Effects of full-scale substrate pretreatment with a cross-flow grinder on biogas production

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Abstract: The enhancement of the degradation rate of energy crops, agricultural residues and manure by different lab scale pretreatment pathways is shown in previous studies. In general, the pretreatments resulted in higher degradation efficiencies and an increase in methane yield for lignocellulosic and fibrous biomass. The major drawback of most of the different pretreatment methods is that either they are not feasible for application in practice or the high energy demand makes them economically inefficient. The aim of this study was to evaluate the effects of a full-scale mechanical pretreatment with a cross-flow grinder on commonly used energy crops (maize silage, grass silage and rye grain silage) and horse manure. Furthermore, the optimal treatment intensity for the highest energy output was estimated. A grinding time of 15 s led to a significant increase in methane yield for horse manure (+ 9.2%) and a mixture of energy crops and horse manure (+ 9.7%). However, only lower treatment intensities proved to have a positive energy balance. An increase in treatment intensity resulted in a further reduction of particle size but showed no effects on the degradation efficiency. Hence, it can be concluded that the utilization of the mechanical treatment enables the digestion of lignocellulosic and fiber-rich substrates like residuals and organic wastes and therefore increases the environmental sustainability of energy production by anaerobic digestion.

Keywords: anaerobic digestion, biogas production, mechanical pretreatment, lignocellulosic materials, horse manure

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1 Introduction

Today, the production of energy by turning agricultural substrates into biogas is a common technique (Weiland, 2006). Triggered by the renewable energy act, which grants priority and financial support to sustainable energy sources, the number of biogas plants in Germany increased quickly in the last decade (Mennel, 2012). This act enabled farmers to develop a new branch of business, which generates a year-round stable additional income. While the initial upswing in biogas plant construction was driven by subsidies, the biogas industry has yet to prove its economic viability and sustainability for further development in other countries. Thereby, the crucial points are the optimization of the methane yield per unit input and the decrease of the acquisition costs for the substrates. To accomplish this, the optimal utilization of energy crops, agricultural residues and animal manure needs to be ensured. As for the energy crops, the most important factors to increase the methane yield per hectare are identified. The plant breeders' intensive work resulted in particular varieties for anaerobic digestion. Furthermore, crop farming and harvest, as well as ensiling and storage of energy crops is a widely established and optimized process (Herrmann and Rath, 2012).

The pretreatment of biomass before digestion in order to enhance the biodegradability of lignocellulosic materials is the subject of a large number of scientific studies (Carlsson et al., 2012). In general, the methods are classified as physical, chemical and biological pretreatments (Agbor et al., 2011). All these methods aim to overcome the kinetic bottleneck of the anaerobic

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process, which in most cases is the degradation of lignocellulosic material via hydrolysis (Lynd et al., 2002; Strong et al., 2011). Bruni et al. (2010a) reported that the chemical pretreatment with calcium oxide and sodium hydroxide resulted in the highest methane yields in comparison to mechanical, biological and steam treatment. However, the costs for the chemicals and the extra investments for prerequisite equipment need to be taken into account. In addition, the chemical treatment in agricultural biogas plants is not feasible. The handling of corrosive chemicals and the disposal of the digestate can be environmentally unfavorable (Schwarz et al., 2009). Biological pretreatments such as the application of hydrolases to enhance methane production are controversial. According to Quiñones et al. (2012) enzyme application is the best way to increase biodegradability since the hydrolysis of lignocellulose is the rate-limiting step of the biogas process. In contrast, Brulé et al. (2008) could not determine an effect of enzyme addition to the methane yield, leading to the assumption that present enzyme activities are sufficient for the biogas conversion. In addition, the accessibility of substrate surface to the enzyme and therefore the decrease of particle sizes is crucial in order to obtain optimal conversion rates (Gharpuray et al., 1983; Schwarz et al., 2009).

