Enhancement of biogas production from straw and manure
An annotated bibliography

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Abstract

This bibliography gives an overview of the methods available to enhance biogas production from manure and straw. Information is given on the effects of retention time, temperature, high temperature pre-treatment, addition of trace elements, addition of surface active elements, addition of enzymes, addition of bacteria, co-digestion of manure with straw and co-digestion of manure with straw pre-treated with fungi. Methane yields of 380 l/kg volatile solids (75 % energy recovery) can be obtained with mixtures of manure and straw and long retention times (120 days). High solids digestion of cattle manure with long retention times in family-size digesters gave methane yields of 230 l/kg volatile solids (45 % energy recovery).

Key words: Biogas production; straw; manure; methane yield

1. Introduction

All-renewable energy resources are necessary to reduce dependency on fossil fuels from politically unstable regions of the world. Biomass is one such renewable energy resource, but it must not compete with food production since the clearance of forest for farmland gives a significant contribution to the increase of CO2 in the atmosphere. Therefore, organic wastes and residues are preferred.

Yadvika et al. (2004) gave a review of the enhancement of biogas production from solid substrates, but quantitative numbers of the conversion into methane are not given.

This paper is a compilation of research on the production of biogas from straw and manure. Included are data on methane yield. The purpose is to find the conditions under which the methane formed contains 60% of the energy in the substrate (300 l methane per kg volatile solids VS) and find a method that needs low investment and running costs.

2. Overview

The energy content of the animal residues (mostly manure) produced worldwide is equivalent to an average power of 50 – 150 W per person (9 -25 EJ/a). The energy content of crop residues (mostly straw) is also 50 – 150 W per person (Hoogwijk et al. 2003). Worldwide energy consumption is 2.5 kW per person (500 EJ/a). Oil production worldwide is 80 million barrels a day (1 kW per person or 200 EJ/a). Biogas from straw and manure can replace about 10 - 30 % of the world oil production. This substitution can be doubled by the use of forest residues.

Farm residues as such cannot replace fossil fuels. Such residues have to be converted into gas, liquid or electricity. Anaerobic digestion converts organic waste and residues into biogas, an energy source which can be used for cooking; the production of electricity and as transportation fuel

In Asia there are over ten million family-size biogas plants which mainly utilize cow and pig manure. The biogas produced is primarily used for cooking. There are significant health advantages in using biogas, compared to the local alternative of burning of cow manure, leaves, and wood inside the houses.

There are a few thousand centralized biogas plants in Europe that use manure with a whole range of easily digestible waste materials. Other biogas plants in Europe use sludge from waste water clean-up plants. They convert the biogas into electricity.

In Europe and in several states of the USA there are requirements to gradually introduce biomass-derived fuels in the transport sector. Approximately 5 million cars currently run on compressed natural gas. These can also run on upgraded biogas. The digestate, after the production of biogas, should be used as an organic fertilizer. This will recycle the macro elements nitrogen, potassium, phosphorus and carbon. Recycling of carbon is essential for high soil productivity and will reverse the trend of lowering of crop yields. (Hossain 2001).

3. Biodegradability

Agricultural waste materials like straw and part of the manure are lignocellulosic materials. These materials are strong, flexible and protected against decay. They consist of cellulose, hemicellulose and lignin. Lignin cannot be converted into biogas, and only part of it can be depolemerized into soluble components. Part of the cellulose and hemicellulose is covered with lignin. This shielded cellulose and hemicellulose can also not be convert into biogas. The anaerobic digestion is thus a complex process which is slow compared to chemical processes.

4. Discussion

4.1 Longer retention times

Doubling of the retention times increases the gas yield with 30 – 50 % (Table I)

Doubling of the volume of a digester will increase the investment cost with 70 %. The amount of work to load and unload the digester and to transport the digestate to the fields remains the same. The cost (including work) of extra gas formed will not be significantly higher than that of a smaller digester with a lower gas yield.

