Ultrasonic disintegration of biosolids – benefits, consequences and new strategies

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Abstract

Huge amounts of waste biosolids are produced from biological processes as waste water treatment, agriculture and food production. The volatile compounds could be utilised as a source for renewable energy in anaerobic processes. However, the anaerobic degradation is slow so that large fermenters are necessary. By ultrasonic disintegration the rate limiting hydrolysis of volatile solids is substituted resulting in a considerable intensification of the anaerobic biogas process. In case of sewage sludge the anaerobic digestion time could be 4-times reduced without losses in biogas yield. Even at reduced fermentation times the anaerobic degradation was enhanced. Therefore ultrasound disintegration has a strong potential to reduce fermentation times and hence to minimise the volume of new anaerobic digesters. This paper reviews new strategies and resulting benefits for biosolids treatment which are opened up by the application of new ultrasound technology.

Introduction

In biological conversion processes large quantities of biosolids are produced. Main biosolids sources originate from biological waste water treatment and agriculture. In Germany, the municipal waste water treatment is resulting in 60 Mio. m³ sewage sludge each year. In agriculture about 190 Mio. m³ of liquid manure are produced. Further amounts of biosolids are available from forestry and industrial food production. The biosolids predominantly consist of particulate microbial or plant cell material.

Compared to forest and agricultural biosolids, waste water biosolids are mainly composed of highly putrescible volatiles. It is necessary to treat the raw sewage sludge biologically assuring a subsequent environmentally safe utilisation and disposal. The standard stabilisation process for waste water solids is the anaerobic fermentation. More than 80% of sewage sludge amounts in Germany are treated anaerobically (Esch & Krüger, 1999). In this process a net reduction of the biosolids mass and volume is realised. A portion of the volatile solids is microbiologically converted into methane and carbon dioxide. This biogas is used energetically. The

TU Hamburg-Harburg Reports on Sanitary Engineering 35, 2002
Neis U. (ed): Ultrasound in Environmental Engineering II
ISSN 0724-0783; ISBN 3-930400-47-2

final product are stable, innocuous biosolids, that can be used as a fertiliser (Malina & Pohland, 1999).

Compared to other fermentation methods the principal advantages of anaerobic treatment are:

- Production of a stabilised biosolids residue that enables further treatment and environmentally safe utilisation.
- Production of biogas, mainly consisting of energy-rich methane. About 1,000 litres of biogas are produced per kg degraded volatile solids (Table 1).
- Odour and pathogens associated with the raw biosolids are markedly reduced.

The principal disadvantage of the anaerobic biosolids fermentation is the long hydraulic retention time, required for the conversion of particulate organics into biogas. Retention times, in excess of 20 days, are responsible for high fermenter volumes and thus high capital costs. Large, covered tanks along with pumps for feeding and circulating the biosolids, heat exchangers and compressors for gas mixing are required.
Despite the long retention times during anaerobic digestion, no complete degradation of the biosolids is achieved. Because of the complex structures, the biosolids are only partially biodegradable. Structure and organisation appear to be important in controlling rate and degree of degradation (Stuckey & McCarty, 1984). In case of sewage sludge fermentation reduction of volatile solids ranges between 20 and 60%.

Table 1: Production of biogas and its composition during anaerobic degradation (Malina & Pohland, 1999).

substrate	biogas production [L/kg]	methane composition [%]
carbohydrates	790	50
fats	1250	68
proteins	700	71

Compared to sewage sludge treatment, anaerobic processes for agricultural or forest biosolids are new techniques (Gomez & Tentscher, 2001). In 2001 about 1,500 biogas fermenters were operated in rural areas of Germany. The German Environmental Agency estimates a potential of 200,000 new anaerobic fermenters for energetic utilisation of agricultural biosolids. The resulting energy from methane biogas production could substitute about 20 to 30% of natural gas consumption or 5% of total energy demand, respectively. Therefore, biosolids are considered as a main source for renewable energy to reduce the CO_2-emissions. Recently, since the year 2000, production of electrical power from biosolids has been financially promoted by the so-called renewable energy law ("Erneuerbare-Energie-Gesetz", EEG).

