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Environmental consequences of anaerobic digestion of manure with different co-substrates to produce bioenergy: A review of life cycle assessments

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Abstract. Consequential life cycle assessment approach is needed to assess the environmental impacts of increase in biogas production. To see the full impacts of anaerobic co-digestion all possible environmental consequences caused by this change, i.e. the impacts of changed management and possible substitution impacts of substrates, should be taken into account. Generally anaerobic digestion of manure shows great environmental benefit instead of managing it conventionally, especially for the global warming potential. Environmental performance of co-digestion depends strongly on the initial use of the substrate. Co-digestion with wastes/residues has a great potential to produce bioenergy and reduce global warming potential. Co-digestion with land dependant special energy crops increases the bioenergy output but also increases the environmental impacts due to the need to substitute the substrate and thus should be avoided or limited.

Key words: life cycle assessment, biogas, anaerobic digestion, environmental impacts.

INTRODUCTION

The demand for renewable energy is continuously growing and anaerobic digestion offers a great potential to support it. Manure-biogas based energy production in the European Union (EU) is currently far below its full potential (Hamelin et al., 2014), however biogas production is planned to be increased drastically in the EU in the near future (Beurskens and Hekkenberg, 2011). Due to too low carbon (C) content of manure, the usual practice is to mix manure with C-rich co-substrate for anaerobic digestion. Environmental consequences of increased bioenergy production need to be studied comprehensively to avoid the situations where environmental impacts are higher than savings.

Life cycle assessment (LCA) is a standardised environmental assessment methodology that aims to assess the potential environmental impacts and use of resources through a product's life cycle, i.e. from raw material acquisition, via production and use phases, to waste management (ISO-14040, 2006). There are two main approaches for LCA: (i) the attributional LCA which is aimed to analyse the environmental impacts through product`s life cycle as a static system; and (ii) the consequential LCA, the aim of which is to show the environmental consequences of the decision that is assessed by the LCA. Accordingly, to assess the impact of increased biogas production, all possible environmental consequences caused by this change should also be taken into account. If co-substrates are taken away from their initial use, it leads to environmental consequences, e.g. caused by the need to substitute them. The initial function of co-substrate may be, for example, composting, using it for animal feed or fertilizer etc. The consequences of changed management of substrates also need to be included to the analyses to see the full impacts of the change. According to the consequential approach, all impacts from taking the substrates away from their previous use, and also the consequences of substituting the marginal resources as fossil fuels, mineral fertilizers etc. should be included in the system boundaries.

However, attributional LCA is still the most commonly used LCA method and this practice can be strongly misleading for the policy-makers (Plevin et al., 2014). Attributional LCA results are often presented as comparisons of different alternatives, without accounting for the consequences each decision may cause in the real world (Plevin et al., 2014). A number of biogas LCA studies (e.g. Poechl et al., 2012; Huopana et al., 2013; Lijó et al., 2014) and some reviews have been published in recent years (e.g. Muench and Guenther, 2013; Huttunen et al., 2014), but not all the environmental consequences of changed management were considered in those studies, especially the substitution impacts of substrates was not accounted.

Based on the recent scientific literature, the goal of this study was to identify the environmental life-cycle consequences of anaerobic digestion of manure with different co-substrates, also taking into account the lost alternative of the substrates.

MATERIALS AND METHODS

LCA studies assessing environmental consequences of anaerobic digestion of manure with different co-substrates were searched from Scopus, the database of peer-reviewed scientific literature, using the key words ‘biogas LCA’ and ‘anaerobic digestion LCA’. Selected papers were focused on full life-cycle of the anaerobic co-digestion of manure, starting from the production of substrates and the excretion of manure to application of digestate on field. Mono-digestion of manure was also included as an alternative scenario often included in co-digestion studies.

