Bioresource Technology 149 (2013) 425–431

Contents lists available at ScienceDirect

Bioresource Technology

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

The potential for biomethane from grass and slurry to satisfy renewable energy targets

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HIGHLIGHTS

- A biomethane potential (BMP) assessment of grass silage yielded 107 m^3 CH_4 t^{-1}.
- Mono-digestion of grass silage is problematic due to mineral deficiency.
- Co-digestion of slurry and grass led to reduced methane yields of between 4% and 11%.
- 1.1% of grasslands in Ireland can generate 10% renewable energy in transport.
- 170 digesters treating 10,000 t a^{-1} of grass and 40,000 t a^{-1} of slurry are required.

ARTICLE INFO

Article history:
Received 8 July 2013
Received in revised form 17 September 2013
Accepted 21 September 2013
Available online 29 September 2013

Keywords:
Gaseous biofuel
Grass silage
Slurry
Biogas
BMP

ABSTRACT

A biomethane potential (BMP) assessment of grass silage yielded 107 m^3 CH_4 t^{-1}. Long term mono-digestion of grass silage can suffer due to a deficiency in essential nutrients; this may be overcome by co-digesting with slurry. Mono-digestion of slurry achieved a low yield of 16 m^3 CH_4 t^{-1}. BMP assessments at a range of co-digestion ratios indicated methane yields were between 4% and 11% lower than the values calculated from mono-digestion. This paper suggests that co-digestion of the majority of slurry produced from dairy cows in Ireland with grass silage quantities equivalent to 1.1% of grassland on a 50:50 volatile solids basis would generate over 10% renewable energy supply in transport (RES-T). The industry proposed would equate to 170 digesters each treating 10,000 t a^{-1} of grass silage and 40,000 t a^{-1} of slurry from dairy cows.

1. Introduction

1.1. First- and second-generation biofuels

First-generation biofuels are derived from food crops and include ethanol from wheat, and biodiesel from rapeseed oil. Second-generation biofuels are based on non-edible crops such as perennial grass and agricultural residues. The Renewable Energy Directive requires that 10% of all energy in transport must be renewable by 2020 (EC, 2009). The directive states that biofuels must emit a minimum of 60% less greenhouse gases (GHGs) than the fossil fuels they replace. Both wheat ethanol and rapeseed biodiesel struggle to satisfy this reduction with reference values of 32% and 45% (EC, 2009), respectively. Furthermore, as of October 2012, new EU proposals may limit the use of food-based biofuels to 5% of energy in transport in order to stimulate the application of second-generation biofuels (EC, 2012). The renewable energy supply in transport (RES-T) target for Ireland is 10% by 2020. Ireland's forecasted energy in transport in 2020 is 188 PJ (Murphy and Thamsiriroj, 2011). Second-generation biofuels derived from lignocellulosic materials (such as grass silage) and residues (including agricultural slurries) shall be considered at 2 and 4 times their energy content (EC, 2012), respectively, when considering compliance with renewable energy targets.

1.2. Resource of grass and slurry in Ireland

Ireland has approximately 4.19 million hectares of agricultural land of which 92% is under grass (McEniry et al., 2013). Annual yields of grass in Ireland are potentially high in a European context – values of ca. 12 to 16 t dry solids (DS) per hectare may be achieved (O'Donovan et al., 2011). The requirement from grassland

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http://dx.doi.org/10.1016/j.biortech.2013.09.094

in Ireland is set to increase. Food Harvest 2020 is a government initiative to increase exports, particularly in the beef and dairy industries. A targeted increase of 50% in milk production and 20% in beef has been assigned (DAFF, 2010).

McEniry et al. (2013) estimated that using current production practices and excluding Food Harvest 2020, an annual average of approximately 1.7 million t DS of grass is available in excess of current livestock requirements. This would equate to silage produced from 155,000 ha or 3.9% of grassland in Ireland assuming an average yield of 11 t DS ha^{-1} a^{-1} (Smyth et al., 2009), that would potentially be available for anaerobic digestion.

If nitrogen fertiliser was applied to the limit permitted by the EU Nitrates Directive and if the grazed grass utilisation rate of cattle was increased from 0.60 to 0.80 kg DS ingested per kg DS grown, the excess grass available could be increased to 12.2 million t DS a^{-1} (McEniry et al., 2013), even when factoring for Food Harvest 2020. This quantity of silage is equivalent to that which could be produced on 1.1 million ha or 28% of Irish grassland – a significantly higher quantity of material available for anaerobic digestion.

According to the Central Statistics Office (2010) there were 1,070,755 dairy cows in Ireland. A single dairy cow produces 0.33 m^3 of slurry per week (DAFF, 1994). Farmers are obliged to store slurry for ca. 20 weeks over the winter period. This would generate 7.07 M t DS a^{-1}. Slurry is typically applied to land in its raw form. The majority of slurry systems do not include for straw and are primarily comprised of faeces and urine with a dry solids content of 6–10% of which 75–85% would be volatile solid. There is currently no significant biogas industry in Ireland; at most there are 4 small farm scale digesters.