The objective of this study was to investigate biosolids disintegration on the following anaerobic digestion. The biodegradability of biosolids can be improved by solubilisation. Positive effects were shown for thermal pre-treatment (Haug *et al*., 1983; Pinnekamp, 1989), ozonation (Yasui & Shibata, 1994; Scheminski *et al*., 1999), chemical hydrolysis by acidification (Gaudy *et al*., 1971; Woodard & Wukasch, 1994) or alkaline addition (Mukherjee & Levine, 1992), and mechanical disintegration (Müller, 1999). In general, these techniques have not been successful as yet technically and economically.
The concept of this study is based on the idea that due to biosolids hydrolysis obtained by ultrasound treatment, the anaerobic digestion is accelerated. The experiments are focussed on the reduction of residence time required in the anaerobic fermenters and on the maximisation of biogas yield. Consequences for the operation of biosolids fermentation processes and the design of new digesters are drawn. Options for co-utilisation of agricultural and waste water biosolids in existing municipal fermenters are set up. Three exemplary cases of application are evaluated economically.

Anaerobic fermentation of sonicated biosolids

Our experiments were done at the municipal waste water treatment plant Bad Bramstedt, Germany. This treatment plant serves about 85,000 population equivalents. We used 200-liter pilot-scale fermenters that were operated in a semi-continuous mode with five parallel tank fermenters at 37°C (Neis *et al*., 2000). Hydraulic retention times (HRT) was varied between 4 and 22 days. Three different types of sludges were sonicated: waste activated sludge (WAS), raw sludge and digested sludge. The sonication of sewage sludge was done immediately before feeding to the pilot fermenters. The degree of sludge cell disintegration DD_{COD} was assessed by determining the chemical oxygen demand (COD) in the supernatant of centrifuged samples (Neis *et al*., 2001). The production of biogas was recorded and its methane content analysed by gas chromatography. The concentration of volatile solids (VS) was determined in inflow and outflow of each fermenter and related mass balances were established.

Fermentation of waste activated sludge

First we investigated the effect of disintegration of WAS on the anaerobic degradation at constant HRT of 8 days. At short sonication times no increase in soluble COD was recorded. There was no cell lysis but we observed an improved microbial activity because the sludge flocs were dispersed to smaller units and single bacteria. More about this effect is described in Tiehm *et al*., 2001. When the sonication time was raised cell lysis occurred and raising degrees of disintegration DD_{COD} were observed.

The disintegration resulted in a better anaerobic degradation of the biosolids as presented in Figure 1. Table 2 summarises the results and shows how the increase in VS degradation follows the degree of preliminary cell disintegration: the anaerobic digestion is intensified with increasing degrees of disintegration. The VS reduction

was highest (33.7%) in the digester which was fed with sludge of the highest degree of disintegration. The VS reduction of the control fermenter was 21.5%.
In the fermenters fed with disintegrated material the biogas production increased significantly by more than 50%. The percentage of methane in the biogas also increased with increasing degree of disintegration. The specific biogas production, i.e. the biogas production related to the mass of VS degraded, was slightly lower for the disintegrated biosolids as compared to the control. The reason for that is not clear. Following sonication more released organic cell material is available. The molecular structure of these large molecules is not known in detail and their biological degradation might be slower as compared to the original soluble substrate.

Table 2: Impact of ultrasonic disintegration of WAS on subsequent anaerobic digestion. The applied ultrasonic frequency was 41 kHz, HRT of the fermenters was 8 days.

	control	sonicated		
A) Disintegration				
degree of disintegration DD_{COD} [%]	0.0	4.7	13.1	23.7
B) Fermentation				
volatile solids degraded [%]	21.5	27.3	31.4	33.7
biogas/VS degraded [L/kg]	483	441	433	436
CH_4 [%]	62.8	65.9	67.3	68.9
CH_4/VS degraded [L/kg]	303	291	291	300

