can regenerate. The regenerating concentration of bacteria depends on the digester volume, on the existing and supplied concentration of bacteria, and on their growth parameters. Since the generation time for methanogenic microorganisms is several

Table 2
Analysis plan for samples.

Sample taken from	Monitoring
Feedstock	DM content, VS content, pH value, Weender analysis
Digester, secondary digester	DM content, VS content, pH value, Kjedahl-N, NH_4-N, organic acids; N_{org}, C_{org}, total energy content, sugar content, starch content
Separator inflow, liquid and solid phases	DM content, VS content, pH value, Kjedahl-N, NH_4-N, organic acids, P and K content

days, short retention times fall below their generation time, leading to loss of microorganisms and a decreasing degree of degradation (Grepmeier, 2002).

The degree of degradation indicates which percentage of organic volatile solids is broken down during the retention time (Schulz and Eder, 2006). The decomposition achieved in the digester depends upon the active biomass. The more anaerobic microorganisms are present, the faster decomposition occurs. The rate of fermentation can be only be increased by increasing the number of microorganisms present. The specific decomposition rate also depends on the processing environment (temperature, pH value) and on feedstock composition. The decomposition rate varies for different substrate components. Proteins, sugars and fats are broken down more rapidly compared to structural components such as structural carbohydrates, for example cellulose and hemicellulose. Water-soluble compounds are typically broken down more quickly than insoluble compounds, since the acid and methanogenic bacteria can only contact dissolved substances.

The volume load represents another characteristic property of fermentation, denoting the quantity of substrates supplied daily per unit volume of the digester. The volume load is determined by the substrate concentration and the retention time. The specific methane yield derives primarily from the type and composition of feedstock, as well as processing conditions in the digester.

Determination of these characteristic values was vital for the interpretation of the analysis of the output streams, and made possible an overview of entire flow of material through working biogas plants.

The separation efficiency was calculated as a proportion of the separator inflow to the total mass recovery of solids or nutrients in the solid fraction (Møller et al., 2000). The computations for mass flow are based on laboratory analysis of the dry matter content of the fermenting residue in the solid and liquid phases of the outflow. For a system with two unknown quantities, relative proportions between 0 and 1 result, where the sum of these two fractions is equal to 1 (Reulein et al., 2007).

$$DM_{FR} = xDM_S + yDM_L$$

Where: DM = dry matter; FR = fermentation residue; s = Solid phase; L = liquid phase; x = fraction solid phase; y = fraction liquid phase

This calculation was made using the experimentally determined dry weights for each phase. The separation efficiency was calculated as a proportion of the separator inflow to the total mass recovery of solids or nutrients in the solid fraction.

Calculations and results analysis were performed using Excel and the statistics package SPSS 15. The differences in chemical composition between fermentation residue and solid phase and between fermentation residue and liquid phase were tested by the Paired-Samples *t*-test. The level of significance was set at $P < 0.05$.

3. Results and discussion

3.1. Biogas plant and feedstock data

Various feedstocks were used in the examined biogas plants, with an emphasis on cellulose-rich energy crops such as maize silage, sunflower silage, cereal-WPS, and grass silage in combination with liquid manure. In Table 3, the average daily feedstock introduced into the examined plants is given in tons of fresh mass and dry matter. It can be seen that the two biogas plants exhibited very different feedstock quantities despite producing the same electrical output. This difference resulted from the different dry matter contents of the silages (Biogas plant 2 utilized higher DM content silage), and also from the fact that due to a leaky gas tank Biogas plant 1 used more gas than would actually be necessary to operate the CHP. Under normal running conditions (without the gas leak) Biogas plant 1 needed approx. 8700 kg DM per day at full capacity. The daily feedstock input (in kg dry matter) was similar to results from research by Wiese and Kujawksi (2008), Resch et al. (2008) and Lindorfer et al. (2007).

3.2. Process parameters

The 7-week experimental period and accompanying sample analyses made possible a precise determination of process parameters for the two biogas plants. Determination of characteristic values for the volume load, degree of decomposition, retention time and specific methane yield are crucial for understanding the efficiency and productivity of a biogas plant. In Table 4, process parameters for the two examined biogas plants are compared, and an in-depth examination of each follows.