Another important criterion was that the environmental impacts of lost alternative of the substrates had to be included in to the studies. Increase in manure-based biogas production changes initial manure management chain and also the initial management of co-substrate. The consequences of lost alternatives have to be included if the goal is to measure the impacts of the change in the system. The importance of such approach in designing the system limits of biofuel LCA studies is well described in Wenzel (2009) and the general principles of consequential LCA are detailed in Ekvall and Weidema (2004).

Basic principles of system boundaries for consequential LCA of anaerobic co-digestion are visualised in Fig. 1, with an example of scenario where manure is co-digested with an energy crop.

In conclusion, the system boundaries for all the papers reviewed here (Table 1) included not only the processes directly involved in biogas production chain, but also the processes affected by the change, i.e. increased biogas production. The results of those studies are presented as net impacts, by subtracting the avoided impacts from induced impacts for each scenario. Overview of included studies in Table 1 details the studies by different co-substrates, and also specifies the country, functional unit (FU), environmental impacts studied, and the end use of the biogas for each scenario. The FU is the reference unit for which all the environmental impacts are expressed in LCAs.

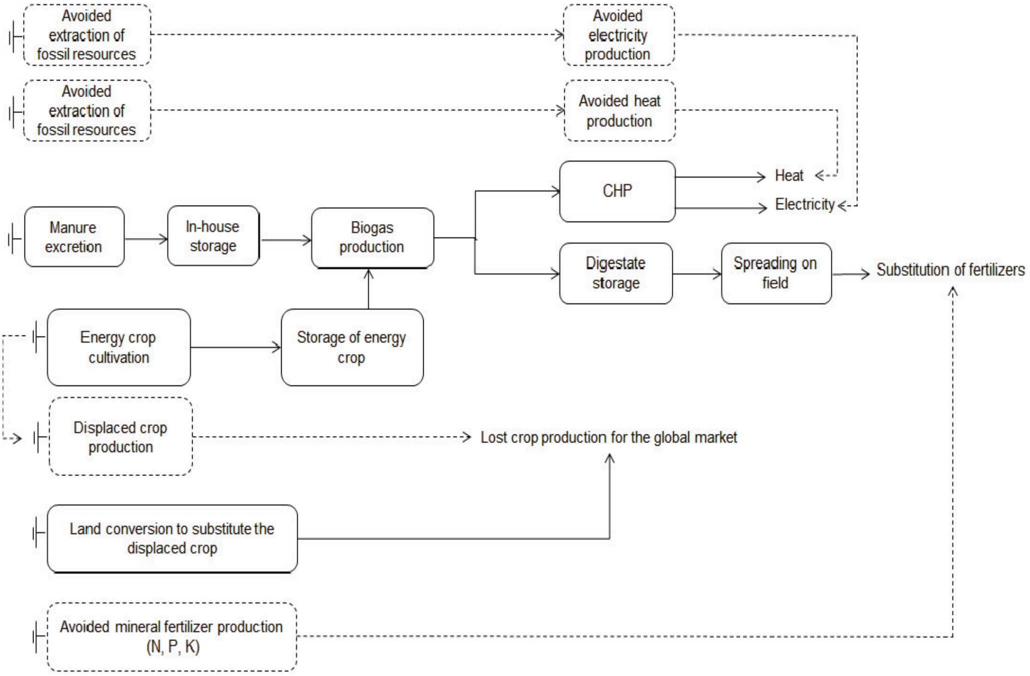

Figure 1. Example of the system boundaries for consequential LCA of the manure co-digestion with energy crop, where the produced energy is replacing the fossil electricity and heat and the energy crop production is causing additional land conversion to cropland.

