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Effects of thermobarical pretreatment of cattle waste as feedstock for anaerobic digestion

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ABSTRACT

Lab-scale experiments were conducted to assess the impact of thermobarical treatment of cattle waste on anaerobic digestion. Treatment was at temperatures of 140–220 °C in 20 K steps for a 5-min duration. Methane yields could be increased by up to 58% at a treatment temperature of 180 °C. At 220 °C the abundance of inhibitors and other non-digestible substances led to lower methane yields than those obtained from untreated material. In an extended analysis it could be demonstrated that there is a functional correlation between the methane yields after 30 days and the formation rate and methane yield in the acceleration phase. It could be proved in a regression of these correlation values that the optimum treatment temperature is 164 °C and that the minimum treatment temperature should be above 115 °C.

1. Introduction

Sustainable and cost-competitive provision of bioenergy resources requires supplies of easily available biomass. Therefore, the bioenergy sector is encouraged to deploy new and as yet untapped biomass resources such as agricultural by-products and wastes. Livestock waste represents a huge, still only marginally exploited potential as feedstock for conversion processes. At present, 152 million tons of pig and cattle waste, comprising 120 million tons of liquid and 32 million tons of solid waste, are available in Germany annually (Schultheiß et al., 2010). Owing to low dry matter content, livestock waste is not appropriate for combustion without previous energy-intensive drying. By contrast with biomasses rich in sugars and oils, it is much more difficult to convert lignocellulose-rich biomasses such as bedding straw enclosed in the wet matrix into biogas. Lignocellulose and especially lignin are either not or only slightly degradable under anaerobic conditions (Grabber, 2005; Ward et al., 2008). Thus, the complex structure of lignocelluloses requires appropriate pretreatment to enable hydrolysis and hence efficient fragmentation of less digestible material for the subsequent biogas process.

Previous studies comparing different methods such as mechanical, thermal, chemical and/or biochemical pretreatment have identified thermobarical pretreatment (also called liquid hot water or thermal pressure treatment) as a promising innovative approach (Budde et al., 2008; Carlsson et al., 2012; Hendriks and Zeeman, 2009; Menardo et al., 2011). In principle, high temperatures and pressures (range 140...250 °C and 4...40 bar) are used to hydrolyze high–molecular substances (i.e. lignin, cellulose, hemicellulose) and thus anticipate the biological step. Consequently, applying strong physical conditions might circumvent the hydrolysis bottleneck and reduce the digestion time needed (Mladenovska et al., 2006; Pérez López et al., 2005; Rafique et al., 2010; Yunqin et al., 2009). Advantages of thermobarical hydrolysis (TBH) compared with other pretreatment methods are a very low electric energy input, no additives and a low degree of maintenance. The physicochemical processes of lignocellulosic biomass pretreatment also generate inhibitory compounds and are thus able to reduce the performance of anaerobic digestion (Horn et al., 2011; Owen, 1979).

The aim of this study was to determine the effects of thermobarical pretreatment of dairy cattle waste on anaerobic digestion. For this purpose a test device was designed and installed in the laboratory. The experiments were conducted with an emphasis on differences in cattle waste characteristics, temperature range and the associated saturated water vapor pressure, as well as duration of treatment. After pretreatment the material was investigated in batch anaerobic digestion tests in order to evaluate the overall impact on methane formation rate and yield.

Abbreviations: d, days; DM, dry matter; FM, fresh matter; GC–MS, gas chromatography mass spectrometry; LCM, liquid cattle manure; LHW, liquid hot water; ODM, organic dry matter; OM, organic matter; P1, plant 1; P2, plant 2; PT[n]M[n]S, time period in minutes and seconds; SCM, solid cattle manure; SCMW, solid cattle manure and water; SLCM, solid and liquid cattle manure; TBH, thermobarical hydrolysis; VOA, volatile organic acids.

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Table 1
Origin of raw materials, mixing ratios and chemical characteristics.

Origin	Raw material (abbreviation)	Mixing ratio	pH	DM	ODM	OM[a]	VOA	Crude fiber	NDF	ADF	ADL	Crude fat	Sugar value	Total as acetic acid[b]
		(% w/w)	(% FM)				(g kg^{-1} FM)	(% DM)						(g l^{-1})
Plant 1	Liquid cattle manure (P1-LCM)		6.9	7.8	6.4	7.2	8.0	24.4	47.2	39.1	14.8	5.0	4.9	–
	Solid cattle manure (P1-SCM)		8.3	17.1	15.0	15.7	6.7	26.8	61.3	51.7	20.6	3.0	4.6	–
	Solid cattle manure and De-ionized water (P1-SCMW)	40.1 59.9	7.7	6.9	6.0	6.3	2.7	23.0	46.9	36.9	12.7	3.1	0.3	2.0
	Solid cattle manure and Liquid cattle manure (P1-SLCM)	27.8 72.2	6.9	8.8	7.4	8.1	7.3	28.3	52.8	43.3	14.8	3.6	5.0	6.7
Plant 2	Liquid cattle manure (P2-LCM)		6.6	6.5	5.4	6.0	6.4	26.2	54.6	44.8	17.9	4.4	4.4	–
	Solid cattle manure (P2-SCM)		8.5	19.9	16.3	16.9	5.9	27.4	55.0	50.5	21.6	3.2	4.7	3.0
	Solid cattle manure and De-ionized water (P2-SCMW)	74.1 25.9	8.9	14.7	12.1	12.5	4.3	24.7	49.6	43.3	15.9	3.2	6.4	0.5

ADF – Acid detergent fiber; ADL – Acid detergent lignin; DM – Dry matter; FM – Fresh matter; NDF – Neutral detergent fiber; ODM – Organic dry matter; OM – Organic matter; VOA – Volatile organic acids.
[a] OM = ODM + VOA.
[b] Sum of acetic, propionic, isobutyric, butyric, isovaleric, valeric and caproic acid.