Biogas plant 1 reached 97% of capacity over the entire during the experimental period. Retention times for the two-stage digester setup were 69 days during the first experimental period and 83.7 days during the second experimental period. The shorter retention time during experimental period 1 was due to the leaky gas tank. Biogas plant 2 reached 100% capacity during the experimental period. The hydraulic retention time for this period fluctuated between 40 and 60 days, remaining barely above the minimum retention time of 30 to 40 days identified by Öchsner and Helffrich (2005). The maximum value of 60 days retention time for Biogas plant 2 resulted from a defect in the feeding system. The biogas plant achieved an average hydraulic retention time of 45 days, exactly the value for energy crops determined by Schulz and Eder (2006).

Specific methane yields were very good, with Biogas plant 1 achieving 0.43 m^3 N CH_4 per kg VS during the experimental period 2, and plant 2 achieving 0.40 m^3 N CH_4 per kg VS during experimental period 1. The high specific methane yields resulted from the simultaneous fermentation of manure together with energy crops. Investigations of 41 biogas plants in Austria by Hopfner-Sixt and Amon (2007) found that methane yields from co-fermentation of manure and energy crops averaged 0.45 m^3 N CH_4 per kg VS. Fermentation of energy crops alone gave average specific methane yields of 0.33 m^3 N CH_4 per kg VS.

The value of the volume load is specific for the mode of operation (mesophilic, thermophilic) as well as dependent on the digester volume. For trouble-free operation of a biogas plant, volume loads should be under 5 kg VS/m^3 and day (Schulz and Eder, 2006). Deublein and Steinhauser (2008) found volume loads in biogas plants lower than 4 kg VS/m^3. Öchsner and Helffrich (2005) also point out that the volume load should not be more than 4–5 kg VS/m^3 and day. The volume load in Biogas plant 1 amounted to 4.057 kg VS/m^3 and day in experimental period 1 and 3.69 kg VS/m^3 and day in experimental period 2. Biogas plant 2 had an average volume load of 3.89 kg VS/m^3 and day in both observation periods. The measured volume loads were therefore under the limit of 5 kg VS/m^3 and day.

Due to the different retention times in the two examined biogas plants, different degrees of degradation were observed. The organic volatile solids were clearly broken down better in Biogas plant 1 than in Biogas plant 2, due to the longer retention times. The lower decomposition rate of organic volatile solids had the consequence that the fermentation residue from Biogas plant 2 exhibited a higher volatile solids content than Biogas plant 1.

The degree of degradation in the first experimental period for Biogas plant 1 was only slightly higher than that of plant 2, despite a longer retention time. The cause of this marginal difference was a leaky gas tank. Due to gas loss, Biogas plant 1 had to increase the quantity of feedstock, leading to a lower degree of degrada-

Table 3
Average daily feedstock in kg DM (and kg FM) during the experimental period.

Feedstock		Biogas plant 1 [kg DM d^{-1}]	Biogas plant 2 [kg DM d^{-1}]
Animal manure	Liquid swine manure	540	–
	Liquid cattle manure	240	150
	Chicken manure	–	704
	Poultry waste	–	600
Energy crops	Grass silage	630	1430
	Maize silage	6190	5470
	Millet	20	–
	Sunflower silage	908	536
	Cereal-WPS	655	210
Total		9200 (44,600 kg FM)	9100 (36,900 kg FM)

Table 4
Process parameters for the examined biogas facilities during the experimental periods (EP).