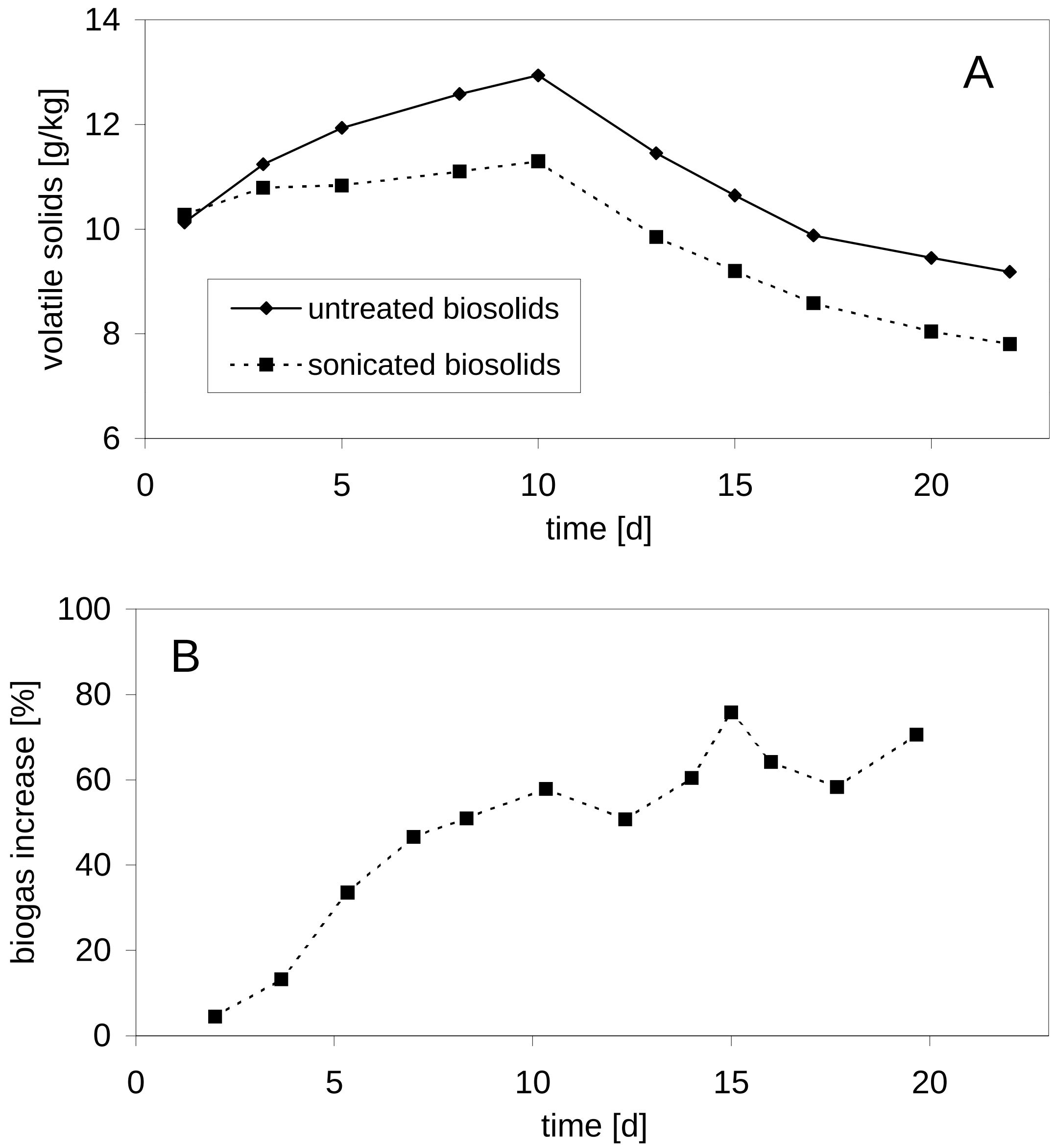


Figure 1: (A) Volatile solids concentration in the fermenters operated with untreated and disintegrated biosolids (DD_{COD} = 23.7%).
(B) Increase of biogas production during fermentation of disintegrated material as compared to conventional fermentation.

Anaerobic degradation in the pilot digesters operated with different hydraulic retention times was studied to evaluate the acceleration of the biosolid's degradation after ultrasonic disintegration. According to the selected hydraulic retention time (HRT), once a day certain volumes of digested biosolids were replaced by fresh sludge. As a control, two fermenters were operated with untreated sludge at HRTs of 16 and 8 days. Three fermenters were fed with disintegrated biosolids at HRTs of 16, 8 and 4 days (Nickel, 1999). Ultrasound of 31 kHz at 8 W/cm² intensity was applied for 90 seconds. This resulted in an average degree of biosolid's disintegration DD_{COD} of 20%.