The mechanical disintegration is a promising technology because it helps to increase the methane yields (Schumacher and Oechsner, 2007; Schwarz et al., 2009; Bolduan et al., 2011; Hjorth et al., 2011), reduces problems like clogging of pipes and pumps, reduces viscosity and thereby avoids floating layers (Hashimoto, 1983; Hartmann et al., 2000). Mechanical pretreatment also offers the possibility to use alternate substrates for biogas production. The intensive reduction of particle size enables the digestion of high proportions of straw-based manure or other fibrous residuals (Sharma et al., 1988; Menardo et al., 2012). The main advantage of the mechanical treatment in the contrast to the chemical and thermal methods is that no inhibitory or toxic byproducts are formed due to the disintegration step (Hendriks and Zeeman, 2008). Additionally, mechanical decomposing devices are readily available and can be easily implemented in existing biogas plants (Lindmark et al., 2012). The main disadvantage of the mechanical pretreatment is the high energy consumption (Bruni et al., 2010a). Hence, the energy efficiency of the disintegration devices needs to be evaluated for different substrates (Kratky and Jirout, 2011). In order to optimize the energy balance, the knowledge about the required intensity of mechanical disintegration for maximizing the economic output is crucial. A variety of mechanical disintegration units is currently available.

This work aimed to analyze the effects of an intensive pretreatment of commonly used energy crops and horse manure by a cross-flow grinder (Figure 1), as horse manure is known as one of the most challenging substrates for anaerobic digestion. In order to determine the biogas and methane yields of the treated and untreated substrates, a batch digestion test was conducted. Additionally, the substrate's degradation kinetics were investigated by utilizing the modified Gompertz equation. The physical effects of the cross-flow grinder were evaluated by determining the particle size distribution and particle structure of the substrates before and after treatment. Finally, the cross-flow grinder's energy demand for the substrate pretreatment was determined in a full-scale measurement.

Figure 1 MEBA cross-flow grinder at the research biogas plant "Unterer Lindenhof"

2 Materials and methods

2.1 Sample collection and pretreatment

The substrates used in this study were collected and pretreated with the MEBA cross-flow grinder (Bio-QZ, MEBA, Nördlingen, Germany) at the research biogas plant “Unterer Lindenhof” of the University of Hohenheim. The cross-flow grinder is patented as a decomposing device for the disintegration of recycling materials (Wabnig, 2004) and consists of a cylindrical working chamber with a rotating casing head which is equipped with two staggered steel chains located on the bottom (Figure 2). For common applications, the chains consist of three links for the disruption of lignocellulosic biomass. The rotating chains cause a radial as well as a vertical biomass flow in the working chamber (crossflow). Due to the high flow velocity, the resulting particle collisions lead to a significant particle size reduction and defibration of the biomass. In general, it is possible to treat the biomass either in batches or continuously. For the batch mode, the working chamber is automatically filled with a portion of material and the treatment runs for a definable time span before the material is released. For the continuous purpose, the substrate release is cracked opened and the material is released continuously. The advantages of a continuous pretreatment are the constant substrate fed to the biogas plant and the increased output efficiency. However, due to the reduced retention time of the material in the working chamber, the disintegration effect decreases. Therefore, the batch mode is recommended if intensive pretreatment is required.

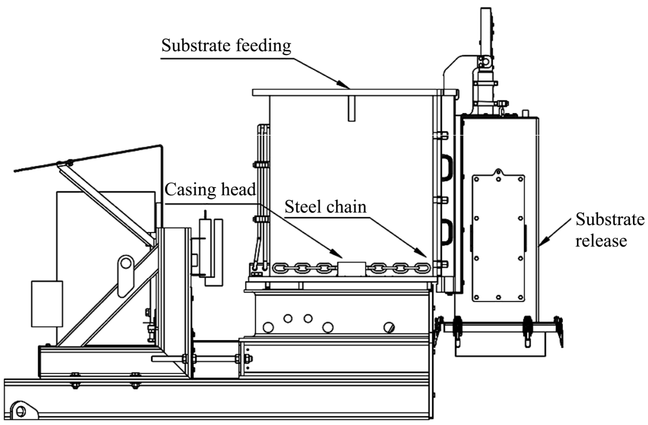

Figure 2 Schematic drawing of the MEBA cross-flow grinder for the mechanical disintegration of biomass