Higher yields can also be obtained by increasing only the solids retention time. This has an effect on the retention of Nitrogen and Potassium. Ann. 2004b report that 60 % of the Nitrogen and 75 % of the Potassium is in the liquid fraction after filtration. The liquid fraction can be spread on the fields or can be concentrated.

Hansen et al 1999 found that by stopping the stirring half an hour before and after feeding increased the VS fraction to 60 g/l as opposed to 45 g/l in the control. Methane production increased to 102 l/kg VS compared to 67 l/kg VS for the control.

Ong et al. 2000 obtained an increase in gas yield compared to a continuously fed and stirred reactor in a continuously fed non-stirred reactor with the outlet in the middle. It seems that some solids removal from the bottom has to take place as accumulation of inert solids will reduce the effective volume of the reactor.

Shyam 2002 demonstrated that cow manure can be digested at 18 % TS. The method increases the gas yield with 40 % using practically the same equipment as before.

4.2 Effect of temperature

The experiments do not show a strong dependency on the temperature in the range 35 – 60 °C.(Table 2) At 25 °C the yield is reduced with 20 %. Above 60 °C the yield is 15 % lower.

Commercial Danish digesters (Karakashev et al. 2005) work either at 37 °C with an average retention time of 22.5 days or at 55 °C with a retention time of 19 days. The lower temperatures consume less heating energy. This heating energy is however “free” when electricity is generated. The investment costs are somewhat lower at higher temperatures and better sanitation is achieved.

4.3 Addition of trace elements

The addition of trace elements has an effect of 10 – 70 % on the methane production (Table 3) The digestion of rice straw seems to be very sensitive to temperature and the adaptation of the microbes. The results at New Delhi (28 °C) are much lower than near Ahmedabad (35 °C).

The Spreri system (Ann. 2004, 2005, 2006) for rice straw has a high gas yield (270 – 300 l/kg VS). They operate with 25 % total solids.

In table 11 we have given the concentration of trace elements for basal medium, sewage sludge and waterhyacinth and compared them with those of methanogenic bacteria

Sewage sludge has at a loading of 10% w/w VS for Mg, Ni, Co, and Mo about the right concentrations. Concentrations for Ca, Fe, Zn, Mn and Cu are an order of magnitude too high. The concentrations of Cu and Zn are 100 % too high for the use of the digestate in agriculture (de Wolf et al. 2005). Much attention is given to reduce the heavy metals in sewage sludge. e.g. by removing the sources of the pollution. Even so reduction of heavy metals in sewage sludge will be at most 50 % in the near future (Loeffen et al. 2005). Heavy elements can be removed from the sludge ???

The leaves of plants and weeds like water hyacinth and duckweed are also a source of essential elements.

4.4 Addition of surface active elements

The addition of iron containing surface active elements glauconite (iron silicate) and iron oxide has a positive effect on the gas yield (Table 4). The culture of Hansen et al. ?? was probably mal-adapted to the pig manure.

4.5 Addition of enzymes

The cost of enzymes that break down lignocellulosic materials is rapidly coming down. Some German companies (Biopract; Gerhardt et al 2005, Bioreact ann. 2006 and Smack Biogas) advertise the application of special enzyme combinations in biogas digesters. They suggest a 30 % faster digestion or a 10 % higher biogas yield. The biogas yield with enzymes for unspecified manure was 440 l/kg total solids (about 200 l methane per kg VS).

Water cleanup secondary sludge is a source of enzymes. The secondary sludge consists mainly of bacteria and the intracellular liquid of these bacteria contains lysis enzymes (Ann. 2006b). The use of about 30 % ultrasonically treated secondary sludge enhances and accelerates the anaerobic digestion of both primary and secondary sludge (Hogan et al. 2004). The amount of ultrasonically treated sludge that can be used is limited to less than 1 % w/w due to the content of heavy metals.