The degradation rate of the sonicated biosolids of 16 days HRT increased by more than 30% (335:257) compared to the conventional digestion (Table 3). The residual concentration of VS in the digested sludge was reduced by 14%. At 8 days HRT ultrasonic disintegration enhanced the degree of anaerobic degradation by more than 40% (38.1:27.0). The highest rate was obtained at the shortest 4-day HRT. Compared to the 16-day HRT control fermenter the specific volumetric degradation rate increased by a factor of 3.93 (1011:257). The data demonstrate that the anaerobic degradation process is considerably accelerated by ultrasonic pre-treatment.

Table 3: Effect of ultrasound pre-treatment (31 kHz) and digestion time on anaerobic volatile solids degradation (VS_{deg}) of waste activated sludge and biogas production.

WAS	HRT [d]	degradation rate [g VS_{deg}/($m^3_{fermenter}$*d)]	degree of degradation [%]	biogas production rate [m³/($m^3_{fermenter}$*d)]
untreated	16	257	32.3	0.19
disintegrated	16	335	42.4	0.21
untreated	8	430	27.0	0.31
disintegrated	8	603	38.1	0.36
disintegrated	4	1011	32.0	0.52

The enhanced degradation rates resulted in a significant increase of biogas production. Compared to the control systems significant more biogas was produced in the fermenters fed with ultrasonically disintegrated biosolids. The highest biogas production rate was observed in the fermenter operated on the 4-day HRT with disintegrated biosolids due to the high trough-put rates and stable anaerobic degradation (Table 3).

Fermentation of raw an digested sludge

Similar experiments were done with other sludge types representing different kinds of biosolid matter. Raw sludge is the mixture of primary sludge and waste activated sludge. Compared to WAS the concentration of microbial cells in the raw sludge is considerably lower. The biosolids resulting from the primary clarifier on a waste water treatment plant (primary sludge) are mainly consisting of fecal and vegetable residues. Usually, municipal raw sludge is treated anaerobically at hydraulic retention times of about 20 days. The end product is digested sludge with a reduced organic content. However, the anaerobically stabilised sludge still consists of about 50% volatiles. It is difficult to degrade more because the structure of the remaining volatile solids is rather complex.

We tested the effect of raw sludge disintegration on subsequent anaerobic stabilisation. Therefore, the raw sludge was sonicated for 64 seconds at 11.5 W/cm² intensity resulting in an average degree of disintegration DD_{COD} of 12%. The digestion time of the sonicated raw sludge was reduced from conventional 22 days to 8 days (factor of 2.75 = 22/8) without negative impacts. The specific volumetric degradation rate increased from 437 to 1166 [g $VS_{deg}/(m^3*d)$] or by a factor of 2.67 (Table 4). Parallel to that the biogas production rate increased from 0.32 to 0.71 [$m^3/(m^3*d)$]. This demonstrates again that a rapid sludge digestion in the anaerobic process is achieved because the sonicated biosolids represent a much better degradable substrate.

Table 4: Effect of ultrasound pre-treatment (31 kHz) and digestion time on anaerobic volatile solids degradation (VS_{deg}) of raw sludge and biogas production.

raw sludge	HRT [d]	degradation rate [g $VS_{deg}/(m^3_{fermenter}*d)$]	degree of degradation [%]	biogas production rate [$m^3/(m^3_{fermenter}*d)$]
untreated	22	437	45.8	0.32
disintegrated	22	480	50.3	0.31
disintegrated	16	647	49.3	0.41
disintegrated	12	830	47.3	0.51
disintegrated	8	1166	44.3	0.71

Anaerobic degradation of sonicated digested sludge was investigated at HRTs between 4 and 16 days. Disintegration was done for 96 seconds at 7.1 W/cm² acoustic intensity and the average degree of disintegration DD_{COD} was 8%. Although the digested sludge had already been stabilised with a retention time of 30 days in the Bad Bramstedt full-scale fermenter, it still contained sufficient quantities of digestible organics (Table 5). By ultrasonic disintegration of digested sludge biogas production rates in a second stabilisation are in a similar range of excess sludge fermentation (see Table 3 and 5).

