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Anaerobic digestion of annual and multi-annual biomass crops

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ABSTRACT

This paper addresses the anaerobic digestion (AD) of seven biomass crops: three multi-annual species, *Arundo donax* (Arundo), *Panicum virgatum* (Switchgrass) and Sorghum Silk; three sorghum hybrids (B 133, Sucros 506 and Trudan Headless); one Maize hybrid as reference crop for AD. Dry biomass yield (DBY) was assessed in a field plot experiment in Northern Italy, and biomass samples were subjected to chemical analysis (volatile solids (VS), raw proteins and lipids, soluble sugars, starch, structural carbohydrates and lignin). Thereafter, an AD assay was carried out in batch mode with 4 g VS l^{-1} at 35 °C for 58 days, during which time potential methane yield (ml CH_4 g^{-1} VS) was determined. Gross energy yield (GE = DBY × VS × potential CH_4 yield × methane lower heating value) and cumulative energy demand (CED) led to net energy yield (NE = GE − CED) and energy efficiency (EE = GE/CED) as indicators of crop suitability for AD. Arundo, B 133 and Sucros 506 achieved ±10% DBY compared to Maize (this latter, 27.8 Mg ha^{-1}). Conversely, Maize prevailed in terms of potential methane yield (316 ml CH_4 g^{-1} VS). Among the six alternative crops, Arundo and Switchgrass exhibited the lowest values (average, 216 ml CH_4 g^{-1} VS), associated with low kinetics of degradation. This is consistent with the two crops' characteristics: low easily degradable fractions as lipids, soluble sugars and starch; high structural carbohydrates and lignin. Maize achieved a top level also in GE (286 GJ ha^{-1}, corresponding to ca. 8400 N m^3 CH_4 ha^{-1}) and NE (248 GJ ha^{-1}). B 133 and Sucros 506 were undifferentiated from Maize in NE (their average, 215 GJ ha^{-1}), whereas Trudan Headless and the three multi-annual species were outperformed (average NE, 149 GJ ha^{-1}). Conversely, Maize ranked worst in EE (7.4 GJ GJ^{-1}) while sorghum B 133 and Arundo attained top levels (average, 12.1 GJ GJ^{-1}), thanks to a good GE associated with a modest CED in B 133; to a very low CED in Arundo. It is concluded that alternative crops to maize deserve attention in view of a low need of external inputs but necessitate improvements in biodegradability (harvest stage and biomass pre-treatments) to bridge the gap in the amount of net energy produced.

1. Introduction

Policy makers all over the world are showing increasing concern for the growth in energy consumption, while promoting the conversion from a fossil fuel-based to a bio-based economy (Richardson, 2012). The agricultural sector participates in this effort, supplying biomass to be transformed into various forms of energy. Among them, anaerobic digestion (AD) can successfully be used for biogas and, ultimately, methane production. Biofuels including methane represent an important strategy to reduce greenhouse gas (GHG) emissions by substituting fossil fuels, thus complying with the Kyoto Protocol and subsequent legislation such as EU Directive 2009/28/EC.

Within the European Union, biogas production increased sixfold from 1990s to 2005 (Murphy et al., 2011) and reached 10.9 million tonnes of oil equivalent in 2010 (EBA, 2012). Biosolids of agro-industrial origin (e.g., crop, market and transformation residues; animal manure and slurries) are valuable feedstocks for AD in view of methane production. Beside them, dedicated biomass crops are increasingly being used, resulting in potential competition for available land with food crops (Murphy et al., 2011).

Abbreviations: AD, anaerobic digestion; AIL, acid insoluble lignin; CED, cumulative energy demand; DBY, dry biomass yield; EE, energy efficiency; FBY, fresh biomass yield; GE, gross energy yield; GHG, greenhouse gas; NE, net energy yield; SNK, Student–Newman–Keuls; TKN, total Kjeldahl nitrogen; TOC, total organic carbon; TS, total solids; VS, volatile solids.

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In the scientific literature, several studies address AD with biomass crops. Beside maize that is the reference feedstock for AD experiments, several sorghum (*Sorghum bicolor*) hybrids including fibre, sweet and forage genotypes have been tested in view of methane production (Jerger et al., 1987; Chynoweth et al., 1993; Bauer et al., 2010; Mahmood and Honermeier, 2012; Mahmood et al., 2013; Sambusiti et al., 2013). However, only some works combine specific CH_4 yield and crop biomass yield, assessing CH_4 yield per hectare (Kralik et al., 2008; Bauer et al., 2010; Kerckhoffs et al., 2011; Mahmood and Honermeier, 2012; Monteiro et al., 2012; Mahmood et al., 2013). In multi-annual biomass species, Switchgrass (*Panicum virgatum*) has recently been investigated in view of CH_4 production (Massé et al., 2011; Frigon et al., 2012). Lastly, Arundo (*Arundo donax*) is the subject of the most recent AD experiments (Di Girolamo et al., 2013; Ragaglini et al., 2014). Despite the abundance of studies on the topic, the substitution of maize that requires high cropping inputs and the best cropland with less demanding species is rarely echoed in the literature on biogas (Kralik et al., 2008; Bauer et al., 2010; Kerckhoffs et al., 2011; Mahmood et al., 2013).

