Bioresource Technology 153 (2014) 260–268

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Assessment of factors influencing the biomethane yield of maize silages

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HIGHLIGHTS

- Biomethane yield per hectare of maize silages was assessed.
- The cropping environment is the most influential factor for the biomethane yield per hectare.
- Late maturing maize varieties harvested at an early stage are advised for biomethanation.
- Volatile solids can predict the biochemical methane potential of maize silages.

ARTICLE INFO

Article history:
Received 14 October 2013
Received in revised form 25 November 2013
Accepted 29 November 2013
Available online 6 December 2013

Keywords:
Biochemical methane potential (BMP)
Biomethanation
Anaerobic digestion
Biogas
Renewable energy

ABSTRACT

A large set of maize silage samples was produced to assess the major traits influencing the biomethane production of this crop. The biomass yield, the volatile solids contents and the biochemical methane potential (BMP) were measured to calculate the biomethane yield per hectare (average = 7266 m^3 ha^{-1}). The most influential factor controlling the biomethane yield was the cropping environment. The biomass yield had more impact than the anaerobic digestibility. Nevertheless, the anaerobic digestibility of maize silages was negatively affected by high VS content in mature maize. Late maturing maize varieties produced high biomass yield with high digestibility resulting in high biomethane yield per hectare. The BMP was predicted with good accuracy using solely the VS content.

1. Introduction

Providing sustainable solutions to meet the world energy demand is a key challenge for the 21st century (Advisory group on energy and climate change, 2010). Several strategies are considered but all scenarios investigated include the increase of renewable energy in the energy mix. The European Commission intends to achieve at least 55% of renewable energy in gross final energy consumption in 2050 (European Commission, 2011). In Luxembourg and Belgium, the target is to reach 11% and 13% respectively, of renewable energy in the gross final energy consumption by 2020 (European Parliament and Council, 2009).

Renewable energies mainly include solar energy (thermic and photovoltaic), wind power, hydroelectricity, geothermal energy and biomass. Local, easy-to-run and multipurpose solutions should be investigated among these various opportunities. Anaerobic digestion appears in this perspective to be a convenient and suitable solution because this biotechnology provides multiple answers to meet energy needs (heat, electricity and fuel), waste management and recycling, and fertilizer requirement for agriculture (Ward et al., 2008).

Anaerobic digestion, also known as biomethanation, is a bioprocess that involves microorganisms which convert organic material into biogas, under anaerobic conditions (Duncan and Nigel, 2003). The produced biogas is mainly composed of methane and carbon dioxide. It can be used in combined heat and power plants to produce both electricity injected in the grid, and heat for local needs (Doušková et al., 2010). More recently, the upgrading of biogas to biomethane allows the injection of the later into the gas grid (Ryckebosch et al., 2011).

One advantage of anaerobic digestion is that a wide variety of organic substrates can be used to produce energy (Weiland, 2009). The feedstock of an anaerobic digester can be liquid or solid materials and residues, originating mainly from food and feed

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http://dx.doi.org/10.1016/j.biortech.2013.11.081

industries, agriculture or households. The amount and the composition of the produced biogas vary from one substrate to another. Anaerobic biogasification potential (ABP) and biochemical methane potential (BMP) assess the volume of, respectively, biogas and biomethane produced through anaerobic digestion, per unit of feedstock matter (mL g^{-1}) (Schievano et al., 2008). Various energy crops have been investigated for the purpose of biomethane production (Amon et al., 2007a). Among these, maize is the most commonly used crop for biogas production since it offers high crop yield, agricultural practices related to its cropping are well known, and maize varieties are available to fit most climatic conditions encountered around the world (Amon et al., 2007b; Poeschl et al., 2010).

For decades, plant breeders and farmers have assessed and improved the nutritive value of maize, either for feed or food. Nowadays, efforts are also made to improve maize biomethane yield per unit of cropped area, calculated according to the following equation:

$$\text{Biomethane yield } (m^3\ CH_4.ha^{-1}) = \text{BMP } (m^3\ CH_4.t^{-1}) * \text{biomass yield } (t.ha^{-1}) \quad (1)$$

To optimise the biomethane yield from maize, factors that influence both parameters, BMP and biomass yield, should therefore be identified and managed. Many factors such as the soil and weather conditions during cropping, the plant variety and the cultural practices used, strongly influence maize characteristics at harvest. These cropping factors influence both the composition and the production yield of the maize biomass. The biomass composition (water content and organic composition) then influence the ABP and the methane content in the biogas (%CH_4) leading to various BMP values (Oslaj et al., 2010; Schittenhelm, 2008; Gao et al., 2012; Bauer et al., 2009; Vervaeren et al., 2010).

Eq. (1) used to calculate the biomethane yield can be further broken down following in Eq. (2):

$$\text{Biomethane yield} = (\%CH_4 * ABP) * (VS * \text{biomass yield}) \quad (2)$$

where %CH_4 is the methane content in the biogas and VS is the volatile solids content of the biomass.