For this trial, we used maize silage, grass silage, whole crop rye grain silage, horse manure with straw bedding and a mixture of the different substrates. The mixture consists of 50.0% horse manure, 16.7% maize silage, 16.7% grass silage and 16.6% whole crop rye grain silage. The mixture was prepared by agitating with a vertical mixer for 15 min. For the characterization of the mechanical pretreatment, each sample was loaded into the vertical mixer, disintegrated with the cross-flow grinder for either 15 or 30 s in batch. Reproducibility was guaranteed by using new steel chains and a thorough cleaning of both the vertical mixer and cross-flow grinder after each substrate. In order to obtain homogenous untreated samples of the horse manure and mixture, the samples were collected at the outlet of the vertical mixer after thorough agitation.

2.2 Analyses and substrate characterization

The analyses of the samples for total solids (TS), volatile solids (VS), volatile fatty acids (VFA), ethanol and 1,2-propandiol was conducted according to the guidelines of the Federation of German Agricultural Investigation and Research Institutes (VDLUFA, 2007) in the laboratory of the State Institute of Agricultural Engineering and Bioenergy (Stuttgart, Germany). The correction of the VFA loss for the TS and VS values was calculated as described by Weißbach and Strubelt (2008a; 2008b). The concentrations of crude fat (XL), crude protein (XP), and crude fiber (XF) were determined by the State Institute of Agricultural Chemistry (Stuttgart, Germany) using the European regulations for the Weender feed analysis (Commission Regulation 2009/152/EC, 2009). Furthermore, the cell-wall fractions, neutral detergent fiber (NDF), acid detergent fiber (ADF) and acid detergent lignin (ADL) were also analyzed at the State Institute of Agricultural Chemistry according to the standard methods of the Federation of German Agricultural Investigation and Research Institutes (VDLUFA, 2007). The particle size distribution of the treated and untreated substrate samples were analyzed by the Fraunhofer Institute for Ceramic Technologies and Systems (IKTS, Dresden, Germany). At first, a separation step with a wet sieve (0.5 mm) was conducted to divide the samples in a coarse and fine fraction. For the characterization of the granulometric status of the samples the image analyzer Fibreshape (Innovative Sintering Technologies, Bremen, Germany) were used. In order to evaluate the effects of the mechanical disintegration the median value of the volume distribution ($Q_{50,3}$), which describes the average particle size, was determined with the software QX (Sympatec GmbH, Clausthal-Zellerfeld, Germany).

2.3 Batch digestion test

The biogas and methane yields of the samples were determined in batch tests in glass bottles with a working volume of 2,000 mL. The tests were conducted according to the guidelines of the VDI 4630 (VDI-Society Energy and Environment, 2006) which was previously described by Bolduan et al. (2011). This procedure enables the investigation of substrates without further chopping or grinding. Each bottle was filled with 1,800 mL inoculum and a fixed amount of 21 g VS of the substrate. The inoculum is the standard substrate for batch digestion tests at the State Institute of Agricultural Engineering and Bioenergy and is based on the digester content of different agricultural biogas plants, running under mesophilic conditions. The batches were incubated for 35 days at mesophilic digestion conditions (37 ± 0.5°C) in triplicates. For the correction of the gas production, the inoculums were incubated without substrate. To quantify the test conditions and activity of the inoculums, a hay standard was used. The determination of the gas volumes took place between one to two times per day according to the amount of produced gas. The methane content of the produced gas was measured manually in Vol% using a gas transducer DTM E (Sensors Europe, Ratingen, Germany). The measured gas amounts were corrected to standard conditions (0°C, 1,013 hPa). The cumulative biogas and methane production of the substrates were calculated to the specific yields, relating to kg VS and expressed as liter (L).