Table 5: Effect of ultrasound pre-treatment (31 kHz) and digestion time on anaerobic volatile solids degradation (VS_{deg}) of digested sludge and biogas production in a second stabilisation.

digested sludge	HRT [d]	degradation rate [g $VS_{deg}/(m^3_{fermenter}*d)$]	degree of degradation [%]	biogas production rate [$m^3/(m^3_{fermenter}*d)$]
untreated	16	186	18.2	0.11
disintegrated	16	226	22.4	0.12
untreated	8	245	12.0	0.15
disintegrated	8	351	17.4	0.19
disintegrated	4	548	13.6	0.28

New strategies

Our experiments revealed that low frequency ultrasonic treatment is well suited for disintegrating particulate organic material whereby the anaerobic digestion process is intensified. This was demonstrated for three different types of biomass/sewage sludge. Both indicators are well improved the fermentation rate as well as the efficiency. The volume of fermenters could be reduced considerably. This is promising option especially for a compact design of the huge numbers of new digesters which will be constructed for the anaerobic treatment of agricultural biomass.

In Germany each year about 50 Mio. m^3 of municipal sewage sludge are treated anaerobically. The fermenters are designed for an average hydraulic sludge retention time of about 20 days. The existing total digester volume for municipal sludge treatment is estimated to 2.7 Mio m^3. By sonication of sludges it is well possible to reduce the necessary digestion time from 20 to 8 days without losses in degradation efficiency. This means that 1.6 Mio. m^3 of existing fermenter volume could be used for biogas production by feeding additional biosolids. For example, in rural areas co-utilisation of waste water and agricultural biomass in municipal sewage sludge fermenters is possible. Selling the electrical power from the additional methane production results in economic benefits. Beside waste water treatment, production of renewable energy from internal and external biosolids will become the second main function of this new type of waste water treatment plant.

The German Environmental Agency estimates the potential number for new fermenters for methane production from agricultural biosolids to 200,000. Assuming an average fermenter volume of only 100 m^3 gives a total potential volume of new anaerobic digesters of 20 Mio m^3. Total investment costs of such a huge amount of new digesters will be $10 * 10^3$ Mio EURO. The design criteria for sewage sludge and agricultural fermenters are similar, hydraulic retention times of 20 days are usual. We assume that by sonication of agricultural biosolids the digester volume could be reduced by 60%. This means saving total investment costs of $6 * 10^3$ Mio EURO for the German market only. However, further work is necessary to test anaerobic degradation of different types of sonicated agricultural biomass in order to confirm the above assumption.

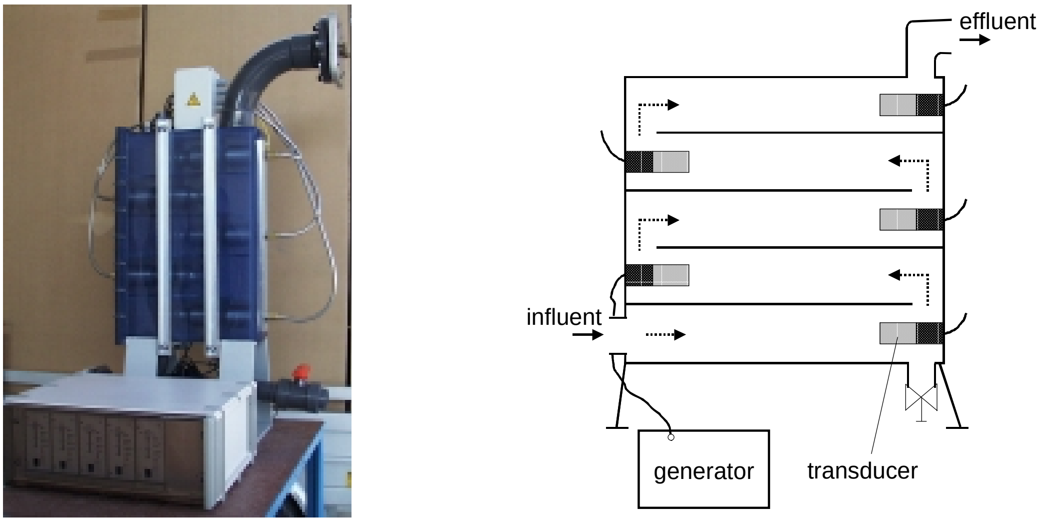
In the following scenarios the cost-benefit ratio of ultrasonic treatment is calculated. As an example a municipal waste water treatment plant (75,000 P.E.) with a daily sludge production of 120 m^3 (dry solids DS = 6 %, VS = 75%) is considered. Based on our results three applications are assessed:

A): A new anaerobic fermenter is needed due to the extension of a sewage treatment plant. Can investment costs be reduced if ultrasound is used?