5.7 Addition of bacteria

The work of Nielson et al. 2007 did not show any improvement compared to the control from 2004. His control is a system at 55 °C. In Table 7 we use as a control a test at 68/55 °C without the addition of bacteria. The controls at 55 °C show a variability of 5 % in methane yield. His conclusion was that the bacteria suddenly died or were washed out from the 68 °C reactor in the middle of the experiments.

There are many candidate bacteria with lysis properties, some of which may well adapt to the environment of high temperature cattle manure.

-Angelidiaki et al. 2000 separated the fibers from cattle manure in a full scale biogas plant. The separated fibers were treated with the hemicellulose bacterium B14 at 70 ºC for seven days. The fibers were digested at 55 ºC. The methane yield increased from 230 l/kg VS for untreated fibers to 300 l/kg VS for the treated fibers after 40 days of digestion.
-Chakrabothy et al. 2000 isolated cellulose degrading bacteria from the intestinal fluid of the silver cricket. The culture was developed anoxigenically and the optimum pH was found to be between 7 and 8.
-Syutsobo et al 2005 performed cellulosic degrading experiments with Clostridium sp. Strain JC3.
-Miah, 2005 demonstrated enhanced biogas production on sewage sludge by a culture

of the AT1 strain that is closely related to Geobacillus thermodenitrificans. They obtained a reduction of 21 % in volatile solids .

-Kovacs 2006 obtained a 50 % increase in the digestion of pig manure using a culture of Caldicellulosiruptor saccharolyticus. The baseline was not given.

-Palmerston et al. 2006 increased the methane yield from the anaerobic digestion of Jose Tall Wheatgrass from 180 l/kg VS to 230 l/kg VS. They used 25 % v/v rumen fluid and the balance waste water cleanup sludge.

A 5 % w/w TS addition of compost can be made. The compost will serve as a source of many different bacteria and enzymes that are capable to break down lignocellulosic materials.

Kempter et al. 2006 have developed a multi stage process for the separated municipal waste with a VS fraction of 75 %. In a first stage with a retention time of 15 days the easily degraded components were degraded. In a second stage water was drawn off by use of a microfiltration module, increasing the concentration and the retention time of the more difficult degradable organics solids. A degradation of the VS of 75 % was reached. The fermentation residue was concentrated to a total solids content of 20 % and converted aerobically with Chaetomium cellulolyticum (a cellulases and xylanases producing fungus) in a third stage. The VS content was reduced by 6 % of the original VS. The residue treated with the fungus was finally anaerobically digested, resulting in a VS reduction of 95% of the original VS.

The system can be simplified by recycling the myco-compost into the second fermentor. This will enhance the biogas yield of this digester as cellulases and xylanases are introduced into this digester. A slipstream has to be maintained in order to prevent the accumulation of non digestable and non composting material

5.8 Pretreatment of straw with fungi

Pretreatment of straw with fungi has a negative effect on the energy recovery. Post treatment of the solid fraction of the digestate and re-digestion offers a high conversion. This is done by a German farmer (Horsch 2011)

5.09 Chemical pretreatment of the straw.

Lime is a relatively cheap chemical and calcium improves the fertility of the soil. Gunnerson et al. 1987 advise to compost straw with lime (Calcium hydroxide), water and dung. In this method a fraction of volatile solids is lost. Raju et al. demonstrated an energy recovery of 50 % using a pretreatment at 1.5 % $Ca(OH)2$ /VS with lime.

5.10 Co-digestion of manure and straw

Straws are difficult to digest as they contain a significant fraction of lignin. The carbon to nitrogen ratio is also too high and fertilizer (N and P) or manure has to be added for a reasonable gas yield. An admixture of 5-10% herbaceous biomass in cattle dung slurry has been tried successfully in various fixed dome designs in India.

However, when the proportion of biomass exceeds a threshold, solids separate out from the liquid phase. The stratified mass develops into a floating scum layer. The scum layer is seen as a nuisance. In the test by Moeller et al. 2006 and Lehtomaeki 2006 a layer of recalcitrant material was formed (Scum layer) that negatively influenced the operation of the system. Hesse, M. et al. 2007 looked at the problems associated with small dome type digesters in Northern Vietnam. 53 out of 111 plants visited reported problems with scum formation. Only one plant had a blocked gas line. Most plants removed the scum layer to improve the structure of the soil.