Process parameters		Biogas plant 1		Biogas plant 2	
		EP 1	EP 2	EP 1	EP 2
Volume load (kg VS m^{-3} digester)	Mean	4.06	3.69	3.89	3.89
	SD	0.32	0.23	0.30	0.31
Degree of degradation (%)	Mean	77.30	82.14	76.34	73.60
	SD	6.60	4.00	2.28	2.29
Retention time (d)	Mean	68.98	83.72	45.45	45.57
	SD	4.30	4.62	5.47	6.76
Specific methane yield (Nm^3 CH4 kg^{-1} VS)	Mean	0.363	0.43	0.40	0.38
	SD	0.03	0.02	0.03	0.04

tion. In the second experimental period this defect was repaired and the degree of degradation rose from an average of 77.3–82.14%. The lower degree of degradation in Biogas plant 2 can be explained by the absence of a secondary digester. When the attained degrees of degradation for plants 1 and 2 are compared with the value of up to 80% for energy crops given by (Schulz and Eder, 2006), these values fall in an acceptable range despite the relatively short retention time. Hopfner-Sixt and Amon (2007) observed for Austrian biogas plants with horizontal completely mixed digesters a degradation rate about 78.6–84.5%.

3.3. *Phase separations*

3.3.1. *Process parameters for the separators*

Two different separator types, a screw extractor separator and a rotary screen separator, were compared to each another in the two observation periods. A detailed description of both separator types was published by Ford and Fleming (2002). Substantial differences were observed between the performances of the two separators in both observation periods. The screw extractor separator had a significantly higher power consumption (3.74 kW) than the rotary screen separator, which used 2.18 kW. The throughput and degree of separation were also clearly higher with the screw extractor separator. The lower throughput and degree of separation with the rotary screen separator was due to the fact that the rotary screen separator was not yet adapted to the higher dry matter content and higher temperatures of the fermentation residue from biogas plants. Both separator types obtained similar results when tested on fresh liquid manure (Ford and Fleming, 2002). The most important process parameters of the separators are compared in Table 5.

Table 5 shows the high tendency for breakdown of the rotary screen separator, which allowed only one 7-week period of reliable measurements. The breakdowns were due to the higher temperature of the fermentation residue (approx. 40 °C), since the plastic rollers were not adjusted for these high temperatures. Additionally, the high fibre content led to constant displacement of the screen, and in the end a damaged gearbox. The results of the examination of practicality showed that the rotary screen separator is not yet applicable on commercial biogas plants. The large advantages of the screw extractor separator were in particular the dependability and the low labour expenditure needed for maintenance and operation. In Table 6 the practicality of the two separators is compared.

Table 5
Process parameters of the examined separator types.

	Screw extractor	Rotary screen
Observation period	14 weeks	7 weeks
Breakdowns	No	Yes
Running time (EP 1)	130 h	176 h
Running time (EP 2)	108 h	34 h
Connected load	3.74 kW	2.18 kW
Throughput	15,500 kg h^{-1}	10,400 kg h^{-1}
Output efficiency	ca. 4000 kg h^{-1}	ca. 2500 kg h^{-1}
Costs	17,000 €	30,000 €

Table 6
Practicality of both separator types.

Screw extractor separator	Rotary screen separator
Device adjustment: customization for operating conditions possible	Device adjustment: customization for operating conditions possible
Maintenance, care: no special maintenance or care required	Maintenance, care: regular cleaning of the screen is necessary – gearbox damage
Capability and dependability high	Capability: not appropriate for warm fermentation residues and high fibre content of energy crops Dependability: low
Labour expenditure: approx. 15 min per day	Labour expenditure: constant oversight (2 h)

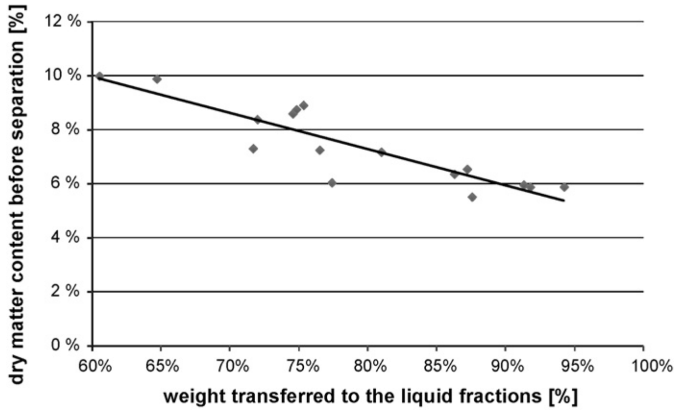

Fig. 2. Relationship between the dry matter content in the inflow and the proportion of the liquid phase (pooled data from screw extractor and rotary screen separator experiments). The following linear regression equation was derived from the data: $y = -13.428x + 18.046$ ($r^2 = .7851$).

