Resources, Conservation & Recycling 136 (2018) 110–117

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

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

Full length article

Closing nutrient loops through decentralized anaerobic digestion of organic residues in agricultural regions: A multi-dimensional sustainability assessment

Céline Vaneeckhaute[a,b,*], David Styles[c], Thomas Prade[d], Paul Adams[e], Gunnar Thelin[f], Lena Rodhe[g], Inga Gunnarsson[h], Tina D'Hertefeldt[h]

[a] BioEngine, Chemical Engineering Department, Université Laval, 1065 avenue de la Médecine, Québec, QC, G1V 0A6, Canada
[b] CentrEau, Centre de recherche sur l'eau, Université Laval, 1065 avenue de la Médecine, Québec, QC, G1V 0A6, Canada
[c] School of Environment, Natural Resources and Geography, Bangor University, Gwynedd, LL57 2UW, UK and Plant & AgriBioSciences Centre, Ryan Institute, NUI Galway, Galway, Ireland
[d] Department of Biosystems and Technology, Swedish University of Agricultural Sciences, Alnarp, SE-23053, Sweden
[e] Department of Mechanical Engineering, Bath University, North East Somerset, BA2 7AY, UK
[f] Ekobalans, Scheelevägen 22, Lund, SE-22363, Sweden
[g] RISE Research Institutes of Sweden, Uppsala, SE-75007, Sweden
[h] Department of Biology, Lund University, Lund, SE-22362, Sweden

A R T I C L E I N F O

Keywords:
Anaerobic digestion
Bio-based fertilizers
Circular economy
Resource recovery
Sustainable farming
Nutrient management

A B S T R A C T

Decentralized anaerobic digestion (AD) of manure and organic residues is a possible strategy to improve carbon and nutrient cycling within agricultural regions, meanwhile generating renewable energy. To date, there has been limited adoption of decentralized AD technology in industrialized countries owing to low profitability for plant operators. There remains a need to demonstrate the wider sustainability of small-scale, decentralized AD in order to justify policy support for such a strategy. This study applies a multi-dimensional assessment of the environmental, economic and social sustainability of two scenarios of decentralized, farm-scale AD of pig slurry and organic residues in Southern Sweden. The environmental dimension was assessed by means of an expanded boundary life cycle assessment, in which trade-offs between fertilizer replacement, soil organic carbon accumulation, digestate/manure storage and application, transport and soil emissions were evaluated. The economic dimension was assessed through modelling of the net present value and internal rate of return. Finally, the social dimension was assessed by means of a stakeholder perception inquiry among key stakeholders in the field. It was concluded that the overall environmental balance of decentralized AD was favorable, while also the net present value could be positive. Fertilizer replacement, soil organic carbon and digestate storage effects were identified as important factors that should be accounted for in future life cycle assessments. A key issue for interviewed stakeholders was product quality assurance. Wider application of multi-dimensional sustainability assessment, capturing important nutrient cycling effects, could provide an evidence base for policy to support sustainable deployment of decentralized AD.

1. Introduction

The European Union has committed itself to an average reduction of greenhouse gas (GHG) emissions of 20% by 2020 and 40% by 2030 relative to 1990 (EuroStat, 2017). Herewith, agriculture is projected to obtain a 17% reduction in GHG emissions by 2020, partly due to decreasing use of fertilizers and increasing productivity (EuroStat, 2017). Indeed, the agricultural sector is responsible for more than 40% of anthropogenic methane (CH_4) emissions and more than 50% of nitrous oxide (N_2O) emissions (EuroStat, 2017). Both CH_4 and N_2O are GHGs with global warming potentials that are, respectively, 25 and 298 times greater than that of carbon dioxide (CO_2) (EuroStat, 2017). The main sources of CH_4 are enteric fermentation and manure management, while N_2O is mainly derived from the turnover of nitrogen in fertilizers, manure and crop residues, and indirectly from the turnover of nitrogen lost to the environment via ammonia volatilization or nitrate leaching

* Corresponding author at: BioEngine, Chemical Engineering Department, Université Laval, 1065 avenue de la Médecine, Québec, QC, G1V 0A6, Canada.
E-mail addresses: celine.vaneeckhaute@gch.ulaval.ca (C. Vaneeckhaute), d.styles@bangor.ac.uk (D. Styles), thomas.prade@slu.se (T. Prade), p.w.r.adams@bath.ac.uk (P. Adams), gunnar.thelin@ekobalans.se (G. Thelin), lena.rodhe@ri.se (L. Rodhe), tina.dhertefeldt@biol.lu.se (T. D'Hertefeldt).

https://doi.org/10.1016/j.resconrec.2018.03.027
Received 11 August 2017; Received in revised form 25 March 2018; Accepted 28 March 2018
0921-3449/

(EuroStat, 2017). Significant reductions in GHG emissions are therefore expected if CH_4 and N_2O emissions can be reduced via improved management practices in agriculture.