2.4 Energy consumption

In order to estimate the energy efficiency of the substrate pretreatment by the cross-flow grinder, an electronic, three-phase transformer connected meter (DAB 13000, ABB, Zürich, Suisse) was installed at the research biogas plant. The reliability of the data was acquired by recording the energy demand for the different intensities of mechanical disintegration for 5 days each. Therefore, the vertical mixer was fed with one of the investigated substrates for one day each. The feeding of the digester takes place twelve times per day and the feeding portion was set to 340 kg substrate per meal. The consumed energy was recorded for each feedstock in kWh/d. The energy demand per ton (t) fresh matter (FM) was calculated with the recorded data of the daily feed input of the vertical mixer. The energy balance was drawn with the electrical equivalence of the methane yields of the samples and in the case of the pretreated samples, with the estimated electric energy consumption of the cross-flow grinder. The expected energy output from the samples was calculated as following:

$$E_{sample} = LHV \times \eta \times \frac{1 \times \mathrm{CH_4}}{tFM} \tag{1}$$

where, *LHV* is defined as the lower heating value of methane with 9.971×10^{-3} kWh/L (Deutsches Institut für Normung e. V., 1997); η is the electrical energy conversion efficiency of the combined heat and power unit, which is assumed to be 38% for the conversion from methane to electrical power.

2.5 Calculations and statistical analyses

The degradation kinetics were estimated by fitting the cumulative specific methane production to the modified Gompertz equation (Nopharatana et al., 2007; Budiyono et al., 2010) assuming that the methane production is a function of bacterial growth:

$$M = P \times \exp\left\{-\exp\left[\frac{R_m \times e}{P}(\lambda - t) + 1\right]\right\} \tag{2}$$

where, M is the cumulative methane production, L/kg VS; P the methane production potential, L/kg VS; R_m the maximum daily methane yield, L/kg VS*d; λ the duration of the lag phase and t the duration of the assay, d. The parameters P, R_m and λ are constants and can be estimated by using non-linear regression. The first derivation of Equation (2) was used in order to assign a time to R_m. The statistical analyses were performed with the Kruskal-Wallis test using the statistical software R (R Core Team, 2012).

3 Results and discussion

3.1 Substrate characteristics

The results of the Weender feed analysis for the treated and the untreated substrates are shown in Table 1. The cross-flow grinder did not affect the TS and VS values of the substrates. Furthermore, no variations in chemical composition between the treated and untreated samples were recognized. In addition, the data regarding the horse manure and the mixture indicate that the vertical mixer is an appropriate tool for the preparation of homogenous samples. The contents of volatile acids and alcohols were analyzed for the determination of the thermal effects on the substrates during the mechanical disintegration (Table 2). Clearly losses of volatile components due to the grinding were observed for the rye grain silage and the grass silage treated for 30 s. As expected, the highest yields of easily degradable compounds were detected for the grass and maize silages.

Table 1 Chemical characteristics of the investigated substrates

Substrate	Treatment time, s	TS, % FM	VS, % FM	XP, % TS	XL, % TS	XF, % TS	NDF, % TS	ADF, % TS	ADL, % TS
Maize silage	0	29.69	28.68	8.5	2.6	21.7	42.2	25.3	2.2
Maize silage	15	29.13	27.77	9.1	2.8	22.6	44.4	26.7	2.0
Maize silage	30	27.48	26.12	9.9	2.9	22.9	44.5	27.5	2.2
Grass silage	0	36.85	33.09	17.2	3.8	25.2	44.6	31.6	2.8
Grass silage	15	33.89	30.15	17.1	3.6	24.9	45.0	31.5	3.3
Grass silage	30	34.16	30.36	17.1	3.8	24.8	44.3	31.6	3.0
Rye grain silage	0	39.08	37.00	9.5	2.5	27.1	49.8	31.4	3.4
Rye grain silage	15	37.21	34.33	9.5	3.2	23.9	45.9	30.5	3.3
Rye grain silage	30	35.43	32.24	9.5	3.0	24.1	46.7	30.7	3.2
Horse manure	0	36.07	32.48	6.6	1.4	40.0	73.5	49.9	7.7
Horse manure	15	33.64	29.96	6.6	1.3	38.0	73.7	50.8	7.2
Horse manure	30	34.05	30.37	6.7	1.6	39.0	74.0	50.9	7.4
Mixture	0	36.69	31.89	8.9	2.0	32.4	61.3	47.8	9.4
Mixture	15	34.68	30.04	9.0	1.8	32.2	60.9	48.2	10.1
Mixture	30	35.26	30.22	8.8	1.9	32.9	61.4	47.6	10.4

