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Applicability of biogas digestate as solid fuel

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1. Introduction

Biogas digestate is a byproduct in biogas plants. A common biogas plant with a power of 500 kW emits more than 10,000 t of digestate per year with a dry matter of about 10% [1]. Up to now, that digestate has been used as fertilizer. Economies of scale led to further increase of electric power from biogas plants within the last years and thereby to a drastic increase of digestate that cannot be used locally. Studies of Döhler and Schliebner [2] have shown that the costs for transportation and output of digestate exceed the costs of its fertilizer value when transport exceeds distances of 5–10 km.

Using the dried digestate as solid fuel seems to be a promising alternative. In order to reduce costs for transport and storage, digestate can be dried close to the biogas plant. The waste heat of the power plant can be used to dry digestate up to a dry matter content of around 80–90%. The bulky material can be pelletized, to produce a storable and transportable product with nearly consistent properties. After combustion of digestate fuel pellets, fertilizer nutrients such as phosphor, potassium and calcium remain in the ash. Ash with defined composition and high concentration of nutrients would be a valuable fertilizer. However, after combustion the heavy metals of digestate feedstock are found in coarse, cyclone and filter ash. Especially cadmium, lead, zinc and mercury are highly volatile and are usually found after recondensation in the filter ash [3].

Currently, digestate is not considered in regulations or standards for biofuels. As an alternative fuel, it has not been investigated so far. Therefore, the objectives of this work were to verify whether digestate from biogas plants is suitable as a solid biomass fuel and to classify the digestate according to current regulations for biofuels. In addition, combustion experiments in a biomass combustion facility were carried out to ascertain both, emissions and combustion behavior. Furthermore, the coarse ash was analyzed to evaluate the suitability as fertilizer.

2. Material and methods

2.1. Test fuel

Two digestates based on different feedstock were used as test fuel. Feedstock composition is presented in Table 1. Origins of both

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Table 1
Feedstock composition of digestates used as test fuels (% of fresh mater).

Digestate	Feedstock components	%
1	Maize silage	50
	Grass and grass silage	40
	Potatoes	10
2	Maize silage	81
	Sugar sorghum/sudan grass silage	9
	Poultry manure	7
	Corn cob mix (CCM)	3

digestates were biogas plants with wet fermentation technology. The digestates were first drained by using a decanter and afterwards dried with a drum drier to a moisture content of 15–20% wet basis. For combustion the dried material was pressed into pellets without further additives.

2.2. Fuel characterization and ash analyses

Characterization and analyses of the test fuel pellets and ash were done according to the standard methods listed in Table 2.

2.3. Combustion experiments

The combustion experiments were carried out with the biomass-heating system OEKO-THERM, type C0 (A.P. Bioenergietechnik GmbH, Ort, Germany) with a nominal power of 49 kW, Fig. 1, normally used for straw and grass pellets, corn grains, miscanthus, wood pellets, wood chips and other granulated solid biomass. The combustion chamber is a water-cooled transversal system with an automatically ash removing slider. The water-cooled trough avoids slagging of the ash. Primary and secondary air is directed through lateral holes to create a whirl, which improves mixing with the gasification products of the solid fuel. This secures complete incineration and reduction of air excess rate. The control system of the combustion unit comprises the speed controlled fans for primary and secondary air and the induced draft fan on the boiler discharge. A programmable logic controller (PLC) communicates with the lambda and temperature sensors situated in the flue gas exit. The combustion unit is equipped with a downstream electrostatic filter for flue gas. During the experiments, the fuel was continuously fed by a screw conveyor into the combustion unit.

Table 2
Standard methods applied for characterization and analysis of test fuels and ash.

Parameter	Method
Pellet characterization	DIN CEN/TS 14961
Density	DIN 52182
Calorific value	DIN 51900
Moisture content	DIN 51718
Ash content	DIN 51719
Hydrogen content	DIN 51732
Carbon content	DIN 51732
Nitrogen content	DIN 51732
Oxygen content	DIN 51732
Sulfur content	DIN 51724-1
Chlorine content	DIN 51577-3
Ash fusibility	DIN 51730
Potassium	DIN 38406-22 by ICP-OES[a]
As, Cd, Cr, Cu, Hg, Pb, Zn	DIN 38406-29 by ICP-MS[b]
As, (ash)	EN ISO 11969 D18
Pb, Cd, Cr, Ni, (ash)	DIN EN ISO 11885
Hg, (ash)	DIN EN 1483
Th, (ash)	VDI 3796

[a] ICP-OES – inductively coupled plasma optical emission spectrometry.
[b] ICP-MS – inductively coupled plasma mass spectrometry.

