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Biochemical methane potential and anaerobic biodegradability of non-herbaceous and herbaceous phytomass in biogas production

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HIGHLIGHTS

- The Biochemical methane potential (BMP) of non-herbaceous phytomass was 159.3–249.5 CH_4 NL kg VS^{-1}.
- Wood cuttings had half the BMP of lawn cuttings but a similar BMP to cow manure.
- Wild plants showed a clear trend for lower biodegradability than lawn cuttings.
- Lawn cuttings from gardens proved to be the most suitable substrate.
- Lignin of 100 g kg VS^{-1} was the critical biodegradability point of phytomass.

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ABSTRACT

The suitability of municipal plant waste for anaerobic digestion was examined using 57 different herbaceous and non-herbaceous samples. Biochemical methane potential (BMP) and anaerobic biodegradability were related to the degree of lignification and crystallinity of cellulose. The BMP of herbaceous garden plants (332.7 CH_4 NL kg VS^{-1}) was high, although lower than that of energy crops (400–475 CH_4 NL kg VS^{-1}). Herbaceous wild plants from natural grassland contained most lignocelluloses, leading to relatively low BMP (214.0 CH_4 NL kg VS^{-1}). Non-herbaceous phytomass had a high degree of lignification and a high concentration of crystalline cellulose, but due to the content of non-woody parts with a low concentration of lignocellulose the BMP was relatively high, 199.9 and 172.0 CH_4 NL kg VS^{-1} for hedge cuttings and woody cuttings, respectively. There were indications that a plant lignin concentration of 100 g kg VS^{-1} is the critical biodegradability point in anaerobic digestion of phytomass.

1. Introduction

Biogas production is one of the most socio-economically cost-efficient renewable energy technologies, using organic waste and plant biomass as feedstock (Nielsen et al., 2002). It is also an efficient method of reducing greenhouse gas emissions (GHG) (Sommer et al., 2004; Dhingra et al., 2011). The European Commission has set mandatory national targets for renewable energy to account for 20% of energy consumption by 2020 and to reduce GHG emissions (EREC, 2010). In accordance with the European Commission targets, the Danish government has set a target for increasing the use of animal slurry as feedstock for biogas production from the current level (5%) up to 40% by 2020 (Green Growth, 2009). However, biogas production using only animal manure is not economically sustainable and addition of biomass from other sources is needed (Møller et al., 2007; Triolo et al., 2011). Energy crops have been widely used as co-substrate in Germany and Austria, particularly maize, sunflower, grass and Sudan grass (Amon et al., 2007). In Denmark industrial organic waste is co-digested with animal manure, but domestic sources of industrial organic waste have been exhausted and alternative biomass resources need to be explored (Møller et al., 2007; Raven and Gregersen, 2007). One source is imported organic industrial waste, which at present produces 0.68 petajoule (PJ) biogas in Denmark (Jørgensen, 2009). There is still the potential for 15.9 PJ biogas production from crop residues and municipal plant litter, which can significantly contribute to achievement of the Danish target on non-fossil fuel energy production. Cultivating energy crops for biogas production may not be viable due to production costs (Tilman et al., 2006; Raju et al., 2011). Moreover, there is a risk of increasing food prices if the area of agricultural land used for food and feed production is reduced (Hensgen et al., 2011). Herbaceous phytomass from natural grasslands, gardens and parks is cheap and use of this biomass for energy production would not affect food prices. However, the energy yield of such biomass is variable because the harvested plant

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material is diverse in terms of both plant species and organic composition. Furthermore, the biogas production potential may be low because the fibre content is high (Bühle et al., 2012).

In Denmark, 557,000 tons of green garden waste are delivered annually to local municipal recycling centres. This corresponded to 17% of total household waste and 7% of total domestic waste in 2005 (Waste Statistics, 2005). The amount of garden waste increased 10-fold (96%) from 1994 to 2005 (Waste Statistics, 2005). Green garden waste consists of both herbaceous and non-herbaceous phytomass such as lawn grass, lawn weeds and residues from hedge and tree trimming, and is currently recycled after being composted and not used for biogas production (Hensgen et al., 2011). The reason could be that biogas plants are reluctant to use organic waste with a high content of lignocellulose, which is not easily transformed to biogas (Menon and Rao, 2012). However, since they are facing "aggressive biogas growth" with no available co-substrates, biogas producers are becoming increasingly interested in using herbaceous garden waste as a cheap feedstock. To our knowledge, no previous study has examined the biochemical characteristics of a wide range of green garden waste in terms of methane potential, anaerobic biodegradability and crystallinity of cellulose in order to assess the quality of this biomass as a feedstock for biogas production. Hence, in this study we investigated the biogas production potential of different forms of municipal herbaceous phytomass, as well as non-herbaceous material, i.e. green garden waste, energy crops, grass from natural grassland and woody waste. Biochemical methane potential (BMP) was determined and a distributional analysis was made of each organic component using data obtained from physicochemical analyses. These included Van Soest characterisation and determination of the crystallinity index of cellulose in different lignocellulosic materials using X-ray powder diffraction (XRPD). Anaerobic biodegradability was assessed using the concentration of lignocellulosic fibre in each biomass group and the BMP was correlated to the anaerobic biodegradability.