3.3.2. Phase separation of fermentation residues with screw extractor separator

A core element of this investigation was the allocation of dry matter and nutrients between the solid and liquid fractions. Fig. 2 shows the connection between the dry matter content of the fermentation residue and the proportion of the liquid phase after separation. The higher the dry matter content in the inflow to the separator, the lower the proportion of the liquid phase. The dry matter content in the inflow therefore correlated negatively with the proportion of the liquid phase. These results confirm the findings of Møller et al. (2002), who showed the linear correlation between dry matter content in the inflow and the proportion of the liquid phase.

Fig. 3 shows the allocation of total mass as well as individual components of the fermentation residue. Over 21% of the mass of the fermentation residue could be separated into the solid phase. This separation efficiency can be compared with results from Møller et al. (2002), Mukhtar et al. (1999), Amon (1995) and Jungbluth et al. (1994).

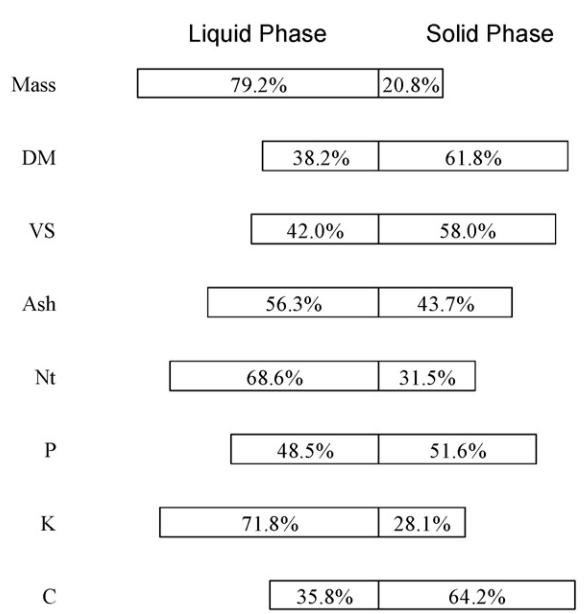

Fig. 3. Efficiency of phase separation of the fermentation residue (pooled data from screw extractor and rotary screen separator experiments).

Dry matter content was highly enriched in the solid phase. The average dry matter content in the inflow to the separator was 7.31%, and after separation the average dry matter content of the solid phase was 19.3%, compared to only 4.5% in the liquid phase. Therefore 61.8% of the dry matter found in the inflow was recovered in the solid phase. The same changes could be observed in VS content. The VS content in the inflow was 5.38%, increasing in the solid phase to 16.54%, and dropping to 3.13% in the liquid phase. 58% of the VS found in the inflow were present in the solid phase. The same partition tendencies were found for the ash and carbon components of the fermentation residue.

The partition fractions of various residue components (as average values of all results from both observation periods and biogas plants) are presented in Table 7.

The partitioning of residue components between the solid and the liquid phases is presented in detail in Table 8. The dry matter (+175%), the volatile solids (+217%) and associated carbon content (+222%), as well as raw ash (+54%) and phosphate (+139%), were statistically significant ($P \leq 0.001$) enriched in the solid phase. The nitrogen was slightly enriched in the solid phase, the potassium content decreased slightly in the solid phase. The changes in the content of nitrogen, ammonia nitrogen, and potassium were not statistically significant (Paired-Samples *t*-test: $P < 0.05$).

No significant influence of the used separator type on the above mentioned parameters was observed. This can be ascribed to the similar settings of the separators during the observation period and the same slot width of the sieve. The enrichments of dry matter, volatile solids and associated carbon content, as well as the raw ash and phosphate content in the solid fraction were found in each sample. The intensity of the changes depends more on the settings of the separator than on the separator type.