2.4. Flue gas

The flue gas temperature was measured between heat exchanger and flue gas fan. Samples for gas analyses were taken behind the electrostatic filter. Measurements of O_2, CO_2, NO_x and CO were done continuously by using a gas analyzer ecom-EN2 (rbr Messtechnik GmbH, Iserlohn, Germany). Dust concentration was measured continuously by light scattering principle using the dust measurement system FW100 (SICK MAIHAK GmbH, Reute, Germany). Measurement of CO, NO_x and dust were expressed as concentration in mg/m^3 on basis of normal cubic meter (0 °C; 0% r.f.; 1013 mbar). All measurements were started when reaching maximum boiler power and performed in a 1-s interval. Total measurement duration was about 20 h per test fuel.

2.5. Reference values

As no reference values for fuel, ash and flue gas properties were available for combustion of digestate, results were compared with combustion of pellets made from pinewood with bark, reported by Puttkamer [4]. Furthermore, emissions of polluting components flue gas and ashes were checked against the threshold values of the German Federal Immission Control Ordinance '1. BImschV' [5] and the German Fertilizer Regulation, Deutsche Düngemittelverordnung' [6]. In addition, for classifying the ash, the German Biowaste Regulation 'Bioabfallverordnung' and the German Sewage Sludge Regulation 'Klärschlammverordnung' were considered.

3. Results and discussion

3.1. Energy balance of digestate pellets

Table 3 shows the specific energy demand for the different production steps of the digestate fuel pellets. The decanter removes the water of the digestate to a dry matter of 25%. Subsequent to the de-watering, the digestate was dried in a drum dryer to the finally content of 80–85% of dry matter. Specific electrical energy demand for decantation and pelletizing was low and averages in 0.27 kWh/kg of digestate fuel pellets. Thermal energy for drying of digestate was about 2.97 kWh/kg and it averages 92% of production energy. The energy for drying was provided by waste heat from biogas production. The calculated ratio between the total energy input for the production of the digestate pellets and the net calorific value was 0.74 for digestate 1 and 0.78 for digestate 2 and therefore smaller than one.

3.2. Fuel characteristics

Based on the analyses the digestate pellets were specified according to the pre-standard DIN CEN/TS 14961, as shown in Table 4. The average dimensions of the pellets, diameter/length, are 10.0/17.5 mm for digestate 1 and 5.8/17.3 mm for digestate 2. Bulk density of both digestates was 1.24 kg/dm^3. Ash content was high with 18.3% for digestate 1 and 14.6% for digestate 2. Moisture content of the pellets was low for both digestates with 9.2% and 9.9%, respectively. Fine fraction for digestate 1 was 3.1% and therefore about 50% higher than for digestate 2 with 2.2%. Nitrogen content of digestate 1 (2.86%) was about 9.5 times and digestate 2 (1.54%) about 5 times higher than the threshold value for wood pellets according DIN 51731 [7]. In contrast, common pinewood with bark remains about 40% below this threshold value. In case of higher amount of nitrogen in biogas feedstock, the increased concentration of nitrogen oxide during combustion should be considered.

The calorific values of the digestate in comparison to pinewood pellets are shown in Table 5. The net calorific value of digestate 1

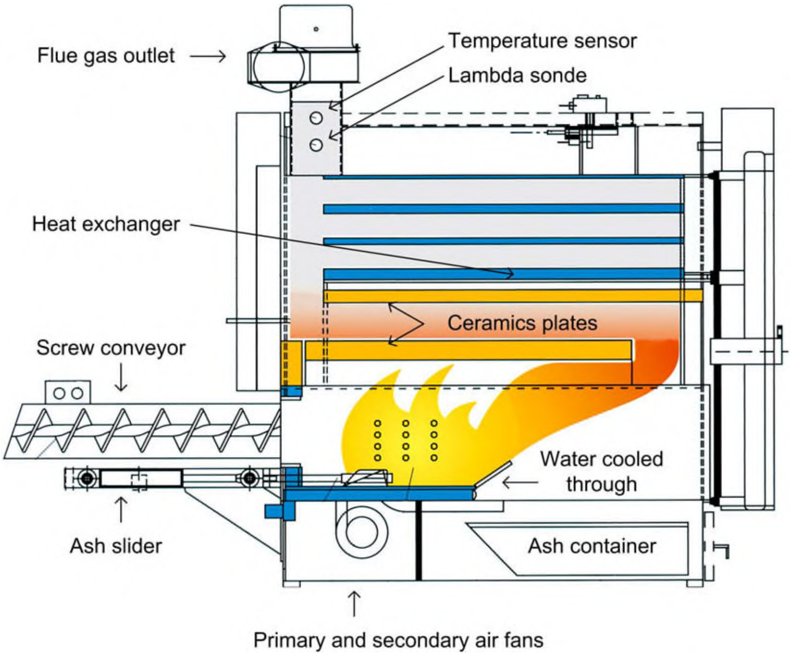

Fig. 1. Compact biomass-heating system Ökotherm (A.P. Bioenergietechnik GmbH).