A wet scum layer can contribute to the digestion of recalcitrant material if submerged in digester liquid for a sufficient long time (Chanaya and Moletta 2004). Their tests have been done on leaves and weeds and not on straw which is more recalcitrant. Test of Lehtomaeki 2006 suggest, that straw has to be submerged no longer than 20 days at 35 °C to be digested, even if it is above the digestate level.

There are several options:

- Up to 10 % straw can be used without problems.
- The invention of Rossow, N. 2011 keeps the scum layer wet by spraying the supernatant with digestate from the bottom of the digester. A mixer below the scum layer rotates this layer, so that only a few nozzles need to be used. A jet in the scum layer can also provide the rotation. The thickness of the layer can be more than 40 % of the height of the digester.
- The Dranco system (Baere, L. de 200) uses four nozzles in a tall digestor (H/D 3). This can also be done in squat digesters (H/D 0.4)with a large number of nozzles.
- Horsch, M. 2011 reported on a mixing device that pulled up liquid above the supernatant layer, there by wetting this layer and giving a rotation to this layer.
- A further reduction of the layer of recalcitrant material is possible by adding enzymes. A German companiy (Biopract; Gerhardt et al 2005) advertises with the fact that their enzyme mixtures reduce the formation of scum layers.
- A combination of a continuously stirred reactor and a fixed straw bed reactor. Digestate from the continuously stirred reactor is percolated through the fixed straw bed and recycled to the continuously stirred reactor. The straw bed is replaced periodically. Kalyuzhnyi et al. 2000 used a straw bed as a filter for pig manure. The group at Lund used a straw bed for two stage and single stage digesters (Svenson et al. 20005 and Andersson et al. 2002). Only tests with a bed of 0.5 meters have been performed.

6. Increase in solids content

A reduction in digestion plant size can be obtained by increasing the solids content. The amount of work in transporting and spreading the digestate is also reduced.

A simple system to increase solid content in a continuously stirred reactor is to halt stirring for one to two hours prior to removal of digestate using an extraction point in

the middle of the reactor. The content of the reactor will separate into three layers. The middle layer has the lowest content of volatile materials.
The digestate can be separated by a screw press or a centrifuge into a solid and a liquid fraction. Recycling of the solid fraction will increase the solid content of the digesters further. The solid fraction will yield between 60 – 200 l/kg VS depending on the pH (Balsari, P et al 2010).

Disposal of the liquid fraction into a sewer or into surface water requires the removal of phosphate and nitrogen. Phosphate can be separated by the addition of magnesium and precipitation of Magnesium Ammonium Phosphate (Struvite). The production of ammonium requires about 30 MJ/kg and it seems prudent to recover the ammonium. This can be done by adding extra phosphate and magnesium to the effluent The nitrogen can also be removed in the form of ammonia by air sparging and reaction of the ammonia in a sulphuric acid or phosphate acid solution.

Tuerker and Celen (2007) give a cost for chemicals of 7.7 $/kg N removed (Price level of 2001) for Magnesium chloride and Phosphoric acid and Sodium Hydroxide. About a third of the cost is for the Sodium Hydroxide necessary for the adjustment of Ph. Struvite is not a conventional fertilizer and the price of it is quite speculative, but it should be at least the value of the phosphate 2.9 $/kg N.

Karakashev et al. (2007) came to the conclusion that micro-filtration is unsuited for treatment of digested pig manure due to membrane clogging. They developed a method at laboratory scale to clean the supernatant after decanting-centrifuging. It involves an UASB reactor, precipitation of Magnesium-ammonia-phosphate (struvite) by adding Magnesium oxide, partial aeration and ammonium removal by anaerobic ammonia-oxidizing bacteria.