B): A fermenter is existing, the anaerobic degradation has to be enhanced, the output of digested biosolid mass is to be minimised.

C): The biogas production in the existing digester should be maximised. The acceleration of the anaerobic sludge degradation allows feeding of additional organic co-substrates from agriculture or food production.

We design for the treatment of 120 m³/d sewage sludge an ultrasonic reactor of 30 kW power. A new high-power ultrasound system for biosolid's disintegration was developed by WAVES Water- and Environmental Technologies in co-operation with the Technical University of Hamburg-Harburg. An ultrasound reactor module with a volume of 25 litre is equipped with five 20 kHz sonotrodes (Figure 2). Each sonotrode is supplied by a 2 kW generator. Assuming a life-cycle of 10 years for ultrasound equipment results in annual investment costs of about 30,000 EURO for a 30 kW system. The operating costs are dominated by the electrical power consumption: the average price is 0,075 EURO/kWh$_{el}$. The annual operating costs then are 19,710 EURO.



A) Image B) Scheme

Figure 2: (A) Image and (B) Scheme of a new high-power ultrasonic reactor for biosolid´s disintegration (WAVES Water and Environmental Technologies Hamburg, Germany).

<u>Scenario A):</u> Conventionally, the new anaerobic sludge digester is designed for a volume of 2,400 m³ (20 d HRT). If sonicated the necessary digestion time could be reduced to 8 days. This is a reduction of 1.440 m³ digester volume as compared to the conventional size. Assuming a 30 years life-cycle, annual investment costs of about 60,000 EURO are saved. Consequently the annual economic yield operating the 30 kW ultrasound system is 10,000 EURO.

<u>Scenario B):</u> The sludge is treated conventionally with 16 days average digester hydraulic retention time. The stabilised sludge is dried and incinerated. Specific costs for thermal treatment amount to 500 EURO per ton dry solids. Due to ultrasonic pre-treatment the degree of anaerobic degradation is enhanced by comparatively 20%: Assuming a conventional degree of degradation of 40%, anaerobic digestion of disintegrated sludge resulted in a 48% destruction of volatile solids. This means an additional reduction of annually 158 tons dry solids in the digested sludge saving 79,000 EURO. Simultaneously, biogas production is increased: Specific methane production of 700 L/kg degraded volatile solids (see Table 1) is resulting in a surplus of 110,600 m³ methane each year. Calorific value of methane is 10 kWh/m³, electrical

power use can be done with an efficiency of 0.32. Thus, excess biogas production results in an additional electrical power of 354,000 kWh annually. In Germany, energy from renewable sources (for example biosolids) is paid by 0,10 EURO/kWh. Energetic utilisation of the additional biogas results in a benefit of 35,400 EURO. Total benefits in this example are 114,400 EURO as compared to total annual costs of about 50,000 EURO.

Scenario C): Considered is the combined treatment of sewage sludge and co-substrates in the existing municipal fermenter, designed for a HRT of 20 days. By sewage sludge sonication 60% of the digester volume could be used for biogas production from feeding co-substrates. In this example the fermentation of 180 m^3/d co-substrate (DS = 6%, VS = 80%) from food production results in a daily additional methane production of about 3,000 m^3. Selling the electrical power from utilisation of additional methane gas 350,000 EURO each year can be earned.

Conclusions

Biosolids from agriculture, food-production and waste water treatment show a great potential as a source of renewable energy to be transformed by anaerobic processes. The resulting energy from methane/biogas production could substitute about 5% of the total energy demand in Germany. It is estimated that a large number of new fermenters will be built in the next years.

By using ultrasound the design hydraulic retention time for fermenters can be reduced by about 50%, thus new digesters will we be much more compact. In existing municipal sewage treatment plants ultrasound application offers the opportunity for feeding co-substrates from agriculture and food production whereby there might arise a benefit for the operators by the production of renewable energy from internal and external biomass.

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