Table 3
Specific energy consumption for production of digestate pellets in comparison to their energy contents.

Parameter	Unit	Digestate 1	Digestate 2
Decanter	kWh_{el}/kg	0.12[a]	0.12[a]
Drying	kWh_{th}/kg	2.97[a]	2.97[a]
Pelletizing	kWh_{el}/kg	0.15[a]	0.15[a]
Total energy input	kWh_{th+el}/kg	3.24	3.24
Net calorific value	kWh/kg	4.81	4.56
Ratio	–	0.74	0.78

[a] Average values from Ref. [1].

resulted in 15.8 MJ/kg at a water content of 9.2%. Pellets of digestate 2 showed a marginal lower net calorific value with 15.0 MJ/kg at a water content of 9.9%. Fuel pellets produced of pinewood with water content of 12.0% show a similar net calorific value with 16.3 MJ/kg.

Table 6 shows the ultimate analysis of the digestate fuel pellets in comparison to pinewood pellets and threshold values according DIN 51731 [7]. Remarkable are the high content of nitrogen, sulfur and chlorine content. Each of these elements is responsible for the formation of noxious emissions during combustion. For digestate 1 and 2, nitrogen content exceeds threshold value by factor 10 and 5, respectively. Overstepping of sulfur was approximately 10 times for digestate 1 and 3.5 times for digestate 2, chlorine content oversteps the threshold value for 28 and nine times, respectively.

Table 4
Specification of digestate fuel pellets according to pre- standard DIN CEN/TS 14961 [8].

Parameter	Unit	Digestate 1		Digestate 2	
		Values	Specification	Values	Specification
Diameter	mm	9.97	D10	5.82	D06
Moisture content	%	9.2	M10	9.9	M10
Ash content	%	18.3	A18.3	14.6	A14.6
Sulfur content	%	0.86	S0.86	0.33	S0.33
Fine fraction	%	3.1	F3.1	2.2	F2.2
Nitrogen content	%	2.86	N3.0	1.54	N3.0

The content of zinc was three times as threshold for digestate 1 and 1.3 times higher for digestate 2. The concentrations both, of arsenic and mercury were almost close to the threshold value whereas cadmium and remained below. Contents of chrome and copper of pinewood with bark was almost on the boundary of threshold value, controversy the concentrations of chrome and copper in digestate which pass over threshold value.

The characteristic fusibility temperatures of the digestate ashes compared to pinewood ash are given in Table 7. The softening temperature of both digestates with 1090 °C and 1110 °C was lower than that of wooden materials like pinewood (1430 °C). Hence, formation of slag could occur in combustion unit designed for wooden materials. In the used biomass-heating system this was prevented by water cooling of combustion chamber particularly of the trough. However, the softening temperature for both digestates were above those of stramineous fuels which are characterized by softening temperatures below 911 °C [9].

3.3. Combustibility

During the combustion of both digestates no disturbance of the feeding system was observed. The combustion process proceeded continuously without disturbance. Marginal ash melting and slight slag creation was noticed in the through as shown in Fig. 2. However, the slag did not impact the ash flow out of combustion area.

Due to lower net calorific value of digestate compared to wood pellets, the power of the combustion unit reached only about 44 kW. The efficiency was estimated to be about 85%, which is less

Table 5
Gross and net calorific value of digestate and pinewood fuel pellets.

	Water content, %	Calorific value, MJ/kg	
		Gross	Net
Digestate 1	9.2	17.3	15.8
Digestate 2	9.9	16.4	15.0
Pinewood with bark[a]	12.0	18.5	16.3

[a] Values from Ref. [4].

Table 6
Approximate analyses of the digestate and pinewood fuel pellets and threshold values according to DIN 51 731 [7]. Figures in bold exceed threshold value.