Phosphate and nitrogen can also be concentrated by removing water from the liquid fraction.

Waste heat (50 – 70 °C) from electricity generation removes only 15% of the water in a single pass. Up to three passes are possible (concentration of a factor of two).

Distillation with vapor recompression has been tried (Melse 2005). The electric energy consumption was about 0.3 MJe/kg water removed. Technical and economical reasons led to abandonment of the process.

The Biorek (Preez 2005) process uses a two step filtration and reverse osmosis process to increase the solids content. One project in the Netherlands was stopped due to operational difficulties.

The Fraunhofer Institut fuer Keramische Technologien und Systeme (Maas et al. No date) is developing micro filtration systems with retention of 50 % on Nitrogen and 98 % of Phosphorous.

7. Use of biogas

At present most biogas is used for heating purposes or in gas engines to generate electricity with an efficiency of 40 %. It is however better to remove the carbon dioxide and to inject the gas into the natural gas grid. It can then be used to generate electricity in highly efficient (55 %) combined cycle plants. An alternative is to liquefy the gas and use the liquefied gas as bio fuel in vehicles. There is much discussion about the competition of bio fuels with food production. Biogas as biofuel does not compete with food production. In fact it enhances as the use of digestate as fertilizer recycles most of the nutrients to the soil.

8. Conclusions and recommendations

Maximum yields of 380 l/kg VS can be obtained with mixtures of manure and straw and long retention times. This gives an energy recovery of 75 %. A mixture of manure and secondary sludge and high temperature pretreatment gives a methane yield of 300 l/kg VS at a retention time of only 20 days. The use of compost, sludge, enzymes and trace elements will improve the methane yield and reduce digestion times.

Addition of 10 % VS straw and 10 % VS sludge in existing centralized manure digesters will pose no operational problems and will increase the gas yield.

Swine manure requires more straw in order to obtain a carbon to nitrogen ratio of about 25. A recycling system of digestate in existing large digesters (H/D 0.4) can keep the scum layer wet and the material will digest. The system replaces the mixing devices.

Test should be done with straw, manure and sludge in a phased batch type percolation reactor system.

In Asia methane yields of 230 l/kg VS for cow dung and 300 l/kg VS for rice straw have been reported. This high total solids digestion of cattle manure is a major breakthrough and funds should be made available to convert the existing biogas installations to this more effective method. It is worthwhile to explore the addition of trace elements of plants with a high concentration of trace elements in the existing biogas installations and look at the operational difficulties. Straw could be added in combination with synthetic fertilizer.

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Table 1 Effect of retention time on methane yield (l/kg VS)

Author	**Material**	**Temperature**	**15 d**	**30 d**	**50 d**	**100d**	**200d**
Hansen et al. 1999	Swine manure	55 ºC.	67	180			
Moeller et al. 2006a	Swine manure	50 ºC	230	300			
Shyam 2001	Cattle manure	30 ºC.			164	230	
Moeller et al. 2006b	Wheat Straw	35 ºC.			190	250	
Torres-Castillo et al. 1995	Barley straw	35 ºC.			145	195	
Torres-Castillo et al. 1995	Barley straw	25 ºC.				160	240

Author	**Conditions of tests**
Hansen et al. 1999	Continuously stirred and semi-continuously filled reactors at 55 ºC. Loading rate was 45 g/l.
Moeller et al. 2006a	Solid matter content of an estimated 15 % using chemical separated swine manure solids. 15 days at 50 ºC and 15 days at 30 ºC
Shyam 2001	Semi-continuously filled reactor. Total solids loading rate at 50 days is 70 g/l and at 100 days 150 g/l.
Torres-Castillo et al. 1995	Batch dry fermentation with leachate recirculation; 4% w/w VS digested cow dung and 2 % w/w digested pig manure as inoculum.