RESULTS AND DISCUSSION

Environmental impact categories

Generally, the most often studied environmental impact categories of manure co-digestion LCA studies are global warming potential, acidification potential and eutrophication potential (Table 1). Also, those categories are usually investigated for agricultural LCAs (e.g. de Vries and de Boer, 2010), and reflect the main impacts of the manure management chain well. Additionally, in connection with production of co-substrates impacts, land use area and biodiversity impacts would also be relevant to include in some cases. While land occupation is rather simple to account, the biodiversity impacts are much more complex and it is not possible to do straightforward generalizations and simplifications, for that reason biodiversity is mostly excluded from LCAs. However, one of the main drivers of biodiversity loss is habitat and land use change, thus, proper methods are needed to quantify the biodiversity impacts on a global scale (De Baan et al., 2013). Using the residual grass from semi-natural grasslands for co-digestion would increase biodiversity; therefore, including biodiversity assessment would improve the environmental performance of this scenario even more than it is showed already for the global warming potential (Pehme et al., 2014).

Mono-digestion of manure

Overall mono-digestion of manure reduces environmental impacts in categories as global warming potential and resource depletion potential compared to a scenario where manure is not digested. However, for the acidification potential, eutrophication potential, and land use impacts the benefits of mono-digestion are not so clear (De Vries et al., 2012; Hamelin et al., 2014; Styles et al., 2014). Main reduction impact of mono-digestion is caused by avoided traditional manure management, and to a smaller extent, also by the fossil energy that is avoided by providing biogas-based energy.

Slurry-based biogas production has also been found to be one of the most cost-effective methods to reduce global warming potential from the life cycle perspective compared to other possible measures (Landbrug og klima, 2008), but the problem is how to assure the economical profitability of this production cycle for the companies. There are three main strategies to increase the economic feasibility of biogas (Hamelin et al., 2011): (i) to increase carbon input by using energy crops, (ii) to change housing systems to collect urine and solid manure separately to increase carbon input, (iii) to separate the slurry into a liquid and concentrated fraction and use the latter as co-substrate for slurry; (iv) to accept the lower biogas yields of mono-digestion of slurry and to compensate it with higher retention time in bigger digesters. There is also an option to use wastes/residues from other production chains but the amount of the material is limited and in some countries already in use.

Hamelin et al. (2011) compared different slurry separation technologies for biogas production and all slurry separation technologies resulted in lower or equal net impacts for all impact categories compared to traditional manure management. Environmental benefits of such practice depended strongly on the efficiency of the separation technology, as higher DM separation means higher amount of easily degradable volatile solids (VS) which leads to higher energy production and a greater displacement of fossil energy (Hamelin et al., 2011). Croxatto Vega et al. (2014) also found that slurry separation reduces the impacts for most of the categories. Slurry separation offers a good potential to reduce environmental impacts and increase biogas production, and is most likely to fit well for the countries where farmers have surplus manure and they need to transport it to longer distances.

Co-digestion with special energy crops

Maize and different grasses are the most commonly suggested energy crops for anaerobic co-digestion due to their relatively high biogas potential; accordingly they have been also included in different biogas LCAs (Table 1). One of the critical issues related to all special energy crops is their land dependency. Energy crop which is produced specifically for anaerobic digestion is most likely displacing some other crop that cannot be produced on the same land any more. Land use changes (LUC) caused by the expansion of specific crop in the area are considered as direct land use changes (DLUC) in consequential LCAs. The impacts of avoided crop production are subtracted from induced impacts of energy crop production and the result represents the net direct land use change (DLUC) impacts which can be either positive or negative, depending on the both crops and the practice. The displaced i.e. the marginal crop is the crop that will most probably be replaced by increased energy crop production. The marginal crop is for instance considered to be barley (e.g. De Vries et al., 2012; Tonini et al., 2012) or feed maize (Hamelin et al., 2014).