2. Methods

2.1. Biomass samples collected

In total, 57 samples were collected from a wide variety of sources in Funen, Denmark, during the period July–October 2011 (Table 1).

The samples obtained were separated into two groups, herbaceous plants that do not have a persistent woody stem and non-herbaceous material such as hedge and tree trimmings. The material was then subdivided into five groups: (1) herbaceous lawn waste from private gardens or public parks ('lawn cuttings'); (2) hedge trimmings from the sites where lawn waste was collected ('hedge cuttings'); (3) tree trimmings from the sites where lawn waste was collected and willow from wetland ('wood cuttings'); (4) herbaceous plants from natural grassland ('wild plants'); and (5) crops/crop residues from agricultural land ('crops').

Most of the lawn waste consisted of lawn grass clippings and lawn weeds, e.g. smooth meadow-grass, clover, short bluegrass, etc. The hedge clippings were from common species such as oval-leaved privet and beech hedge and also contained hedge weeds. The tree trimmings were from birch and coniferous trees (Lawson's cypress), as well plane trees from the roadside, and the willows from wetland included two dominant species in Denmark, namely weeping willow and sharpleaf willow. The hedge and wood cutting samples consisted of leaves, fruit bodies and branches around 20 cm in length. The wild plant samples from natural grassland were obtained from green areas beside roads or from wetland, for example, green areas beside streams and lakes, etc., and most were either perennial grasses or perennial flowering plants. The crop samples consisted of maize, sugar beet and wheat straw.

Apart from grass samples, which consisted of relatively homogeneous leaves, all the other plant samples were heterogeneous and consisted of a distinct plant body such as stem, leaves, fruit bodies and occasionally branches. Hence, to improve analytical precision the samples were well homogenised by milling to a maximum size of 1 mm after drying at 60 °C prior to analysis. A control BMP test carried out on eight randomly chosen samples showed that the drying/milling process did not affect BMP and other biogas production characteristics ($p > 0.05$). On the other hand, from the repeatability test, the lower relative standard deviation was found in the dried/milled 2.61(±1.61)%, while that in fresh samples was much higher at 9.18(±8.19)%, showing that milling could improve the precision in BMP tests.

2.2. BMP assay

The BMP of samples was determined according to VDI 4630 (2006) using 1.0-L (working volume) batch infusion digesters. Inoculum was obtained from the Fangel biogas plant, which operates at mesophilic conditions (37 °C), and is fed a mixture of 80% animal slurry and about 20% organic industrial waste. The inoculum was degassed for 2 weeks at 37 °C. The average pH of the inoculum was 8.1 and the volatile solids (VS) concentration was 67.3% of dry matter. The average methane (CH_4) concentration in biogas released from the inoculum was 61.7%. When fermenting the plant residues, the inoculum:substrate ratio was set to 3:1 on a total solids (TS) basis. Following the recommendation in the standard protocol (ISO, 1995; VDI, 2006), 100 mL of anaerobic buffer solution with medium was added to the inoculum substrate mixture. Each reactor was flushed with nitrogen gas to ensure an anaerobic atmosphere.

All assays were performed in triplicate. Fermentation was carried out under mesophilic conditions, at 37 °C. Digestion was terminated when daily biogas production per batch was less than 1% of cumulative gas production according to VDI 4630 (VDI, 2006), which corresponded to batch fermentation for approximately 60 days. A couple of times during a working day, the reactors were thoroughly mixed by hand shaking to avoid dry layers and to encourage degassing. The gas volume measured was corrected to a dry gas basis by excluding the water vapour content in wet biogas. Pressure and temperature for a norm litre (NL) of gas were corrected into standard temperature and pressure (STP) conditions (273 K, 1.013 hPa), according to VDI 4630 (2006). The CH_4 concentration in the biogas was determined by a gas chromatograph (HP 6890 series), equipped with a thermal conductivity detector and a 30 mm × 0.320 mm column (J&W 113-4332). The carrier gas was helium (30 cm/s), and injection volume was 0.4 mL. Injector temperature was 110 °C, and detector and oven temperature was 250 °C.

Biomethane was quantified assuming that the dry biogas was composed of $CO_2 + CH_4$ alone. Consequently CH_4 production volume was calculated according to VDI 4630 (2006) by multiplying the dry gas production by the $CH_4/CO_2 + CH_4$ ratio.

The BMP of cellulose (Avicel PH-101 cellulose) was determined as a control and inoculum as a blank. The BMP of cellulose was 393.3(±4.1) CH_4 NL $(kg\ VS)^{-1}$ and the ratio of BMP to theoretical BMP (TBMP) was 94.8%. The TBMP of cellulose is 415 CH_4 NL $(kg\ VS)^{-1}$.

2.3. Physicochemical analysis

Dry matter (TS), volatile solids (VS), crude lipid (XL), total ammoniacal nitrogen (TAN = $NH_3 + NH_4^+$) and total Kjeldahl nitrogen (TKN) were determined according to standard procedures