Note: TS = total solids; VS = volatile solids; XP = crude protein; XL = crude fat; XF = crude fiber; NDF = neutral detergent fiber; ADF = acid detergent fiber; ADL = acid detergent lignin.

Table 2 Content of volatile fatty acid and alcohols of the treated and untreated substrates

Substrate	Treatment time, s	Lactic acid, g/kg FM	Acetic acid, g/kg FM	Propionic acid, g/kg FM	Ethanol, g/kg FM	Propandiol, g/kg FM
Maize silage	0	15.55	5.72	0.00	0.80	0.00
Maize silage	15	16.20	6.19	0.04	0.90	0.00
Maize silage	30	18.65	6.21	0.04	0.90	0.00
Grass silage	0	20.05	13.88	0.00	0.75	0.00
Grass silage	15	21.70	13.95	0.14	0.80	0.00
Grass silage	30	15.55	14.01	0.13	0.80	0.00
Rye grain silage	0	11.75	17.08	0.21	2.65	11.80
Rye grain silage	15	8.80	11.57	1.12	1.55	3.80
Rye grain silage	30	8.70	11.05	1.19	1.70	4.10
Horse manure	0	0.45	1.63	0.00	0.00	0.00
Horse manure	15	0.70	2.60	0.06	0.00	0.00
Horse manure	30	0.80	2.60	0.08	0.00	0.00
Mixture	0	4.35	5.99	0.82	0.90	1.10
Mixture	15	4.35	5.89	0.81	0.80	1.00
Mixture	30	4.40	6.02	0.83	0.60	1.05

The physical changes of the substrates due to the disintegration with the cross-flow grinder were characterized by a particle size analysis (Table 3). The results indicate a considerable reduction in the particle size of the investigated substrates with increasing grinding time. However, the first 15 s of the treatment provide a larger reduction of particle size than the last 15 s. The median values of the volume distribution for the maize and rye grain silage are in the same range. These findings suggest that the forage harvester was used with the same setup for harvesting these substrates. Furthermore, the effect of grinding on theses substrates is nearly identical. As the lowest initial $Q_{50,3}$ values were observed for the substrate mixture, it could be assumed that preparation of the mixture in the vertical mixer already resulted in a partial disintegration. The 30 s treatment with the cross-flow grinder resulted in a particle size reduction to $Q_{50,3}$ below 0.5 mm in the case of maize and rye grain silage as well as for the mixture. As the final $Q_{50,3}$ value for all these samples was 0.2 mm, it seems likely that a treatment duration of 30 s leads to the maximum decrease in particle size for these substrates. Further treatment will result in larger energy consumption without affecting the substrate characteristics.

Table 3 Effects of the mechanical disintegration on the physical parameters of the substrates

Substrate	Treatment time, s	Coarse fraction, %	Fine fraction ,%	$Q_{50,3}$, mm	Reduction ratio, %
Maize silage	0	70.8	29.2	5.1	0.0
Maize silage	15	51.9	48.1	1.0	80.0
Maize silage	30	47.3	52.7	0.2	96.3
Grass silage	0	70.2	29.8	3.7	0.0
Grass silage	15	58.1	41.9	2.0	45.6
Grass silage	30	54.3	45.7	1.1	70.2
Rye grain silage	0	71.6	28.4	5.2	0.0
Rye grain silage	15	51.8	48.2	1.0	80.9
Rye grain silage	30	47.7	52.3	0.2	96.3
Horse manure	0	83.3	16.7	10.1	0.0
Horse manure	15	67.1	32.9	3.1	69.4
Horse manure	30	66.4	33.6	1.8	82.1
Mixture	0	56.8	43.2	2.2	0.0
Mixture	15	53.7	46.3	1.1	50.2
Mixture	30	48.1	51.9	0.2	91.3

Note: $Q_{50,3}$ = median value of the volume distribution.