According to consequential rationale, the displaced production needs to be substituted and the global market will most likely react to the need by intensification, land conversion to cropland in somewhere else (Tonini et al., 2012; Hamelin et al., 2014) or the combination of both (De Vries et al., 2012). Land conversion refers to indirect land use chances (ILUC), and it has a significant climate change impact due to induced CO_2 emissions. Although co-digestion with energy crops (maize, grasses or willow) has significantly higher energy output compared to mono-digestion, this scenario results in higher climate change impact than the scenario when biogas is not produced at all, and this is caused mainly by the ILUC impact (De Vries et al., 2012; Tonini et al., 2012; Hamelin et al., 2014). Co-digestion with energy crops increases also the land use, acidification and eutrophication potential as there are more nutrients available across the flow chain (De Vries et al., 2012; Hamelin et al., 2014).

Co-digestion with substrates competing with animal feed

The environmental consequences of using the beet tails, maize silage and wheat yeast concentrate for anaerobic co-digestion instead of using the substrates for animal feed have also been studied (Table 1). All authors concluded that co-digestion with substrates with alternative use as an animal feed increased bioenergy output, but also increased most of the environmental impacts due to the need to substitute the feed. The main impact was again caused by the ILUC based on the logic described in the last section. The co-digestion with energy crops should be avoided or limited to avoid large greenhouse gas emissions due to the need to replace the fodder by more concentrate feed (Styles et al., 2014).

Co-digestion with wastes/residues

Wastes/residues considered in this study were straw, roadside grass, food wastes/household wastes and garden wastes (Table 1). Co-digestion of wastes or residues gave the best environmental performance compared to other scenarios (except the source-segregation of manure). The roadside grass co-digestion showed the best impact reduction in all categories and it was mainly caused by the avoided composting with significant amount of N_2O emissions (De Vries et al., 2012). Croxatto Vega et al. (2014) showed that the straw, which otherwise would have been left on field, has the best impact environmental reduction potential. Hamelin et al. (2014) also concluded that straw is a great option to reduce GWP, but the result was not positive for AP and EP. Food waste, bio-waste and garden waste scenarios presented GWP savings, but also higher AP and EP because of the higher nutrient content of the material (Hamelin et al., 2014; Styles et al., 2014).

Table 1. Characteristics of the studies included to review

Study	Country/context	Functional unit of the study	Environmental impacts studied*	Use of biogas
1	*2*	*3*	*4*	*4*
Mono-digestion of manure				
De Vries et al., 2012	North-Western Europe/Netherland	1 ton of substrate entering to digester	GWP, AP, EP, FFD, PMF, LU	Heat and electricity
Hamelin et al., 2014	Denmark	1 ton of manure ex-animal	GWP, AP, EP	Heat and electricity
Styles et al., 2014	UK	1 year of farm operation	GWP, AP, EP, RDP	Heat and electricity
Separated solid part of the slurry				
Hamelin et al., 2011	Denmark	1 ton of manure ex-animal	GWP, AP, EP, POF, RI	Heat and electricity, natural gas grid
Hamelin et al., 2014	Denmark	1 ton of manure ex-animal	GWP, AP, EP	Heat and electricity
Vega et al., 2014	Denmark	1 ton of manure ex-animal	GWP, AP, EP, FD	Natural gas grid
Maize				
De Vries et al., 2012 (special energy maize)	North-Western Europe/Netherland	1 ton of substrate mixture entering to digester	GWP, AP, EP, FFD, PMF, LU.	Heat and electricity
Hamelin et al., 2014 (special energy maize)	Denmark	1 ton of manure ex-animal	GWP, AP, EP	Heat and electricity
Styles et al., 2014 (fodder maize)	UK	1 year of farm operation	GWP, AP, EP, RDP	Heat and electricity
Grass				
Tonini et al., 2012 (ryegrass)	Denmark	1 ha of farmland to grow the energy crops	GWP, EP	Heat and electricity
Tonini et al., 2012 (Miscanthus giganteus)	Denmark	1 ha of farmland to grow the energy crops	GWP, EP	Heat and electricity
Styles et al., 2014 (grass silage)	UK	1 year of dairy farm operation	GWP, AP, EP, RDP	Heat and electricity