Møller et al. (2000) also found that after separation of liquid manure through a sieve with a slot width over 0.5 mm, the content of nitrogen and phosphorus was not significantly shifted between the liquid and solid phases. However, according to Møller et al. (2000) a significant enrichment of nutrients in the solid phase is expected after filtering through a slot width under 0.5 mm. These assumptions may be addressed through further investigations using separators with screens whose slot width varies over and under 0.5 mm, and a useful nutrient distribution in the two phases may potentially be achieved.

The compositions of untreated fermentation residue, of the liquid phase, and of the solid phase per ton substrate and per m^3 substrate are in summarized in Table 9. The density of the untreated fermentation residue was 946 kg/m^3, of the liquid phase was 994 kg/m^3, and of the solid phase was 780 kg/m^3. The nutrient contents of the fermentation residue, solid and liquid phases are summarized in Table 9. The content of nitrogen and potassium differed only slightly between the untreated fermentation residue and the liquid phase.

The nitrogen and potassium contents of the solid phase, however, were lower than in the untreated fermentation residues. The content of phosphate was clearly higher in the solid phase than in the untreated residues. Table 9 points out the clear rise in dry matter and volatile solids per m^3 solid phase in comparison to the inflow. 73.1 kg of dry matter and 53.8 kg volatile solids were present per ton of untreated fermentation residue. After separation the dry matter content of the solid phase rose to 193.1 kg and the in volatile solids content rose to 165.4 kg per ton. In the liquid phase, these contents fell to 45.0 kg of dry matter and 31.3 kg of volatile solids per ton.

The most conspicuous change occurred in the phosphate content. Phosphate content rose to 2.5 kg per 1000 kg in the solid phase and fell to 0.9 kg per 1000 kg in the liquid phase. The total nitrogen content was 4.6 kg per 1000 kg in the solid phase, around 0.4 kg per 1000 kg higher than in the untreated fermentation residue. In the liquid phase, the nitrogen content decreased by around 0.2 kg to

Table 7
Summary of experiments (pooled data from screw extractor and rotary screen separator experiments).

Parameter		Solid phase	Fermentation residues	Liquid phase
Allocation (%)	Mean	20.80%	–	79.20%
	SD	10%	–	10%
Dry matter (%FM)	Mean	19.31	7.31	4.50
	SD	4.01	1.51	0.95
VS (%FM)	Mean	16.54	5.38	3.13
	SD	3.75	0.87	0.62
Ash (%FM)	Mean	2.76	1.93	1.38
	SD	0.45	0.74	0.35
N_t (%FM)	Mean	0.46	0.42	0.40
	SD	0.13	0.12	0.12
P (%FM)	Mean	0.25	0.12	0.09
	SD	0.06	0.04	0.04
K (%FM)	Mean	0.34	0.36	0.35
	SD	0.07	0.08	0.11
C (%FM)	Mean	9.26	2.96	1.78
	SD	2.13	0.43	0.39

Table 8
Percent change of the composition of the solid and liquid phases after separation (compared to untreated fermentation residue). (Pooled data from screw extractor and rotary screen separator experiments).

Parameter	Solid phase		Liquid phase	
	(%)	*p*-value	(%)	*p*-value
DM	174.53	0.000[a]	−36.57	0.000[a]
VS	216.54	0.000[a]	−40.38	0.000[a]
Ash	53.68	0.001[a]	−23.95	0.001[a]
Nt	9.54	0.357	−5.93	0.087
NH_4-N	12.98	0.052	−4.87	0.118
P	139.09	0.000[a]	−27.13	0.000[a]
K	−3.66	0.126	0.10	0.059
C	222.15	0.000[a]	−39.13	0.000[a]

[a] Within a column indicates significant difference at $P < 0.01$ (Paired-Samples *t*-test).

4.0 kg per 1000 kg. The content of potassium remained in the range of 3.4–3.6 kg per 1000 kg in both phases.