3.2 Methane yields

The methane yields of the treated and untreated substrates are shown in Figure 3. The results indicate a high reproducibility between the replicates with low standard deviations. The cumulative methane yields of the batch digestion tests are consistent with previous studies (Mukengele et al., 2006; Kusch et al., 2008; Mittweg et al., 2012). The mechanical pretreatment shows no significant effect on the methane potential of the silages. For the untreated maize silage, 328.4 ± 9.3 L CH_4/kg VS were detected after 35 days of digestion. The treatment of the maize silage with the cross-flow grinder for 15 s resulted in 333.4 ± 7.2 L CH_4/kg VS and for 30 s in 342.4 ± 11.8 L CH_4/kg VS. The digestion experiments with grass silage and rye grain silage indicate no differences in the methane yields dependent on the disintegration grades. Thus, the mechanical pretreatment and larger surface area did not affect the methane yields in the batch digestion assay. Hence, it can be assumed that the particle structure of the silages is sufficient and a further reduction in particle size does not enhance the biodegradability and the methane potential. This is consistent with the results of Schumacher and Oechsner (2007) and Schwarz et al. (2009). In their investigation, the extrusion of maize silage indicates a maximum increase in methane yield of 5%. It can be concluded that the prehydrolysis step during the ensiling process has the highest effect on the methane yield of silages and the particle size reduction has little effects (Herrmann and Rath, 2012). The grinding of the horse manure resulted in a significant increase in methane yield after 15 s, as well as 30 s treatment time. The disintegration for 15 s in the cross-flow grinder led to a yield of 257.1 ± 2.7 L CH_4/kg VS in comparison to 236.2 ± 2.7 L CH_4/kg VS for the untreated manure. The retention time of 30 s showed no further increase, but rather resulted in slightly lower values (249.4 ± 3.3 L CH_4/kg VS) than the 15 s treatment. Similar results were observed for the mixture. The treatment for 15 s enhanced the methane yields approximately 10% in comparison to the untreated material and the grinding for 30 s only about 5%. These results are surprising because a liberation of inhibitory compounds due to the mechanical treatment is unlikely (Agbor et al., 2011). Therefore, it seems that the longer retention times resulted in a further increase in surface area, but did not affect the biogas production (Chang et al., 1997). Identical observations were reported by Kaparaju et al. (2002) and De la Rubia et al. (2011). In their work, the methane yield was also lower for the highest pretreatment intensity. This leads to the hypothesis of a process inhibition by an accumulation of volatile fatty acids due to the higher hydrolysis rate (De la Rubia et al., 2011). In the case of the horse manure and the mixture in a batch digestion test, this is unlikely. As described by Kratky and Jirout (2011) most of the required energy during the grinding process is wasted as heat and not utilized for the disintegration of the materials. Thus, the consequence of a long treatment time with the cross-flow grinder is a rise of substrate temperature, which might cause a reduction of degradable compounds, which could not be detected by the applied methods. Overall, the digestion assays with horse manure showed relatively high methane values in comparison to previous results. Therefore, it can be assumed that the use of substrates with a higher recalcitrance to anaerobic digestion will result in larger differences between the treated and untreated samples.

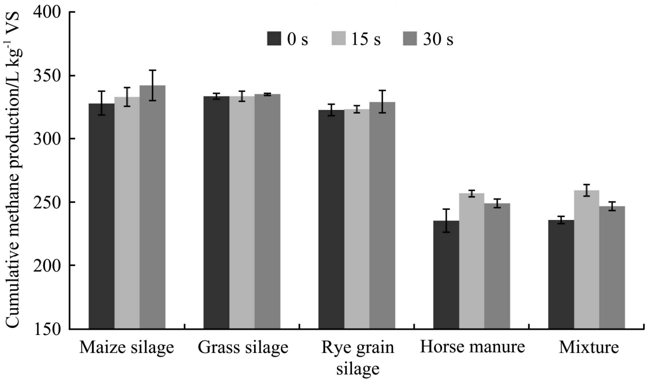

Figure 1 Cumulative methane production of the treated and untreated substrates after 35 days