Table 2
Variants and results of thermobarical treatment experiments (mean ± standard deviation of *R* replicates).

Raw material	Number of replicates *R*	Set-point temperature	Average of measured maximal temperatures	Average time until set-point temperature is reached	Average rotational speed		Stirring device speed-change
					Start	End	
			(°C)	(mm:ss)[a]	(rpm)		(%)
P1-LCM	4	140	143.5 ± 0.5	25:34	201	206	2.6 ± 1.5
P1-LCM	4	160	163.9 ± 0.9	27:48	210	219	4.7 ± 3.0
P1-LCM	4	180	180.9 ± 0.6	29:37	346	358	3.5 ± 1.1
P1-LCM	4	200	202.6 ± 0.7	36:50	360	375	4.2 ± 0.9
P1-LCM	4	220	222.0 ± 0.3	36:56	340	358	5.3 ± 1.8
P1-SCM	6	140	144.9 ± 0.8	15:37	323	340	5.4 ± 2.6
P1-SCM	6	160	162.8 ± 1.9	18:32	314	335	6.8 ± 2.2
P1-SCM	7	180	181.6 ± 1.4	27:55	322	347	8.0 ± 3.1
P1-SCM	6	200	200.6 ± 1.0	27:21	331	354	7.0 ± 2.6
P1-SCM	4	220	221.2 ± 0.8	31:11	331	384	16.2 ± 1.9
P1-SCMW	4	140	143.5 ± 0.9	23:40	353	362	2.5 ± 0.6
P1-SCMW	4	160	162.2 ± 0.7	25:52	337	351	4.2 ± 2.9
P1-SCMW	4	180	181.2 ± 0.3	31:47	329	346	5.3 ± 1.6
P1-SCMW	4	200	201.9 ± 0.3	35:44	302	323	6.8 ± 2.4
P1-SCMW	4	220	223.3 ± 1.6	40:24	311	330	6.3 ± 2.1
P1-SLCM	4	140	142.9 ± 1.4	25:21	191	199	4.2 ± 1.5
P1-SLCM	4	160	162.8 ± 1.0	24:43	196	206	5.4 ± 1.9
P1-SLCM	4	180	183.6 ± 1.3	30:05	202	218	7.6 ± 1.2
P1-SLCM	4	200	203.4 ± 0.5	34:45	358	383	7.1 ± 1.5
P1-SLCM	4	220	221.9 ± 0.7	42:56	351	381	8.6 ± 1.1
P2-LCM	5	140	142.0 ± 0.2	19:43	362	373	3.2 ± 0.9
P2-LCM	5	160	161.1 ± 0.6	26:46	368	382	3.8 ± 0.6
P2-LCM	5	180	180.9 ± 0.5	30:27	372	384	3.3 ± 0.6
P2-LCM	5	200	201.7 ± 0.1	35:14	381	397	4.4 ± 0.5
P2-LCM	5	220	222.0 ± 0.4	40:10	365	389	6.5 ± 1.9
P2-SCM	6	140	147.5 ± 1.5	13:53	357	376	5.2 ± 2.0
P2-SCM	6	160	161.4 ± 3.3	17:00	370	380	2.8 ± 1.3
P2-SCM	9	180	181.6 ± 1.1	23:34	376	397	5.7 ± 1.4
P2-SCM	9	200	200.7 ± 1.0	27:39	391	414	5.9 ± 0.9
P2-SCM	9	220	220.2 ± 0.9	32:10	390	420	7.7 ± 0.8
P2-SCMW	6	140	140.5 ± 0.6	22:15	338	355	5.0 ± 1.0
P2-SCMW	5	160	161.7 ± 1.1	20:38	351	376	7.4 ± 4.5
P2-SCMW	6	180	181.3 ± 0.9	24:10	351	370	5.4 ± 1.3
P2-SCMW	6	200	200.5 ± 0.5	28:48	364	388	6.7 ± 1.0
P2-SCMW	7	220	220.7 ± 0.7	30:36	390	423	8.8 ± 3.0

rpm – Revolutions per minute.
[a] mm:ss – Time in minutes and seconds.

2. Materials and methods

2.1. Raw materials and mixtures

Dairy cattle waste was obtained from Fehrbellin (plant 1, abbreviated below to P1) and Groß–Kreutz (plant 2, abbreviated below to P2), two dairy cattle farms in the North-East of Germany. Two kinds of raw materials were collected from each source: solid cattle manure (SCM) and liquid cattle manure (LCM). The latter includes parts of the litter and feed residues that fall through the slatted floor of high-performance dairy cattle housing in both places. SCM from P1 contained less straw than SCM from P2, as the latter was used for dry cows and heifers.