Table 2 Effect of temperature on methane yield (L/kg VS)

Author	**Material**	**25° C**	**35° C**	**40 ° C**	**50° C**	**55 ° C**	**60 ° C**	**65 ° C**
Varel et al. 1980	Cattle manure		260	270	250	280	270	240
Ahring et al. 2001	Cattle manure					202		165
El-Mashad et al. 2004	Cattle manure				260		230	
Torres Castillo et al. 1995	Barley straw	160	195					
Komatsu et al.	66% sewage sludge; 33 % rice straw		283			211		

Author	**Conditions of tests**
Varel et al. 1980	Retention time 18 days; Loading rate 3.3 g/(l.d) VS
Ahring et al. 2001	retention time 15 days; Loading rate 3.0 g/(l. d) VS
El-Mashad et al. 2004	retention time 20 days; Loading rate 2.0 g/(l.d) VS
Torres-Castillo et al. 1995	Batch dry fermentation with leachate recirculation; 4% w/w VS digested cow dung and 2 % w/w digested pig manure as inoculum.; 100 days retention time
Komatsu et al.	

Table 3 High temperature pretreatment (Methane yield l/kg VS)

Author	**Pretreatment temperature**			**68º**	**73 º /55 º**	**90 º /35 º**	**120º /35º**
	Digestion temperature	35º	55º	55º			
Nielsen et al. 2004	Cow manure		215	235			
Mladenovska et al. 2007	40% Cow manure 40% Pig manure; 20 % Sludge		260		300		
Moeller 2005	Wheat straw	100					170
Raju 2011	Swine manure digestate plus wheat straw	160				220	225
Zhang et al. 1999	Rice straw (Whole)	190				200	
Zhang et al. 1999	Rice straw (25 mm)	200				230	

Author	**Conditions of tests**
Nielsen et al. 2004	Continuously fed and stirred reactors. Loading rate 3 g/(l.d) VS. 3 days at 68 ºC and 12 days at 55º
Mladenovska et al. 2007	Continuously fed and stirred reactors. 2 days at 73º C 13 days at 55º C
Moeller (2005)	25 days retention time
Raju 2010	Batch experiments, continuously stirred reactor; pretreatment time 15 min; 32 days retention time

Zhang et al. 1999	Two stage batch fed reactors 24 days; 20 mg ammonia per gram dry straw for control and tests; pretreatment for 2 h; loading 50 g/l.

Table 4 Effect of trace elements

Author		**Control Methane**	**Test Methane**
	Rice straw		
Bardiya et al	25 ppm Fe	63 l/kg VS	120 l/kg VS
Bardiya et al.	Single dose Ni	63 l/kg VS	107 l/kg VS
Ann. 2006	FeCl3		300 l/kg VS
Ann. 2006*	FeCl3		270 l/kg VS
	Cow Manure		
Preeti Rao et al. 1993	20 mM FeSO4	128 l/kg VS	182 l/kg VS
Guengoer-Demirci et al. 2004	Basal Medium	260 l/kg VS	290 l/kg VS
	Pig manure		
Hansen et al	10% w/w Glauconite	67 l/kg VS	90 l/kg VS

Author	**Conditions of tests**
Bardiya et al.	Batch tests, 40 days retention time; ambient temperature New Delhi, India (28 °C); 9 % total solids, 10 % inoculum (pre-digested slurry, Urea and rock Phosphate added.
Ann. 2006	Batch system, 35 **°C**, 35 days batch processing, 744 kg rice straw 25 % TS, 37 kg Castor cake, 0.032 kg FeCl3 and 744 kg 25 % TS partially digested material of previous batch
Ann. 2006*	Batch system, 33 °C, 35 days batch processing, 744 kg rice straw; 25 % TS, 37 kg Castor cake, 0.032 kg FeCl3 and 744 kg 25 % TS partially digested material of previous batch.
Preeti Rao et al	Continuously fed reactor at 37 ºC; 16 days retention time,

Guengoer-Demirci et al. 2004	Batch experiments 35ºC 4.3 %TS 90 days retention time; Basal medium Table X
Hansen et al. 1999	Continuously fed and stirred reactor; 15 days retention Time; 55 ºC and 45 g/l VS