When considering nutrient content in terms of volume, it was found that untreated fermentation residues contained 69.2 kg of dry matter and 51.1 kg of volatile solids per cubic meter. After phase separation, the dry matter content in the solid phase rose to 150.6 kg and the volatile solids content rose to 129.0 kg/m^3. In the liquid phase, the dry matter content dropped to 44.8 kg and 31.0 kg of organic volatile solids per m^3. The phosphate content per unit volume also changed significantly. The phosphate content in the solid phase rose to 2.0 kg/m^3 and dropped in the liquid phase to 0.9 kg. The total nitrogen content of the solid phase was 3.6 kg/m^3, around 0.4 kg lower than in the untreated fermentation residue, while in the liquid phase no change in comparison to the inflow was detected. The content of potassium dropped from 3.4 kg/m^3 in the inflow to 2.7 kg/m^3 in the solid phase. The separation of fermentation residue helps to put the residue into a form that is easily transported, stored, and handled so that it can be used for nutrient export at a competitive price.

Table 9
Nutrient content per volume and per ton of the inflow to the separator, the solid phase, and the liquid phase (pooled data from screw extractor and rotary screen separator experiments).

	Solid phase		Inflow		Liquid phase	
	kg/1000 kg	kg/m^3	kg/1000 kg	kg/m^3	kg/1000 kg	kg/m^3
DM	193.1	150.6	73.1	69.2	45.0	44.8
VS	165.4	129.0	53.8	51.1	31.3	31.0
N_t	4.6	3.6	4.2	4.0	4.0	4.0
NH_4N	3.0	2.3	2.7	2.6	2.6	2.6
P	2.5	2.0	1.2	1.1	0.9	0.9
K	3.4	2.7	3.6	3.4	3.5	3.5

The screw extractor separator's advantage is that it is more cost effective than the rotary screen separator. The annual costs of the rotary screen separator were higher by the coefficient of 2.5–2.6. The demand of storage capacity for liquid fermentation residues can be reduced by separation into a solid and a liquid fraction and leads to cost savings of 1400–6300 Euro per year. On the other hand the annual costs of the separators are 10,400–48,400 Euro (Stürmer et al., 2008).

The transport costs for fermentations residues are strongly affected by the concentration of plant nutrients and by the transport radius. Møller et al. (2000) found that the transport costs can be reduced by separating the manure into a nutrient-rich solid phase and liquid phase, when the liquid phase is transported over low distances to the arable lands and the solid, nutrient-rich phase over high distances. High reduction of transportation costs can be archived by a strongly concentration of the nutrient in the solid phase.

In this experiment, slight changes in the concentration of nitrogen and potassium – statistically significant changes for phosphate – were found after separation of fermentation residues through a sieve with a slot width over 1.0 mm. However, according to Møller et al. (2000) a strong enrichment of nutrients in the solid phase is only expected after filtering through a slot width under 0.5 mm.

The results show, that due to the separation of fermentation residues a solid as well as a liquid fraction can be produced. The solid fraction can be used as fertilizer before seeding, whereas the liquid fraction can be optimally used as rapidly available fertilizer during the vegetation period. Additionally the liquid fertilizer will infiltrate more quickly and consequently the ammonia emissions can be reduced.

Furthermore, the separation of fermentation residues can be the first step of a treatment of fermentation residue to divide the solids and nutrients from water. The reconcentration of solids and nutrients reduces the transport volume of the liquid fraction and can therefore help to reduce transport costs.

4. Conclusion

Both investigated biogas plants digest energy crops and animal manures. The technical standard of the plants was high. Biogas plant

1 can be optimized by increasing the volume load. By increasing the volume load, more biogas and electricity can be produced. Biogas plant 2 has a digester volume of only 2000 m^3 with the same connected electrical load of 500 kW. Due to the shortened hydraulic retention time a relatively high amount of green house gas and ammonia emissions may be expected from the secondary fermentation tank. These emissions can be reduced by gastight covering the fermentation residue store and connecting it to the gas bearing system of the biogas plant.

The results show that a screw extractor separator is better suited for biogas slurry separations than a rotary screen separator. The screw extractor separator exhibited a high throughput and good separation efficiency. In addition, the expenditure of labour during operation was minimal and it is a low-maintenance machine. To achieve the same results with a rotation screen separator, the plastics press cylinder and the rotating screen must be adapted to the substrate-specific conditions existing in modern biogas plants, especially the higher temperature and dry matter content.