Table 1 continued

1	*2*	*3*	*4*	*5*
Straw				
Hamelin et al., 2014	Denmark	1 ton of manure ex-animal	GWP, AP, EP	Heat and electricity
Vega et al., 2014	Denmark	1 ton of manure ex-animal	GWP, AP, EP, FD	Natural gas grid
Beet tails				
De Vries et al., 2012	North-Western Europe/Netherland	1 ton of substrate mixture entering digester	GWP, AP, EP, FFD, PMF, LU	Heat and electricity
Wheat yeast concentrate				
De Vries et al., 2012	North-Western Europe/Netherland	1 ton of substrate mixture entering digester	GWP, AP, EP, FFD, PMF, LU	Heat and electricity
Roadside grass				
De Vries et al., 2012	North-Western Europe/Netherland	1 ton of substrate mixture entering digester	GWP, AP, EP, FFD, PMF, LU	Heat and electricity
Food wastes/household wastes				
Hamelin et al., 2014	Denmark	1 ton of manure ex-animal	GWP, AP, EP	Heat and electricity
Vega et al., 2014	Denmark	1 ton of manure ex-animal	GWP, AP, EP, FD	Natural gas grid
Styles et al., 2014	UK	1 year of farm operation	GWP, AP, EP, RDP	Heat and electricity
Garden waste				
Hamelin et al., 2014	Denmark	1 ton of manure ex-animal	GWP, AP, EP	Heat and electricity

*GWP – global warming potential; AP – acidification potential; EP – eutrophication potential; FFD – fossil fuel depletion; RDP – resource depletion potential; PMF – particulate matter formation; POF – photochemical ozone formation; RI – respiratory inorganics; LU – land use.

General discussion

The results of the consequential LCA depend strongly on the impacts of ‘lost alternative’, i.e. the initial use of the manure and co-substrate. The worse is the environmental impact of baseline situation the bigger is the possible change. If the initial use of the substrate is animal feed, there are no environmental advantages using it for biogas. Producing biogas from waste substrates, which would otherwise be composted or left on field, has a great GWP reduction potential. Still, it often does not improve the AP and EP.

If the ‘lost alternative’ is the food/feed crop production, then it leads to large GWP impact through ILUC, caused by the need to substitute the product. Surely, it can be argued if ILUC impact is always the case in reality, especially when there is a significant amount of unused agricultural land resource available in some countries. Also, small changes in co-substrate use will probably not affect the global market, but when planning the broader changes and long-term policies, the land use strategies need to be analysed carefully in order to have sustainable solutions for food, feed and energy production. The partial use of abandoned farmland or the restoration of opened peat-land with perennial grass would probably be an option to avoid the land competition and ILUC impacts.

Although there is no methodological consensus on how to quantify the ILUC impact (so it is rather uncertain value), it is still important to include it based on best available data.

Also the choice of the avoided marginal processes, e.g. the type of energy replaced etc. may affect the results. A consequential methodology considers the markets affected by the decisions by defining the main affected technology, e.g. the marginal technology (Ekvall & Weidema, 2004), thus the selection of the marginal energy is important as also previous LCAs have concluded (Vad Mathiesen et al., 2009). In current studies biogas is assumed to replace fossil fuels and it gives significant reduction impact, but this may not necessarily be the case in the future when more renewable alternatives might be available; this would reduce the environmental impact reduction potential of anaerobic digestion compared to present studies.

CONCLUSIONS

* Commonly anaerobic digestion of manure shows great environmental benefit instead of managing it conventionally, especially for the GWP.

* Impacts of co-digestion depend strongly on the type of the co-substrate and the initial/alternative use of the substrate. Co-digestion with wastes/residues as source-segregated solid manure, straw, garden wastes, roadside grass and food wastes is the most promising option to produce bioenergy and reduce global warming potential.

* Co-digestion with land-dependent special energy crops competing with food/feed products, e.g. maize or energy grass increases the biogas output but increases also the overall environmental impacts due to the need to substitute the substrate.

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