Table 5 Effect of surface active elements

Author		**Control Methane**	**Test Methane**
	Pig manure		
Hansen et al. 1999	2.5 % (w/w) activated carbon	67 l/kg VS	126 l/kg VS
Hansen et al. 1999	2.5 % (w/w) activated carbon 10% w/w Glauconite	126 l/kg VS	195 l/kg VS
Milan et al. 2001	2 % zeolite (4 % Fe2O3)	155 l/kg VS	210 l/kg VS
	Cow manure		
Anglediaki et al. 1993	1.1 % (w/w) bentonite	200 l/kg VS	200 l/kg VS

Author	**Condition of tests**
Hansen et al. 1999	Continuously fed and stirred reactor; 15 days retention time; 55 ºC and 45 g/l VS
Milan et al. 2001	Batch type reactors, 30 days retention time ambient temperature (about 30 ºC), 16 g/l VS.
Angelidaki et al. 1993	Continuously fed and stirred reactors 15 days retention time 55 ºC and 42 g/l VS

Table 6 Effect of bacteria

Author		**55 º C**	**68 º C/55 º C**
Nielsen et al. 2004	Cow manure	215 l/kg VS	235 l/kg VS
Nielsen et al. 2007	Cow manure/Bacteria	205 l/kg VS	225 l/kg VS

Author	**Condition of tests**

Nielsen et al. 2004	Digestion process in two continuously stirred reactors. First at 68º C for three days and then 12 days at 55 º C in the second reactor.
Nielsen et al. 2007	About 6 million cells per liter of working volume of the first reactor of Caldicellulosiruptor lactoceticus (strain 6 A) were added. Loading rate was 1.5 g/l.d of VS. Washout of the bacteria from the first reactor may have occurred.

Table 7 Codigestion of dung with straw pretreated with fungi

Author	Test	Methane control	Methane
Mueller et al. 1986	Cattle manure + 30 % wheat straw; white rot fungi	182 l/kg VS	233 l/kg VS
Ghosh, A. et al. 1999	Inoculum + rice straw delignified for 20 days with the white rot fungus Phanerochaete chrysoporium	275 l/kg VS	404 l/kg VS
Ghosh A. et al. 1999	Inoculum + rice straw delignified with the brown rot fungus Polyporus ostreiformis	275 l/kg VS	364 l/kg VS

Author	Conditions of tests
Mueller at al 1986	Batch type reactor 40 g/l solids and 37 ºC; white rot fungi
Ghosh A, et al. 1999	Batch reactor working temperature 30 ºC and 64 days retention time; 8 % total solid.. Po rice straw Loss of cellulose and hemicellulose during delignification is not given. Methane yields include methane formed by further digestion of the inoculum.

Table 8 Chemical pretreatment of straw

Author	Material	Chemical	Treament time	Methane Control	Methane
Raju 2010	80 % wheat and 20 % rape straw	1.5 % Ca(OH)2	1 day	160	260

Author	Conditions of test
Raju 2010	Batch experiments, continuously stirred reactor; 35 °; pretreatment time 15 min; 32 days retention time

Table 8 Codigestion of manure with straw

Author	**material**	**CH 4 control**	**CH4 test**
LLabres-Luengo et al. 1988 a	Swine manure + 40 % wheat straw		260 l/kg VS
LLabres-Luengo 1988 et al. b	Swine manure + 40 % wheat straw		360 l/kg VS
Wu et al. 2010	Liquid fraction of Swine manure 90 % wheat straw VS		80 l/kg VS
Moeller et al. 2006b	Swine manure + 30 % wheat straw	280 l/kg VS	380 l/kg VS
Moeller et al. 2006a	Cattle manure + 30 % barley straw	150 l/kg VS	210 l/kg VS
Lehtomaeki, A. 2006 *	Cattle manure + 30 % barley straw		380 l/kg VS
Lehtomaeki, A. 2006 +	Cattle manure + 40 % barley		340 l/kg VS

	straw		
Somayaji	Cattle manure + 40% wheat straw	135 l/kg VS	140 l/kg VS
Somayaji	(Cattle manure) + 100 % rice straw	135 l/kg VS	230 l/kg VS
Demirbas 2006	Cattle manure + 33% wheat straw	205 l/kg VS	200 l/kg VS
Baserga and Egger	Cattle manure and wheat straw		110 l/kg VS
Baserga and Egger *	Cattle manure and wheat straw		210 l/kg VS