Bio-energies that are expected to supply a significant share of future energy demand will require better integrated policies to prevent adverse impacts from land competition. In this respect, a recent report by the Netherlands Environmental Assessment Agency forecasts a drastic reduction of the energy deriving from biomass, due to the lack of surface available for sustainable biomass crops (PBL, 2012). It is generally acknowledged that energy crops should not be cultivated in previous forestland, pastures and virgin soils, because converting these lands to energy crops enhances GHG emissions, in turn accelerating climate change (Campbell et al., 2008). Moreover, the use of good agricultural lands for energy crops is held responsible of increases in food price volatility and the associated risks for food security (FAO, 2008). To overcome these drawbacks, the use of marginal land is considered a sustainable practice for the cultivation of energy crops (PBL, 2012; Campbell et al., 2008). Likewise, biomass crops necessitating low amounts of subsidiary energy (fertilizers, fuels, etc.) may be a more sustainable source of energy in areas where surplus land is available, compared to maize. Especially multi-annual species are proposed as alternatives to maize involving much lower crop inputs (Lewandowski et al., 2003; Heaton et al., 2004; Angelini et al., 2005; Mantineo et al., 2009; Massé et al., 2011).

In this light, the computation of the energy flows involved in the cropping phase, i.e. the amount of energy produced in exchange for that of subsidiary energy consumed to obtain crop biomass, is considered an important tool to evaluate crop suitability in view of anaerobic digestion. However, the appraisal of energy flows in biomass crops for methane production is rarely echoed in the literature, in contrast to biomass crops for combined heat and power generation (Angelini et al., 2005; Mantineo et al., 2009).

Given these premises, we assessed biomass yield in field plots and specific CH_4 yield in an AD assay under batch conditions, comparing six promising biomass crops with maize. Thereafter, the appraisal of the energy flows associated with the cultivation phase allowed us to calculate net energy yield and energy efficiency, the two traits expressing ultimate crop performance in view of anaerobic digestion. The six plants potentially alternative to maize were three hybrids of biomass sorghum and three multi-annual herbaceous species. They were selected for a high potential of biomass production and low need of external inputs. The aim of this work was to assess if a more efficient production of methane could be achieved, replacing maize that is the principal feedstock in the diet of many biogas plants at present.

2. Materials and methods

2.1. Crop management

In the year 2010 seven biomass crops were grown at the experimental farm, University of Bologna, in Cadriano (44°33′ N, 11°21′ E, 32 m above sea level), Italy. The experimental farm features deep alluvial soils with a clayey–loamy texture (average sand, silt and clay, 340, 360 and 300 g kg^{-1}, respectively), under a warm-temperate climate (700 mm, 8.3 and 18.3 °C as average yearly precipitation, minimum and maximum temperature, respectively). Three of the seven crops were multi-annual species: *Arundo donax* L. (Arundo, also known as Giant reed); *Panicum virgatum* L. (Switchgrass) cv. Alamo; the inter-specific hybrid *Sorghum arundinaceum* Stapf × (*Sorghum halepense* Pers. × *Sorghum roxburghii* Stapf), known as Sorghum Silk (S. Silk). The four annual crops included: three sorghum [*Sorghum bicolor* (L.) Moench] genotypes, namely a fibre (Biomass 133; B 133), sweet (Sucros 506; S 506) and forage hybrid (Trudan Headless; Trudan H.); one maize hybrid (Klips, FAO 700 maturity). Maize is the dedicated crop most widely used as feedstock for anaerobic digestion in Italy (Fabbri et al., 2011) as well as in Europe (Herrmann and Rath, 2012). Among multi-annual species, Arundo has proved a promising crop for energy uses in South European areas (Lewandowski et al., 2003); Switchgrass is especially valued in the US, having also proved adapted to the Po Valley in Italy (Monti et al., 2011); Sorghum Silk should combine the good characteristics of forage sorghum (thin stemmed “Sudan” genotypes) with the multi-annual habit, having already staged high biomass potential under Mediterranean conditions (Corleto et al., 2009).

Arundo and Switchgrass had been established in 2002 and were still in full production as of 2010; Maize was seeded on April 1; S. Silk on April 28; the three sorghum hybrids on May 18. All the crops were grown with four replicates in plots of 90 m^2 (multi-annual species) and 27 m^2 (annual species). Weed control was performed through hoeing integrated by hand weeding. In all the crops except Maize, fertilization consisted of 120 kg of N ha^{-1} as urea, incorporated during the early development stage. In Maize 250 kg of N ha^{-1} were split applied as urea, to ensure the achievement of full yield potential of this highly demanding plant. 200 kg of P_2O_5 ha^{-1} had been supplied as triple superphosphate to Arundo and Switchgrass prior to planting in 2002; 92 kg of P_2O_5 ha^{-1} to S. Silk, Trudan H., B 133, S 506 and Maize before seeding in 2010. No K fertilizer was applied, given the good soil status of this specific nutrient. All the crops except Maize were grown in rain fed conditions on a soil with a good water capacity in a year (2010) showing a normal weather pattern; Maize was irrigated with a total 168 mm in the summertime. Both nitrogen dose and irrigation volume represent normal cropping inputs for maize in Northern Italy. No chemical treatment against pests or diseases was needed in any of the seven crops. Maize was harvested as whole plant at hard dough stage on August 5; the three multi-annual species on October 5 at initial senescence; the three sorghum hybrids on October 18 at hard dough stage. Fresh biomass yield (FBY), total solids (TS; 48 h at 105 °C) and dry biomass yield (DBY) per hectare were assessed. Biomass samples were oven-dried (60 °C) and ground at 2 mm for chemical analysis and the anaerobic digestion assay.

2.2. Chemical characteristics

On dried and ground samples of the seven biomass crops, TS (48 h at 105 °C) and VS (4 h at 550 °C) were singly determined in the four field replicates. Thereafter, on average samples the following analyses were carried out in triplicates: total organic carbon (TOC) by the dichromate oxidation method; total Kjeldahl nitrogen (TKN) through titration with 0.1 M H_2SO_4 after