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Environmental performance of manure co-digestion with natural and cultivated grass – A consequential life cycle assessment

Sirli Pehme [a, *], Eve Veromann [a], Lorie Hamelin [b]

[a] Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, Kreutzwaldi 5, 51014 Tartu, Estonia
[b] Institute of Soil Science and Plant Cultivation, Department of Bioeconomy and System Analysis, Czartoryskich 8 Str., 24-100 Pulawy, Poland

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ABSTRACT

The aim of this study was to assess the environmental consequences of increased manure-based biogas production relying on grass as a co-substrate (from both unused and cultivated boreal grasslands). Through consequential life cycle assessment, three biogas scenarios were investigated: i) mono-digestion of dairy cow manure, ii) manure co-digestion with reed canary grass cultivated specifically for bioenergy production and iii) manure co-digestion with unused grass from semi-natural grasslands. A full balance of biogenic carbon was considered including soil carbon changes and indirect land use changes. Mono-digestion of manure showed a potential for an improved environmental performance for global warming and phosphorus-eutrophication, in comparison to conventional manure management, but yielded more than 2 times lower energy production compared to co-digestion. Co-digestion with grass from semi-natural grasslands showed an even 41% better potential to reduce global warming and resulted 2 times lower phosphorus-eutrophication compared to mono-digestion, provided that the grass would have otherwise been left un-harvested on land. Because of the indirect land use change associated with an additional demand for land, and the need for additional fertilizers, co-digestion with cultivated grass showed a 26% worse global warming, 2 times higher acidification, 4 times higher nitrogen-eutrophication and 36% worse phosphorus-eutrophication performance compared to natural grass. Results highlighted that grass co-digestion with manure does lead to an enhanced performance of the global warming and phosphorus-induced eutrophication impacts. This conclusion, however, did not apply for nitrogen-related impacts categories (acidification and nitrogen-induced eutrophication). Results were strongly affected by the choice of the indirect land use change factor for modelling and the energy source displaced. In a nutshell, this study highlighted the environmental relevance of considering energy grass and in particular semi-natural grasslands for the production of manure-based biogas, though it showed the necessity to improve the nitrogen balance of the supply chain of these scenarios, and to carefully consider the counterfactual use of the grass stream.

1. Introduction

Societies are looking for solutions to produce renewable energy in a sustainable way. In line with this, the European Union (EU) has set the goal to reach 20% of total energy consumption based on renewable resources by 2020 (European Union, 2009). Manure is one of the available resources with great potential for energy production through anaerobic digestion, and doing so triggers significant reduction in the environmental impacts of manure management (Agostini et al., 2015; De Vries et al., 2012; Hamelin et al., 2014, 2011). In the EU, manure-biogas production is currently far below its full potential (Birkmose et al., 2007). However, its importance is likely to increase in the near future, in the light of a drastic increase of biogas production that is planned in the EU (Beurskens and Hekkenberg, 2011).

Current anaerobic digestion facilities typically use slurry manure (i.e. less than 10% dry matter; Pain and Menzi (2011)) and due to slurry's low carbon (C) content and carbon-to-nitrogen ratio, addition of C-rich co-substrates is a usual practice (Hamelin et al., 2011). Grass and manure have been considered as key substrates

* Corresponding author.
E-mail addresses: sirli.pehme@emu.ee (S. Pehme), eve.veromann@emu.ee (E. Veromann), lhamelin@iung.pulawy.pl (L. Hamelin).

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for co-digestion with manure in Estonia due to their high availability and methane potential (Luna Del Risco et al., 2011).

This study focusses on the use of grass for manure-based anaerobic digestion. Two grass feedstocks are studied: reed canary grass as one of the dedicated high-yielding energy grasses suggested for the Nordic climate (Kandel et al., 2013; Kukk et al., 2011; Møller et al., 2008) and grass from semi-natural grasslands as a currently clearly underused resource with considerable biogas potential (Melts et al., 2013). Semi-natural grasslands cover ca. 130,000 ha of land in Estonia (Kukk and Sammul, 2006) and are mostly located on floodplain meadows (Heinsoo et al., 2010). The areas are currently partly managed, i.e. the grass is generally cut once per year, but due to its low forage value it is still very often just left on the field. Thus Estonia, like many other countries, is seeking to find appropriate uses for the biomass from those areas (Melts et al., 2013). Continuing to extensively manage these semi-natural grasslands is necessary to maintain the high biodiversity value of those areas (Heinsoo et al., 2010). In this perspective, using the grass for bioenergy production could represent a sustainable opportunity for supplying both renewable energy as well as essential ecosystem services (e.g. erosion regulation, soil carbon sequestration). On the other hand, cultivated grasslands may be seen as a more reliable feedstock to supply a clean and uniform biomass stream to biogas plants. Various studies have highlighted high-yielding energy grasses as one of the most promising feedstock for biorefineries in Europe (Gerin et al., 2008; Korres et al., 2010; Smyth et al., 2009).