Element	% Dry basis								mg/kg dry basis						
	C	N	O	H	P	S	K	Cl	As	Cd	Cr	Cu	Pb	Hg	Zn
Digestate 1	45.3	**2.9**	28.4	5.2	1.3	**0.9**	1.4	**0.84**	**0.93**	0.29	**13.2**	**58.8**	4.4	**0.07**	**304**
Digestate 2	43.2	**1.5**	35.9	5.5	1.1	**0.3**	1.6	**0.27**	0.54	0.15	**21.5**	**18.2**	0.78	0.04	**125**
Pinewood with bark[a]	49.7	0.13	43.3	6.3	0.03	0.02	0.1	0.01	0.48	0.23	6.8	3.5	2.17	0.04	35
Threshold DIN 51 731	–	0.3	–	–	–	0.08	–	0.03	0.80	0.50	8	5	10	0.05	100

[a] Values from Ref. [4].

than by use of wood pellets where efficiency is above 90%. It is supposed that the settings of the process parameters such as feeding rate, primary and secondary air and the intervals of the ash slider were not yet optimal matched. During operation of the combustion unit typical characteristic odor of digestate pellets occurred.

3.4. Emissions

During the combustion of digestate 1 average flue gas temperature was 227 °C and oxygen content was 10.5% as shown in Table 8. Average dust concentration of 100 mg/m^3 was determined. By using the electrostatic filter, average dust concentration was reduced to 40 mg/m^3. The average CO_2–concentration was 10.1%. Based on an O_2–content of 13.0% in the flue gas, the average concentration of carbon monoxide was 275 mg/m^3 and 334 mg/m^3 of nitrogen oxides.

During combustion of digestate 2, average flue gas temperature was 227 °C and oxygen content was 11.5%. An average dust concentration of 106 mg/m^3 was measured and this was reduced to 43 mg/m^3 by using the electrostatic filter. The average CO_2–concentration was 9.2%. Based on an O_2–content of 13.0% in the flue gas, the average concentration of carbon monoxide was 104 mg/m^3 carbon monoxide and 398 mg/m^3 for nitrogen oxides.

In comparison of pinewood with the digestate 1 and 2, the emissions of nitrogen oxides were with 108 mg/m^3 almost three times lower than for digestate 1, and 4 times lower than for digestate 2. The concentration of nitrogen oxides in the emissions is similar to the higher amount of nitrogen content in test fuels. Carbon monoxide content of emissions from pinewood was slightly higher than for digestate, but in comparison to threshold value low.

For non-standard fuels and a power below 50 kW, the German Federal Immission Control Ordinance '1. BImschV' [5] defines a threshold value of 150 mg/m^3 for dust and 4000 mg/m^3 for CO based on an oxygen content of 13.0%. In the combustion experiments these thresholds values were not passed in any case.

Table 7
Ash fusibility of digestate 1 and 2 in comparison to pinewood pellets.

	Temperature, °C		
	Softening	Hemisphere	Flow
Digestate 1	1090	1290	1320
Digestate 2	1110	1150	1390
Pinewood with bark[a]	1430	1600	1600

[a] Values from Ref. [10].

3.5. Ash composition

Table 9 shows the composition of the coarse ash in the combustion chamber compared to coarse ash from the combustion of pinewood with bark and the threshold values according to the German regulation for fertilizers *Düngemittelverordnung* [6]. In general, the ashes of the digestates showed higher concentrations of the major plant nutrients P, K, Ca than ashes from pinewood pellets. The content of Mg is lower for digestate 1 and higher for digestate 2 than for wood ash. The Fe content for digestate 2 was 1.8% and therefore similar that of pinewood ash (2.3%). Noticeable is the high Fe content of digestate 1 with 22.5%. This can be explained by the use of iron chloride which was added into the fermenter during biogas production for desulphurization. Iron compounds were probably accumulated on the bottom of the fermenter, discharged as digestate and therefore found in the ash after combustion.

The ashes did not contain N, as nitrogen escapes almost completely during combustion. The Si content was below the values for pinewood ash and can be thus classified as harmless, especially because silicon oxide behaves ecologically neutral in the soil and is hardly soluble [11]. The Al is also lower in the digestate ashes than in pinewood ash.