3.3 Degradation kinetics

In order to determine the effects of the mechanical pretreatment on the degradation rate, the maximum daily methane yield and the beginning of the decline phase, which describe the time point of the maximum methane production, were calculated with the modified Gompertz equitation (Figure 4). In the case of the 15 s treated maize silage, the calculations neither indicate an increase in the maximum daily methane production nor a shift of the beginning of the declining gas production rate. The pretreatment for 30 s resulted in a maximum daily methane yield of 84.9 L CH_4 instead of 79.3 L CH_4 for the untreated maize silage. Additionally, the gas production rate peak was attained earlier after the 30 s disintegration. The treatment of the grass silage resulted in an increase in the maximum daily methane yield from 70.3 L CH_4 for the untreated grass to 75.4 L CH_4 for the 15 s and to 77.1 L CH_4 for the 30 s treated grass silage. Furthermore, a slight impact on the beginning of declining production rates was observed. The untreated grass silage reached the maximum methane production peak after 1.7 days of digestion. In contrast, the 15 s grinded grass silage peaked after 1.6 days and the 30 s treated sample after 1.5 days. The treatment of the rye grain silage with the cross-flow grinder resulted in an increase of the maximum daily methane yield of only 3.0 L CH_4 for both, the 15 s and 30 s variant. A larger effect was observed to the degradation rate of the treated grain silage. The treatment duration of 15 s lead to a decrease of more than one day for achieving the maximum methane production. The same effect to a smaller extent was observed after 30 s of grinding. Declining production rates were observed after 4.1 days in contrast to 4.5 days for the untreated silage. The treatment of the horse manure lead to a similar rise in maximum daily methane yield as the grain silage. The increase in treatment time also caused a faster degradation rate. In contrast to the previous results, the treatment of the mixture had no impact on the maximum methane production and resulted in a slower degradation rate with increasing treatment time. To recapitulate, it can be assumed that mechanical treatment with the cross-flow grinder has only a small impact on the degradation kinetics of the investigated substrates. As

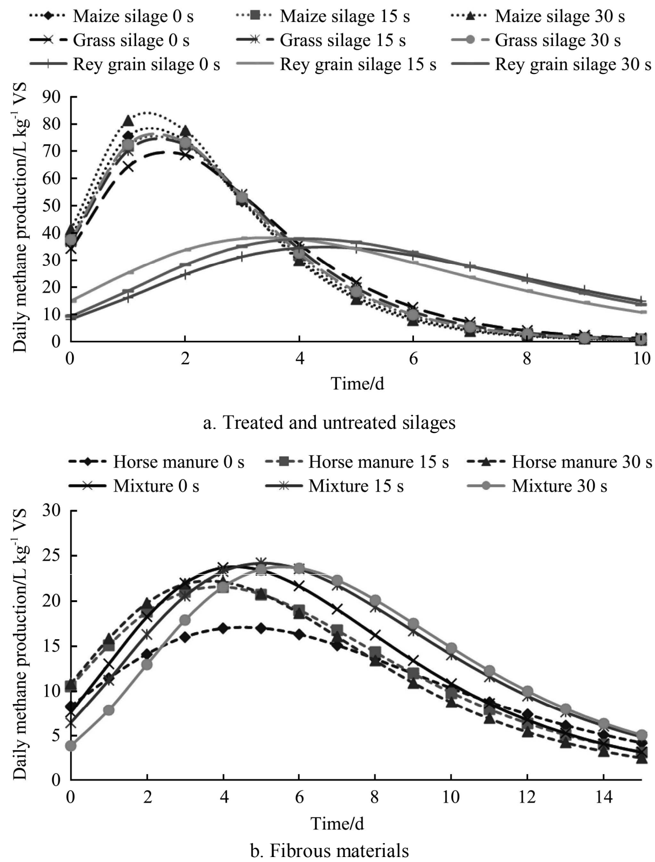

Figure 2 Daily methane production

postulated by Zhang and Banks (2013) the differences in degradation rates for a full-scale continuous biogas plant with hydraulic retention times of more than 15 days are negligible.

