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Environmental consequences of different carbon alternatives for increased manure-based biogas

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HIGHLIGHTS

- Land use change emissions from energy crops were included.
- Soil carbon changes were modeled and included.
- Source-segregated manure was the co-substrate yielding the greatest benefits.
- Energy crop was the co-substrate displaying the worst environmental performance.
- Straw and biowastes should be prioritized for co-digestion with manure.

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ABSTRACT

Manure-biogas is a renewable energy resource rather untapped in Europe in comparison to its full potential. Given the current and emerging renewable energy targets, considerable increases in its production can be expected. This consequential life cycle assessment (LCA) study investigated the environmental consequences of different co-substrate strategies for reaching drastic increases in manure-biogas production in Denmark. Six co-substrates not already fully used for biogas were considered: energy crops, straw, household food waste, commercial food waste, garden waste and the solid fraction deriving from source-segregation of animal urine and feces. Soil carbon changes as well as direct and indirect land use changes were included in the LCA. Source-segregated manure stood out as the environmentally best co-substrate, followed by garden waste. Co-substrates already in use for energy recovery (straw, household and commercial food wastes) displayed a more modest environmental performance while energy crops, here represented by maize silage, was the only option giving rise to net greenhouse gas emissions. This was essentially due to the indirect land use change emissions related to this scenario, which were quantified to 357 t CO_2 eq. ha^{-1} displaced.

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1. Introduction

Recovery of manure biogas is an acknowledged cost-effective mitigation technology for greenhouse gas (GHG) emissions in agriculture [1–3], being not only a source of renewable energy, but also a way to improve the GHG balance of traditional manure management systems. In the perspective of a fully renewable energy system, biogas also offers the possibility to be storable in the gas network, which provides flexibility for buffering the fluctuant energy supply from intermittent sources like wind and sun, as well as a fuel for transport.

In spite of that, the energy produced from manure-biogas in the European Union (EU) is far below its full potential, the ca. 50 PJ produced in 2007 from agricultural biogas plants (including other substrates than manure like energy crops and organic wastes) [4] representing less than 7% of the 827 PJ potential estimated for cattle and pig slurries alone [5]. A recent analysis of the national renewable energy action plans (NREAP) made by the European Member States in the framework of the renewable energy directive (RED) [6] nevertheless highlights that European Member States have provided ambitious biogas targets to meet their renewable energy obligations. In Denmark, for example, a target has been launched to achieve 50% use of manure for biogas by 2020 [7] as compared to the present use of only 5–7% [8].

Animal manures, however, are often too dilute with respect to their carbon (C) content, and it is a common practice for biogas plants to co-digest manures with C-rich substrates, in order to ensure a biogas production safeguarding the economic sustainability of the production [2,9]. On the other hand, using these co-substrates for boosting manure-biogas involves that these are taken away from their other applications, and the environmental consequences of this should be well understood in order to

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establish a sustainable strategy for achieving a colossal increase in manure-biogas.

This study aims to investigate the environmental implications of different C co-substrate alternatives for enriching manure biogas, using Denmark's target for a substantial increase in manure-biogas as a contextual framework. The substrates assessed were those considered to have the greatest potential to supply an increased manure-biogas production, namely: energy crops, straw, various biowaste types (household food waste, commercial food waste, garden waste), and the solid fraction deriving from source-segregation of animal urine and feces. Substrates already fully used for the manure being digested nowadays (e.g. industrial organic residues from fish, fruit, sugar, dairy or oil industries) were not considered.

2. Model description and key parameters

2.1. LCA model

The environmental impacts of the different co-substrate alternatives investigated were compared based on a consequential life cycle assessment (LCA) [10–13]. All input and output flows were related to a functional unit (FU) being the management of 1 tonne of freshly excreted pig manure (manure ex-animal). The manure composition considered is presented in the Supporting information (SI), as well as all emission data and mass balances related its management (as slurry). The geographical scope considered for the LCA was Denmark, i.e. the data inventory for crop cultivation, manure management, and the applicable legislation were based on the Danish context. The life cycle impact assessment was carried out according to the Danish EDIP 2003 methodology [14] for the impact categories global warming (100 years horizon), acidification and aquatic eutrophication (distinguishing between nitrogen and phosphorus being the limiting nutrient for growth). Background (or generic) LCA data were based on the Ecoinvent v.2.2 database [15], and the assessment was facilitated with the LCA software SimaPro 7.3.3. Foreground (or system-specific) LCA data essentially included Danish-specific data for manure management (raw and digested), biogas production, crop cultivation and composition, co-substrates pre-treatment and energy conversion technologies, and are detailed in the (SI).