The concentration of the heavy metal elements As, Pb, Cd, Hg and Tl in the ash was low and did not exceed the threshold value as shown in Table 9. Concentration of Ni in digestate 2 exceeds the threshold value 3.5 times, whereas concentration of Ni for

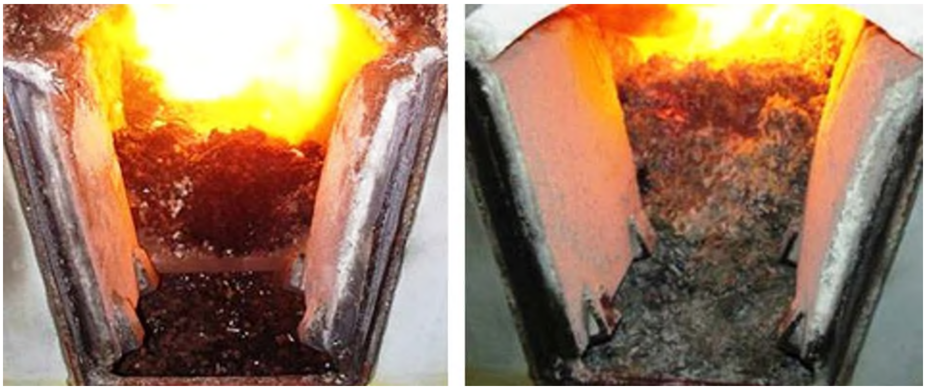

Fig. 2. View into the combustion trough: burnt-out ash of digestate 1 (left) and digestate 2 (right).

Table 8

Emission and dust of flue gas of digestate 1 and 2 compared to German Federal Immission Control Ordinance '1. BImschV' [5].

Average	Temperature	O_2	CO_2	CO^a	$NO_x{}^a$	Dust	$Dust^b$	SO_2	C_C
	(°C)	(%)		(mg/m^3)					
Digestate1	227	10.5	10.1	275	334	100	40	n.d.	n.d.
Digestate 2	227	11.5	9.2	104	398	106	43	n.d.	n.d.
Pinewood[c]	–	–	–	320	108	68	–	–	30
1.BImschV – 50 kW	–	–	–	4000	–	150		–	–

n.d.: Not detected.

[a] 13% O_2.

[b] Electrostatic filter.

[c] Average values from Ref. [3].

Table 9

Composition of coarse ash in comparison to pinewood with bark [9,14] and threshold values of German regulation for fertilizer (Deutsche Düngemittelverordnung) [6]. Figures in bold exceed threshold value.

Oxides of elements	P	K	Mg	Na	Ca	Si	S	Fe	Al	As	Pb	Cd	Cr	Ni	Hg	Tl	PFT
	(%)									(mg/kg)							
Digestate 1	20.4	8.5	2.7	3.1	17.0	18.0	3.2	22.5	3.1	0.8	<1	<0.5	**76**	36	<0.1	<0.5	n.d.
Digestate 2	26.7	15.5	8.4	0.8	13.6	30.4	0.9	1.8	1.2	1.1	2.3	<0.5	**184**	**285**	<0.1	<0.5	n.d.
Pinewood with bark	2.6	6.4	6.0	0.7	41.7	25.0	1.9	2.3	4.6	4.1	13.6	1.2	325.5	66	0.01	n.d.	n.d.
Threshold value	–	–	–	–	–	–	–	–	–	40	150	1.5	2	80	1.0	1.0	0.1

n.d.: Not detected.

digestate 1 was 50% below threshold value. The concentrations of Cr in digestate 1 with 76 mg/kg and in digestate 2 with 184 mg/kg were several times higher than the threshold value.

In general the composition of coarse ash from the combustion chamber of the investigated digestates is suitable for application as fertilizer on agricultural land. However, content of Ni and Cr has to be reduced by suitable methods such as leaching or thermal treatment of ash [12,13].

4. Conclusions

Chemical composition and physical properties of digestate fuel pellets depend on the blend of substrates used as feedstock for biogas production. Combustion behavior, in turn, is determined by the fuel properties. Therefore, in terms of thermal digestate application, feedstock of biogas plants should be kept constant to guarantee a consistent fuel quality. After drying, the digestates under investigation could be pressed into pellets without additives. The mechanical durability fulfilled the requirements according common standards for pellets.

Due to the high ash content of 15–20% and the characteristic odor, the utilization of this fuel is foremost suitable for use close to the point of origin. In conclusion, the digestates investigated in this study can be recommended as a fuel for combustion. The calorific value of digestate fuel pellets was comparable to calorific value of wood. Therefore, digestate fuel pellets constitute an excellent alternative fuel for wood. The emission of flue gas was within the defined limits for biofuels and threshold values were not exceeded. The digestate pellets can be burnt with existing market available combustion technologies. The specific production costs of fuel pellets of digestate are low, because more than 90% of production energy was supplied by waste heat. Further investigations are required to cover a broader range of digestates and combustion techniques.

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