3.4 Energy balance

The full-scale measurement results of the cross-flow grinder's energy consumption for the pretreatment of the different substrates in relation to the methane yield are listed in Table 4. The energy demand for grinding the substrates for 15 s varied between 10.7 kWh/t FM for the mixture and 13.8 kWh/t FM for the horse manure. These values are in the same range as the energy demands of other mechanical treatment devices like the hammer mill or the extruder (Bolduan et al., 2011; Hjorth et al., 2011; Lindmark et al., 2012). The treatment of substrates for 30 s with the cross-flow grinder resulted in an energy consumption of between 14.0 kWh/t FM and 20.5 kWh/t FM. Regarding the additional energy output of the grinded substrates, the treatment leads to a higher energy output as the untreated samples. In order to evaluate the feasibility of the mechanical treatment device the energy consumption was subtracted from the additional energy output. The energy balance of the pretreatment with the cross-flow grinder indicates only positive values for the 15 s treatment of both, horse manure and mixture. In the case of the 30 s treated maize silage, the extra energy yield is negligible and will not generate an economic benefit.

Table 4 Electrical energy balance of the disintegrated substrates in comparison to the raw materials

Substrate	Treatment time, s	Energy consumption, kWh/t FM	Additional energy, kWh/t FM	Energy balance, kWh/t FM
Maize silage	15	11.6	5.4	-6.1
Maize silage	30	14.8	15.2	0.5
Grass silage	15	11.3	0.2	-11.1
Grass silage	30	14.0	2.0	-11.9
Rye grain silage	15	11.8	1.2	-10.6
Rye grain silage	30	16.3	9.2	-7.1
Horse manure	15	13.8	26.5	12.7
Horse manure	30	20.5	17.1	-3.4
Mixture	15	10.7	28.1	17.3
Mixture	30	15.2	13.3	-1.9

4 Conclusions

The aim of this study was to determine the impact of the cross-flow grinder on energy crops and horse manure as substrates with a high degree of lignification. The results indicate that the pretreatment leads to a significant particle size reduction and enlarged surface area with increasing treatment time. The strongest effect of the substrates was observed after grinding for 15 s. Overall, the pretreatment is sufficient for avoiding swim layers due to fiber-rich substrates in continuous anaerobic digestion systems. As expected, the mechanical pretreatment did not cause any significant variations in the chemical composition between the treated and untreated samples. However, the grinding of rye grain silage resulted in a decrease in volatile compounds with increasing treatment time. This indicates that the temperature rise due to the intensive grinding could cause negative effects on the degradation rate and methane yield of treated silages. For the horse manure and mixture, the disintegration was observed to have a positive impact on the methane yields in the batch digestion test. Furthermore, the highest methane yields for both substrates occurred after 15 s of pretreatment. A positive energy balance could only be shown for these two substrates. Thus, the favorable treatment intensity seems to be achieved by 15 s of grinding. Accordingly, the treatment with the cross-flow grinder resulted in a higher degradation of lignocellulosic materials. It can be assumed that the mechanical treatment of the silages did not improve the degradation efficiency. However, mechanical treatment seems to be a promising technology for enhancing the sustainability of anaerobic digestion. Without a sufficient particle size reduction, the utilization of alternative substrates like agricultural residuals and green wastes is not feasible.

Future developments should include the evaluation of the cross-flow grinder's impact on a continuous full-scale biogas plant process. Particular attention should be paid to the energy efficiency and the changes in the energy demand for mixing and pumping of the substrates. In addition, the quantification of the impact of grinded materials to the process parameters in batch digestion tests is crucial. It is also necessary to evaluate if the properties of the decreasing particle size leads to sink layers within the digester.

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