The efficiency of slurry separation depends on the volatile solids content of the fermentation residue. The higher the dry matter content, the higher the proportion of solid phase after separation. In this project, we found out that the fermentation residue could be divided into 79.2% liquid phase with a dry matter content of 4.5% and 20.8% solid phase with a dry matter content of 19.3%. The dry matter, volatile solids, carbon, raw ash and phosphate content – in relation to the mass – were mainly accumulated in the solid phase.

After separation of the fermentation residues through a sieve with a slot width over 1.0 mm, nitrogen, ammonia and potassium content were not significantly shifted between the liquid and solid phases. However, according to Møller et al. (2000) a significant enrichment of nutrients in the solid phase is expected after filtering through a slot width under 0.5 mm. This assumption may be addressed through further investigations using separators with screens whose slot width varies over and under 0.5 mm.

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References

Amon, B., Kryvoruchko, V., Amon, T., Zechmeister-Boltenstern, S., 2006. Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. Agric. Ecosyst. Environ. 112, 153–162.

Amon, T., 1995. Prozesssteuerung der Flüssigmistseparierung mit einem Presssschneckenseparator. Dissertation. Bayerisches Staatministerium für Ernährung, Landwirtschaft und Forsten.

BMLFUW, 2004. EU Nitratrichtlinie. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft.

BMLFUW, 2008. Verordnung des Bundesministers für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft über das Aktionsprogramm 2008 zum Schutz der Gewässer vor Verunreinigung durch Nitrat aus Landwirtschaftlichen Quellen - Aktionsprogramm 2008. CELEX Nr. 391L0676.

Commission of the European Communities, 1991. Council Directive 91/676/EEC of 12th December 1991 concerning the protection of waters against pollution caused by nitrates of agricultural origin. Official Journal of the European Communities L375.

Deublein, D., Steinhauser, A., 2008. Biogas from Waste and Renewable Resources — An Introduction. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

Dosch, P., 1996. Optimierung der Verwertung von Güllestickstoff durch Separiertechnik und kulturartspezifische Applikationstechniken. Landtechnische Berichte aus Praxis und Forschung. Dissertation. Bayerisches Staatsminiterium für Ernährung, Landwirtschaft und Forsten.

Ford, M., Fleming, R., 2002. Mechanical Solid-Liquid Separation of Livestock Manure Literature Review. Report to Ontario Pork, Ridgetown College, University of Guelph.

Grepmeier, M., 2002. Experimentelle Untersuchungen an einer zweistufigen fuzzy-geregelten anaeroben Abwasserreinigungsanlage ömit neuartigem Festbettmaterial. Dissertation. Fakultät Wissenschaftszentrum Weihenstephan für Ernährung, Landnutzung und Umwelt der Technischen Universität Münschen.

Hepherd, R., Douglas, J., 1973. Equipment and methods for the solid/liquid separation of slurries. Agric. Eng., 28.

Hopfner-Sixt, K., Amon, T., 2007. Monitoring of agricultural biogas plants - mixing technology and specific values of essential process parameters. In: 15th European Biomass Conference & Exhibition, Berlin, Germany, 7–11 May.

Hopfner-Sixt, K., Amon, T., Walla, C., Pötsch, E.M., Amon, B., Milovanovic, D., Mayr, H., Weichselbaum, W., 2007. Analyse und Optimierung neuer Biogasanlagen. Österreichische Forschungsförderungsgesellschaft (FFG).

Jungbluth, T., Beck, J., Oechsner, H., Keck, M., Siemers, V., 1994. Feststoffabtrennung aus Flüssigmist mit einem Pressschneckenseparator. Arbeitsbericht. Wien, Institut für Agrartechnik, Lehrstuhl für Verfahrenstechnik und Tierproduktion und landwirschaftliches Bauwesen.

Kaparaju, P.L.N., Rintala, J.A., 2008. Effects of solid-liquid separation on recovering residual methane and nitrogen from digested dairy cow manure. Bioresour. Technol. 99, 120–127.

Karpenstein-Machan, M., 2005. Energiepflanzenbau für Biogasanlagenbetreiber. DLG-Verlags GmbH, Frankfurt am Main.