2.2. System boundary

Except for energy crops, all substrates considered in this study are waste products (i.e. manure, biowastes and straw) from other production systems. Based on the consequential LCA rationale, only processes that would react to a change in demand for manure-biogas should be included in the LCA. As any systems generating waste would, of course, be unaffected by the use of the waste, the processes upstream the generation of these wastes (e.g. the animal production system for manure, the crop production system for straw) were not included in the system boundary. For all scenarios, the system boundary thus starts with 1 tonne of raw manure as freshly excreted (ex-animal), which is afterwards managed as slurry and temporally stored in-house before to be sent to a biogas plant (manure ab-housing). The CH_4 yield considered for manure ab-housing is 319 Nm^3 per t volatile solids (VS) [2]. Further, it was considered that co-substrates are added to this manure in order to get a mixture reaching a dry matter (DM) content of 10% after the first digestion step, and a carbon to nitrogen (C/N) ratio limited to 20, reflecting state-of-the-art practice of Danish biogas plants [2]. From the anaerobic digestion step, two outputs are produced: the digestate and the biogas. The biogas is assumed to be used for combined heat and power (CHP). In this study, the marginal electricity source displaced by the biogas was assumed to be from coal-fired power plants, and the marginal heat from natural gas based domestic boilers. The other output from the anaerobic digestion process, namely the digestate, was assumed to be stored in a concrete tank covered with a straw floating layer [2]. When appropriate, this digestate can be applied on agricultural fields as an organic fertilizer, thereby displacing mineral nitrogen (N), phosphorus (P) and potassium (K) fertilizers, considered to be calcium ammonium nitrate, diammonium phosphate and potassium chloride, respectively (marginal fertilizers). Marginal fertilizers, like for the marginal heat and electricity sources, are, in consequential LCA, those affected by a change in demand [10,11,13], and were identified as described in [16]. The modeling of fertilizer substitution is further detailed in the SI. Changes in soil C occurring as a result of applying the digestate on land instead of raw manure were estimated with the dynamic soil C model C-TOOL [17–19]. For all alternatives, the co-substrates (or the land required to cultivate it, in the case of energy crops), if not used for biogas, would have been used for other applications. Using the co-substrates for biogas thus divert them from their initial use, which implies a variety of consequences, among others that a substitute is needed to supply the service (e.g. energy, fertilizer) no longer provided by the co-substrates. In this study, this service no longer provided is referred to as the lost alternative, and the consequences of it (like the production of a substitute) are included in the system boundary. Similarly, it is considered that the raw manure used for biogas would have otherwise be conventionally stored and applied on land (reference slurry management), in the way described in [2]. The system boundary considered is illustrated in Fig. 1, for the case of straw (scenario 2). System boundaries for all other scenarios are presented in the SI (Figs. S1–S7).

2.3. Biogas production

The biogas production considered in this study is based on a two-steps anaerobic digestion consisting of a completely stirred main digester and a post-digester from which ca. 10% additional CH_4 emissions are captured. It is assumed that the production is operated under mesophilic conditions, and that the biogas produced is constituted of 65% CH_4 and 35% CO_2, with a density of 1.158 kg Nm^{-3} biogas [2] and a LHV of 22.88 MJ Nm^{-3} biogas. Fugitive losses of 1% were assumed, based on recent LCA studies [2,20,21], but a sensitivity analysis with higher losses was performed (sensitivity analysis section). The biogas is considered to be burned in a biogas engine with efficiencies of 46% for heat and 40% for electricity [2], and it is assumed that only 90% of the net heat produced can substitute marginal heat, reflecting the losses occurring in periods with low heat demand [22]. Internal electricity consumption corresponding to 5% of the net electricity production [2,23] was assumed. Internal heat consumption was calculated considering that the mixture is heated from 8 °C (Denmark's average annual temperature) to 37 °C. The heat requirement was calculated considering a specific heat of 3.00 kJ kg^{-1} $°C^{-1}$ for the DM share of the input mixture, and of 4.20 kJ kg^{-1} $°C^{-1}$ for the water, based on [2].

3. Scenarios description and sensitivity analysis

3.1. Scenario 1: energy crops

Maize silage has been chosen as the energy crop to represent this scenario given its high yield and its high C turnover efficiency [24]. It is considered to be produced in Denmark specifically for anaerobic digestion, and as such is displacing another crop [25], which is here considered to be maize for animal feed. Based on this,

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