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Cascaded production of biogas and hydrochar from wheat straw: Energetic potential and recovery of carbon and plant nutrients

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ABSTRACT

The increasing interest in biogas production has brought notable attention to lignocellulosic wastes as a promising and yet unexploited feedstock. As these materials are usually highly recalcitrant the energetic efficiency of biogas production, however, is comparatively low. With the aim to overcome this drawback, a novel cascaded approach was investigated that combines anaerobic digestion with hydrothermal carbonization (HTC). The latter is used to convert the digestate into a carbon-rich product termed hydrochar. An energetic evaluation of this cascaded treatment shows that the energy recovery can be nearly doubled compared to single anaerobic digestion.

Furthermore, systematic HTC experiments with both fresh and digested wheat straw and with reaction temperatures of 190 °C, 210 °C, 230 °C, and 250 °C revealed an effect of reaction temperature on carbon, nitrogen, and phosphorus concentration in the final hydrochar. Carbon, nitrogen and phosphorus are primarily retained in the hydrochar, which could favor its use as soil ameliorant instead of an energy carrier.

1. Introduction

The use of anaerobic digestion for the energetic use of agricultural waste is increasing rapidly. In most cases the digestate is returned to the field as organic fertilizer. However, depending on the size of the biogas plant and transportation costs field application of digestate is not always economically feasible. Additionally, the amount of digestate that can be applied is limited due to its relatively high ammonia content and digestate can account for a significant release of green house gases especially N_2O, NH_3, and CH_4. This issue has been recognized by research institutions and various potential solutions are investigated such as composting, drying, and pelleting [1–3].

A newly discovered possibility to treat digestate and create a value-added product is the thermochemical conversion into a carbon and energy rich product, which can be used as a high-quality alternative fuel or as a soil amender and carbon sink. Both pyrolysis, used by mankind since ancient times [4], and hydrothermal carbonization (HTC) can be used for this purpose. In comparison with HTC, pyrolysis requires dry feedstock and therefore the digestate needs to be dried prior to carbonization. Considering the total solids content of typical digestate, usually 2–10% of fresh matter [1], drying requires a substantial amount of energy. Therefore, the application of the wet conversion process HTC seems to be beneficial.

HTC is a thermochemical conversion process which has been used to simulate natural coalification for decades [5,6].

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Abbreviations

daf	dry, ash-free
DM	dry matter
HTC	hydrothermal carbonization
ODM	organic dry matter
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
UASS	upflow anaerobic solid state

Reactions are carried out in a pressure vessel, containing biomass submerged in liquid, with temperatures of 180–270 °C [7]. Pressures of the reaction are not controlled and are slightly above the saturated vapor pressure due to gaseous by-products [8]. HTC has been applied for a variety of feedstock [9–14]. The main product is solid material with a similar energy density as lignite.

Caused by a partial destruction of the biomass structure by the HTC process, the char product shows an improved dewatering ability, which enables mechanical separation [14,15]. Thus, HTC could be regarded both a conversion process to increase the energy density and dewatering ability of wet biomass resulting in a product with increased value as a fuel [8,9,11,12,16]. Despite the energetic advantage of a mechanical dewatering, model calculations showed different results for the liability of HTC in conversion chains depending on the scenario chosen [17,18].

The aim of this investigation is to determine the benefits gained by carbonizing the digestate from anaerobic digestion by HTC. The focus is placed on the fate of plant nutrients during anaerobic digestion and carbonization and on evaluating the cascaded process in respect to its energetic potential and the carbon and nutrient recovery.

2. Materials and methods

2.1. Anaerobic digestion

Anaerobic digestion of the wheat straw was carried out using the upflow anaerobic solid-state (UASS) process with process liquor circulation [19]. The wheat straw was obtained from winter wheat (*Triticum aestivum* L.) harvested in July 2009 by Dittmannsdorfer Milch GmbH in Kitzscher (Germany) (N 51° 8′ 48″, E 12° 32′ 26″). Before its use, the straw was recovered from the field as long baled straw, shred in two stages to a target chopping length below 20 mm, dedusted by a cyclone, compressed into 20–25 kg plastic-wrapped quad bales, and stored in this state for about one year under dry conditions. Each bale was sampled separately by taking and mixing material from various random locations of the bale (analyses are shown in Table 1). A pair of identical 40 L UASS reactors was operated for 200 days under thermophilic conditions (55 °C) at a fixed organic load rate (dry basis) of 2.5 g $L^{-1}d^{-1}$ with wheat straw as the sole substrate. For the methanization of soluble metabolites, each UASS reactor was connected to an individual 30 L fixed bed reactor. In order to compensate the straw's lack of nutrients and water, nitrogen, trace elements, and tap water were added during reactor operation. The UASS reactors were fed five to seven days a week and the removal of digestate was carried out once a week. Process liquor was removed once a week for analytical purposes. A detailed description of the process performance has been published elsewhere [20].

2.2. Hydrothermal carbonization

The feedstock for the carbonization experiments was fresh wheat straw and digested wheat straw derived from thermophilic digestion as described above. For reference experiments, poplar wood, lignin, and microcrystalline cellulose were also carbonized. Japanese poplar was obtained from an

Table 1 – Composition of the feedstock expressed as mass fraction.

Composition (expressed as mass fraction)		UASS[a]	Hydrothermal carbonization[b]		
		Straw	Straw	Digestate	Poplar
ODM, db	(%)	94.8	95.1	94.4	99.0
Hemicellulose, db	(%)	n.a.	27.8	18.9	12.2
Cellulose, db	(%)	n.a.	45.8	44.6	60.9
Lignin, db	(%)	n.a.	8.5	21.4	19.0
Carbon, daf	(%)	48.4	49.4	51.2	51.1
Nitrogen, daf	(%)	0.4	0.8	1.2	0.3
Sulfur, daf	(%)	0.14	0.31	0.25	0.05
Hydrogen, daf	(%)	7.7	7.2	7.3	7.0
Oxygen, daf, by difference	(%)	43.3	42.3	40.1	43.7
TKN, db	(mg kg^{-1})	3800	7000	11,300	2700
Phosphor, db	(mg kg^{-1})	460	640	870	420
Potassium, db	(mg kg^{-1})	12,300	n.a.	8800	n.a.

daf: dry ash free basis.
db: dry basis.
n.a.: not analyzed.
a $n = 4$ samples.
b $n = 1$ sample.