Lindorfer, H., Pérez, L., Resch, C., Braun, R., Kirchmayr, R., 2007. The impact of increasing energy crop addition on process performance and residual methane potential in anaerobic digestion. Water Sci. Technol. 56, 55–63.

Møller, H.B., Lund, I., Sommer, S.G., 2000. Solid-liquid separation of livestock slurry: Efficiency and cost. Bioresour. Technol. 74, 223–229.

Møller, H.B., Sommer, S.G., Ahring, B.K., 2002. Separation efficiency and particle size distribution in relation to manure type ansd storage conditions. Bioresour. Technol. 85, 189–196.

Mukhtar, S., Sweeten, J.M., Auvermann, B.W., 1999. Solid–Liquid Separation of Animal Manure and Wastewater. Texas Agricultural Extension Service The Texas A&M University System.

Öchsner, H., Helffrich, D., 2005. Technische Anforderungen an landwirschaftliche Biogsanlagen bei der Vergärung Nachwachsender Rohstoffe, VDI-Richtlinnien 2005, VDI-Berichte 1872.

Pfundtner, E., 2001. Der Sachgerechte Einsatz von Biogasgülle und Gärrückständen im Acker- und Grünland. Fachbeirat für Bodenfruchtbarkeit und Bodenschutz. Wien, Bundesamt und Forschungszentrum für Landwirtschaft.

Poelma, H., 1985. In: Imag (Ed.), Mechanische Dunnemestscheiders. Mestscheiding Gebouwen Instituut voor Mechanisatie, pp. 26–41.

Pötsch, E.M., Pfundtner, E., Much, P., 2004. Nutrient Content and hygienic properties of fermentation residues from agricultural biogas plants. Land Use Syst. Grassland Dominated Regions 9, 1055–1057.

Resch, C., Braun, R., Kirchmayr, R., 2008. The Influence of energy crop substrates on the mass-flow analysis and the residual methane potential at a rural anaerobic digestion plant. Water Sci. Technol. 57, 73–81.

Reulein, J., Wachendorf, M., Scheffer, K., 2007. Effizienzsteigerung in der Bioenergieerzeugung durch Abpressen der Biomasse. Bio- und Sekundärrohstoffverwertung. 19.Kasseler Abfallforumund Bioenergieforummit begleitender Kongressmesse. Kassel, Universität Witzenhausen-Institut für Abfall, Umwelt und Energie.

Ruiz, E., Cara, C., Ballesteros, M., Manzanares, P., Ballesteros, I., Castro, E., 2006. Ethanol production from pretreated olive tree wood and sunflower stalks by an SSF process. Appl. Biochem. Biotechnol. 129–132, 631–643.

Schulz, H., Eder, B., 2006. Biogas-Praxis, Grundlagen, Planung. Anlagenbau, Beispiele Wirtschaftlichkeit, Staufen bei Freiburg.

Stürmer, B., Eder, M., Hopfner-Sixt, K., Bauer, A., Handler, F., Amon, T., Ritzmann, A., 2008. Optimierung der Beschaffungs- und Distributionslogistik für Biogasanlagen. Mitteleuropäische Biomassekonferenz 2008. Graz, Mitteleuropäische Biomassekonferenz 2008. Österreichischer Biomasseverband, Mitteleuropäische Biomassekonferenz 2008.

VDLUFA, 2004. VDLUFA - Methodenbuch Band II.1. Die Untersuchung von Düngemitteln. Darmstadt, VDLUFA-Verlag.

Walla, C., Schneeberger, W., 2008. The optimal size for biogas plants. Biomass Bioeng. 32, 551–557.

Weiland, P., 2006. Biomass digestion in agriculture: a successful pathway for the energy production and waste treatment in Germany. Eng. Live Sci. 6, 302–309.

Wiese, J., Kujawksi, O., 2008. Operational results of an agricultural biogas plant equipped with modern instrumentation and automation. Water Sci. Technol. 57, 803–808.

Wright, P., Graf, K., 2003. Anaerobic Digester at Dairy Development International: Case Study. Manure Management Program Cornell University.