Author	**Condition of tests**
LLabres-Luengo et al. 1988	Batch tests; 50 g/l VS; 20 % (w/w) inoculum 90 days retention time; (a 23 ºC b 35)
Wu et al 2010	Batch tests, stirred reactor 80 g/l VS 12,5 % v/v inocculum 24 days retention time. (37 ºC**)**
Moeller et al 2006 b	Continuously fed and mixed digester. Shredding of the scum layer and re-digestion of the material. Microbes had a possibility to attach to the straw**,**
Lehtomaeki 2006	Continuously fed and stirred reactor 20 days; temperature 35 ºC; postmethanation period 100 days (*). Higher loadings of straw reduce the gas yield more than reduction in manure (after 20 days CSTR and 100 days post methanation)(+).
Somayaji et al. 1994	Daily fed, 40 days hydraulic retention time, 10 % TS, New Delhi (India) ambient temperature (28 °C yearly average).
Demirbas 2006	Batch 28 days; 35 ºC. His value for the control is high.
Baserga and Egger	Continuous loaded system 30 m^3, with nine 1 m^3 modules 35ºC. No control available; 11 days retention time, * 27 days retention time.

Table 9 Trace elements

	Methanogenic bacteria 0,1g/l VS		Basal Medium Guengor-Demirci 2004	Sewage sludge Kelly et al. 1984 1 g/l VS	*Sewage sludge Loeffen et al. 2005 1g/l VS	Water hyacinth Blgg 2002 1 g/l VS
	mg/l		mg/l	mg/l	mg/l	mg/l
N	6,5		800	33	80	80
P	1,5		19	23	40	20
K	1,0		130	3		310
S	0,4		40	16		16
Ca	0,3	0,03	15	39		280
Mg	0,3	0,02	4	4		50
Fe	0,18	0,2	11	11		14
Ni	0,01	0,01	0,12	0,08	0,05	
Co	0,008	0,005	2.4	0,004		
Mo	0,006	0,005	0,26	0,03		0.02

Zn	0,006		0,24	1,74	1,5	0,1
Mn	0,002		0,14	0,26		4.6
Cu	0,001		0,19	0,85	0,6	0,03

-Sewage sludge; median values of 200 sludge samples in the United States (Kelly et al. 1984). Values vary by an order of magnitude from sample to sample.
-* Sewage sludge Data from the Netherlands 2002 (Loeffen et al. 2005).
-Concentrations for methanogenic bacteria are from Hulshoff Pol 1995.
-The basal medium is from Guengor-Demirci 2004.
-Water hyacinth (Eichornia) from Bangladesh (Blgg 2002)

Table XI Summary of ways to enhance biogas production

Method	Pig manure	Cattle manure	Barley straw	Rice straw
Retention time	180 l/kg VS	230 l/kg VS	240 l/kg VS	
Temperature		280 l/kg VS	195 l/kg VS	
High temperature pretreatment		235 l/kg VS		230 l/kg VS
Trace elements	90 l/kg VS	182 l/kg VS		300 l/kg VS
Surface active elements	210 l/kg VS	200 l/kg VS		
Bacteria		225 l/kg VS		

Table XII Maximum biogas production for Co digestion

Volatile solids composition					Methane yield l/kg VS
Pig manure	Cattle manure	Barley straw	Wheat straw	Sludge	
40%	40%			20%	300
60%			40%		380
	70%	30%			380
	66 %		33%		200