The present study focuses on the respective influence of %CH_4, ABP, VS and the biomass yield on the biomethane yield of maize. For this purpose, various maize varieties were cropped in various environments and harvested at different dates to obtain a wide range of values of biomethane yields in the final dataset.

The aim of this study was first to assess the influence of the various factors on the biomethane yield, in order to identify the cropping parameters and strategies that can be used to optimise the energy production from maize through anaerobic digestion. A second aim was to determine a model to predict maize silage BMP from fast and easy-to-run experimental measurements.

2. Methods

2.1. Maize production and analytical measurements

In 2007, 2008 and 2009, maize was grown by the Administration des Services Techniques de l'Agriculture (ASTA) in Kehlen, Marnach, Nagem, Overpelt, Pletschterhof and Useldange in Luxembourg, and by the Centre Indépendant de Promotion Fourragère (CIPF) in Corroy-le-Grand, Perwez and Roux-Miroir in Belgium. More specifically, block design trials and randomised complete block design trials were carried out in 9 and 4 environments (field $\times$ year) respectively to produce variability in the harvested samples. Block design trials included a total of 25 different varieties from various seed companies and 1, 2, 3 or 4 field replicates. For all the maize varieties studied, the FAO maturity classes ranged from 220 to 340 except for the variety Peru, which has a maturity class of 900. Randomized complete block design trials focused on 4 varieties: Atletico (FAO-280), Lucatoni (FAO-340), Piazza (FAO-240), and Seiddi (FAO-300). For each of these four varieties, 12 (or 16 for Corroy-le-Grand in 2009) replication plots were cropped in order to harvest 4 field replicates at 3 different dates (4 dates for Corroy-le-Grand in 2009).

The wet weight (WW) biomass yield ($t_{WW}.ha^{-1}$) was measured for each sample at the time of harvest, with a mechanical harvester (Haldrup, Inotech Engineering GmBH, Germany). After harvest, the chopped biomass (particle size around 1–2 cm) was directly ensiled in sealed plastic bags and stored under vacuum at room temperature until laboratory analyses were carried out. The fermentation gas produced during the ensiling process was removed by opening the bag, packing the biomass and resealing the bag under vacuum. In general, this procedure had to be repeated twice to reach a stable ensiled sample. When several harvest dates were investigated, the first date was chosen to correspond to the targeted dry weight content of 25% relative to the wet weight (WW) for the maize crop and the following harvests were realised at one or two weeks intervals.

Total solid (TS) and volatile solid (VS) contents were quantified in the maize silages after 24 h drying in an oven at 105 °C, and after 6 h in a furnace at 550 °C, respectively.

2.2. ABP and BMP measurements

Biogas and biomethane productions were measured following the recommendations of the VDI 4630 standard (Verein Deutscher Ingenieure, 2006). The parameters related to the ABP and BMP assays are summarised in Table 2, as recommended by Raposo et al. (2011 and 2012). Each maize sample was analysed in triplicates. Anaerobic digesters consisted in 2L heavy-duty polypropylene bottles (Nalgene 2126-2000, Thermo Scientific) placed in water baths and kept at constant mesophilic temperature (37 °C). The lid of the digester was equipped with fittings (Nalgene 2162-0531, Thermo Scientific) and connected to a 10L gas-bag (Tecobag, Tesseraux Spezialverpackungen GnbH) through tubing (Tygon R-3603, Saint-Gobain). The digester lids and the venting port of the gas bags were rendered gas-tight using bi-component DP405 adhesive glue (3M Scotch-Weld, USA).

Each digester was filled with the inoculum and a maize sample at the start-up of the experiment. The inoculum was collected from a mesophilic anaerobic digester from the municipal wastewater treatment plant of Schifflange (SIVEC, Luxembourg). The inoculum was incubated at 37 °C for four days for exhaustion of the nutrients present in the inoculum and consequently to decrease the endogenous biogas production of the inoculum. Microorganisms in this inoculum face a wide variety of different organic matters contained in wastewater. This diversity is fully suitable and recommended for anaerobic digestion trials in the laboratory (Raposo et al., 2011). The precise amount of inoculum and maize were recorded at the time of filling the digester.

The produced biogas was measured on a daily basis during the first week, then once a week for the rest of the anaerobic digestion. It was quantified with a wet drum-type gasmeter (TG05 wet-type, Ritter). The biogas composition was analysed to determine the content (expressed as a volume percentage) in methane and carbon dioxide with specific infrared sensors (Dynament, UK). The gas volumes were normalised (273 K, 1013 hPa) according to the temperature and pressure conditions. Batches (triplicates) involving the inoculum alone and the inoculum fed with microcrystalline cellulose as a control substrate (Sigma–Aldrich) were carried out in parallel to the anaerobic digestion of maize samples in order to measure the biogas and biomethane volumes produced by the inoculum solely and to check the inoculum activity. At each gas