1.3. Grass biomethane

An advantage of grass silage for biomethane is the familiarity of the crop with farmers and the avoidance of arable land use (Smyth et al., 2009). Grass is a perennial crop that negates the need for tillage. When including for carbon sequestration in pasture land, grass biomethane has been shown to effect a 75% reduction in GHG emissions compared to the full life cycle analysis of diesel when used as a transport fuel (Korres et al., 2010). Grass is now utilised in over 50% of digesters operating in Germany and Austria (Prochnow et al., 2009), although very rarely in a mono-digestion process. Although timothy, cocksfoot and tall fescue are sometimes used, perennial ryegrass is the principal species used in many countries (Smyth et al., 2009; McEniry and O'Kiely, 2013). The digestion of grass silage has been widely reported in literature (Prochnow et al., 2005; Lehtomäki et al., 2008b; Seppälä et al., 2009). Various digestion systems have been examined for maximising biomethane output from grass silage; these include batch leach-bed reactors (LBR) (Jagadabhi et al., 2010), two-phase continuously stirred tank reactors (CSTR) (Thamsiriroj and Murphy, 2010) and sequencing LBRs coupled with an upflow anaerobic sludge blanket (SLBR–UASB) (Lehtomäki et al., 2008a; Nizami et al., 2011). The yields reported for mono-digestion of grass are quite varied, ranging from 200 to 450 L CH_4 kg^{-1} VS (Pakarinen et al., 2008; Koch et al., 2009; Nizami and Murphy, 2011). Grass silage has, however, been reported to be deficient in some essential trace elements for long-term mono-digestion (Thamsiriroj et al., 2012).

1.4. Co-digestion of grass silage with slurry

Co-digestion of grass silage and slurry has been somewhat less extensively covered in literature (Kaparaju et al., 2002; Xie et al., 2011, 2012). Slurry produces much lower yields of methane than grass in mono-digestion. Values range from 136 to 239 L CH_4 kg^{-1} VS (Allen et al., 2013). This is due to the majority of energy rich substrates having already been eliminated through the digestive tract of the animal (Weiland, 2003; Lehtomäki et al., 2007). Therefore co-digestion with an energy crop is seen as the preferred alternative as it increases the biomethane yield. The specific methane yields from co-digestion of grass silage and slurry are once again quite varied with values reported from 140 to 300 L CH_4 kg^{-1} VS (Mahnert et al., 2005; Lehtomäki et al., 2007; Jagadabhi et al., 2008).

There is limited literature that thoroughly assesses the optimum ratio of co-digestion of grass silage and dairy slurry, and little uniformity can be determined from the results. In an Irish context, Xie et al. (2011) suggested an optimal co-digestion ratio of 1:1 for concentrated pig manure and grass silage. However the substrates used were very different to those examined in this study (concentrated pig manure versus raw dairy slurry, clamp or pit silage versus baled silage).

1.5. Objectives

(1) Calculate the specific methane potential (L CH_4 kg^{-1} VS) for grass silage, dairy slurry and various ratios of co-digestion of grass silage and slurry using biomethane potential (BMP) assays.
(2) Obtain the first- and second-order kinetics of the different substrates investigated in the BMP assays.
(3) Estimate the potential bioresource in Ireland of second-generation gaseous biofuel associated with a matrix of scenarios based on quantities of potential excess grassland as established by McEniry et al. (2013).

2. Methods

2.1. Inoculum

The inoculum used for the experiment was sourced from two existing digesters in Ireland. The first digester operated on food waste while the second operated on a mix of poultry and cattle manure. An equal share of digestate from both digesters was used as the inoculum. The DS and VS of the inoculum are outlined in Table 1. The inoculum for the BMP was acclimatised by heating at 40 °C for 3 days prior to experimental start-up. Cellulose powder (Sigma Aldrich, CAS Number: 9004-34-6) was used as a standard to assess the efficiency of the inoculum.

2.2. Substrates

The grass silage was made from the first cut of a perennial ryegrass (*Lolium perenne*) sward that was harvested at an early maturity stage (low lignocellulosic content) and field wilted for 24 h prior to being baled and wrapped in plastic film. The bales were ensiled for 5 weeks and subsequently assembled into smaller 25 kg bales that were also wrapped in plastic film. These bales were stored anaerobically at room temperature until use. The silage was cut to a particle size of approximately 1–3 cm using a mincer (Buffalo Heavy Duty Mincer, Code: ECD400, 250 kg/h).

Fresh slurry was collected from a dairy farm in the month prior to start-up. The farm consisted of a dairy herd of 180 cows. The

Table 1
Characteristics of substrates and inoculum.

Substrate/inoculum	DS (g/kg)	VS (g/kg)	VS/DS (%)	C:N
Grass silage	292.7 ± 3.4	268.4 ± 2.8	91.7	26:1
Slurry	87.5 ± 2.1	66.9 ± 1.8	76.5	19:1
Inoculum	30.0	18.9	63.3	–