Using substrates for energy production takes them away from their initial use, and this change often has considerable environmental implications, whether positive or negative (De Vries et al., 2012; Hamelin et al., 2014; Pehme and Veromann, 2015; Styles et al., 2014; Tonini et al., 2016). Previous life cycle assessments of biogas production have studied the mono-digestion of manure (e.g. Cherubini et al., 2015; De Vries et al., 2012; Hamelin et al., 2011; Lijó et al., 2014b), manure co-digestion with dedicated energy crops (Agostini et al., 2015; De Vries et al., 2012; Hamelin et al., 2014; Lijó et al., 2014a; Pöschl et al., 2010; Styles et al., 2014; Whiting and Azapagic, 2014; Tonini et al., 2012), with by-products from agriculture, food and feed industry (Croxatto Vega et al., 2014; De Vries et al., 2012; Fierro et al., 2014; Hamelin et al., 2014; Pöschl et al., 2010; Tonini et al., 2016) and with wastes/residues (Cimpan et al., 2015; Croxatto Vega et al., 2014; De Vries et al., 2012; Fierro et al., 2014; Hamelin et al., 2014; Huopana et al., 2013; Pöschl et al., 2010; Styles et al., 2014; Whiting and Azapagic, 2014). Those studies have highlighted the substantial environmental benefits of anaerobic digestion of manure instead of traditional manure management, and the need to focus on co-substrates not competing with food or feed crops for land use. Until now, studies investigating residual grass as a co-substrate for manure biogas focussed on roadside grass (e.g. De Vries et al., 2012) or grass from garden waste (e.g. Hamelin et al., 2014). Semi-natural grass has been included only in a few studies, but these were aimed more at developing a quantification model for land use change impacts (Tonini et al., 2015) or greenhouse gas (GHG) emission factors for a variety of bioenergy pathways (Tonini et al., 2016).

In an endeavour to bridge this gap, the aim of the present study was to assess the environmental consequences of increased manure-based biogas production relying on grass as a key co-substrate. A consequential life cycle assessment (LCA) was performed to quantify the environmental impacts of three anaerobic digestion scenarios: i) mono-digestion of dairy cow manure; ii) manure co-digestion with cultivated energy grass (reed canary grass); and iii) manure co-digestion with residual grass from semi-natural grasslands (alluvial meadows).

2. Materials and methods

2.1. LCA approach

This study was performed through consequential LCA (Finnveden et al., 2009) as the most suitable approach to support decision making processes (Weidema, 2003). The functional unit (FU) to which all input and output flows were normalized was the management of one (wet) tonne (t) of dairy cow manure ex-animal. The prefix “ex” is, throughout this manuscript, referring to the composition of each substrate immediately after leaving the stage following the prefix. Manure ex-animal thus refers to the manure as freshly excreted by the animals. The geographical scope of the study was Estonia (Nordic conditions); foreground data (e.g. biomass yield, fertilizer application, technologies and regulations) were thus based the Estonian context. Impacts associated with capital goods in the foreground processes were excluded due to lack of data. Background data (e.g. imported fertilizers, electricity) were included in the model by combining the Ecoinvent v.3.2 consequential database (Weidema et al., 2013) and relevant scientific literature. The impact assessment methods used for this study were the EDIP2003 methodology (Hauschild and Potting, 2005) for the acidification and eutrophication impacts (distinguishing for nitrogen (N) and phosphorus (P) as the limiting nutrient) and the IPCC 2013 for assessing the global warming potential (GWP, 100 years horizon time; (Intergovernmental Panel on Climate Change, 2013)). These impact categories relate especially with the carbon, nitrogen and phosphorus flows, and are thus seen as the most relevant for the agricultural systems studied herein. The assessment was facilitated by the LCA software SimaPro 8.2.0.

2.2. System boundaries

Three different biogas scenarios were considered in this study: mono-digestion of dairy cow manure, manure co-digestion with reed canary grass and co-digestion with grass from semi-natural areas. All processes affected by the demand for manure-based biogas were included in the LCA model, as illustrated in Fig. 1 (example for the reed canary grass scenario). Consequential LCA is based on market information to identify which activities are affected by a change. In this study each output of the system (including co-products) is assumed to substitute marginal products (full elasticity of supply i.e. 1:1 substitution approach). The processes and technologies to include in a consequential life cycle study are the processes and technologies actually affected by the studied product substitution (Weidema, 2003). In a long term perspective it can be assumed that fossil resources will be phased out by renewables in order to achieve the political CO_2 reduction targets. In this perspective the energy sources with the highest emissions are expected to be the fuels reacting to increased electricity production from waste and biomass (Tonini et al., 2013).

Each biogas scenario was assumed to avoid the conventional management of dairy cow manure (i.e. reference scenario), which represents the current situation (i.e. counterfactual) where manure does not undergo any treatment process. Reference manure management has three main stages: slurry is stored in-house, then pumped to an outdoor concrete slurry tank (natural crust cover) from which it is finally applied to fields when suitable. Further details on the processes and emission flows considered for the reference manure management in Estonia are available in Hamelin et al. (2013). The composition of substrates, emission data, mass balances and process flows for all biogas scenarios are described in the Supplementary material.

In each biogas scenario, manure is collected from the in-house storage (manure ex-housing) and transferred to the anaerobic