Decentralized anaerobic digestion (AD) in agriculture provides possibilities to reduce GHG emissions by producing a CH_4-rich biogas from manure and crop residues. A decentralized biogas plant is a small digester located on a farm that treats substrates from the farm and local sources such as household food waste and waste from food processing plants. Such small biogas plants could fulfill a useful role in rural areas where cumulatively large amounts of organic wastes are often handled sub-optimally owing to costs of transporting them to large centralized AD facilities. The produced biogas can be transformed into electricity, heat or fuel for the farm, while the resulting digested waste, i.e. the digestate, can be returned to land as a valuable organic-mineral fertilizer, thereby reducing the use of chemical fertilizers (Vaneeckhaute et al., 2013a, 2014, 2016). As such, closed loop recycling management systems could be strengthened and emissions from conventional manure storage and application could potentially be reduced. The use of digestate can also contribute to carbon sequestration, since digestate organics are incorporated into the soil (Vaneeckhaute et al., 2013a, 2014). Anaerobic digestion can also create new sources of income for farmers, such as carbon credits.

Despite many opportunities for farm-scale biogas plant development in rural regions, the widespread adoption of decentralized biogas technology has yet to take off (ADAS and SAC, 2007). Currently less than one percent of the potential benefits from anaerobic digestion are being realized (EUBIA, 2017). Reasons for this include the non-supportive regulatory framework, the lack of economic incentives for potential investors, as well as the lack of knowledge and accurate quantitative studies on the potential benefits of decentralized digestion (EUBIA, 2017). There is a need for a scientifically robust evidence base for policy to support decentralized AD, integrating the economic, social and environmental pillars of sustainability.

Life cycle assessment (LCA) is increasingly being applied to evaluate the environmental sustainability of AD (e.g., Chiew et al., 2015; Rehl and Müller, 2011; Vázquez-Rowe et al., 2015), but emphasis is usually placed on energy generation, while nutrient and soil organic carbon (SOC) effects are considered in less detail using crude assumptions, with some exceptions (e.g., Cong et al., 2017). Further, environmental effects of storage of manure or digestate, such as emissions and potential nutrient losses, can wholly or partly offset the benefits of nutrient recycling from these products. Storage of residues is, however, often not fully accounted for, for example, the EU Renewable Energy Directive 2009/28/EC neglects digestate storage, and many existing LCAs seem to overlook the importance of effective manure/digestate storage with respect to nutrient losses and GHG emissions (EC, 2009; JRC, 2014). Moreover, a holistic LCA study should be accompanied with an evaluation of the economic benefits/losses when changing farm management practices. Finally, even if environmental and economic benefits are clear, recycled fertilizer marketing will be highly influenced by the social perception in the agricultural region. Ideally, a more holistic and multi-dimensional sustainability assessment framework for the use of biofertilizers in agriculture should be applied in order to evaluate the real potential benefits of decentralized anaerobic digestion.

The aim of this study was to identify the environmental, economic and social sustainability of using digested waste (pig manure, food waste, slaughterhouse waste and grass silage, notably), hereafter called residue biofertilizers (RBFs), instead of raw animal manure and synthetic fertilizer in decentralized agricultural regions. To this end, a multi-dimensional sustainability assessment is performed for the case of Southern Sweden. A concept map of the research strategy is provided in Fig. 1.

The **environmental dimension** was investigated through an LCA, accounting for trade-offs between digestate storage, fertilizer replacement and soil organic carbon effects, transport and soil emissions for using RBFs, as well as counterfactual effects of the avoided conventional manure and waste management. The **economic dimension** was assessed by means of a techno-economic analysis of decentralized AD and digestate handling at the farm level, resulting in net present value (NPV) and internal rate of return (IRR) economic indicators. The **social dimension** was assessed by means of a stakeholder perception inquiry that investigates the acceptance of RBFs in agriculture among different key stakeholders in Southern Sweden. As such, this research will help identifying key bottlenecks in the widespread implementation of anaerobic digestion and digestate recycling in decentralized regions, and indicate opportunities, e.g., in terms of policy amendments and priority measures, to enable more effective usage of recycled nutrients.

2. Methods

2.1. Environmental dimension

2.1.1. LCA framework for residue biofertilizers

Table 1 lists the key processes and factors to consider when undertaking an LCA of RBFs. A first important issue is where to draw LCA boundaries, which will depend on the type of LCA to be applied (attributional or consequential), the question being asked and the prevailing fate of the residue investigated in the region of study used to define the baseline (Table 1). Fertilizer replacement value (FRV) is a key determining factor for the environmental balance of RBF (Vaneeckhaute et al., 2013a, 2014). Therefore, it is relevant to apply an expanded boundary, or consequential, LCA to fully evaluate the environmental balance of RBFs. Given the multiple nutrients delivered in RBFs, it is difficult to define a simple functional unit. Instead, results may be expressed for a reference flow, such as 1 Mg dry matter (DM) of RBF, considering all relevant incurred and avoided effects. In Table 1, it is suggested that the following impact categories are particularly important to represent main elements of the environmental balance of RBF: i) global warming potential (GWP), ii) eutrophication potential (EP), iii) acidification potential (AP), and iv) fossil resource depletion potential (FRDP), as, e.g., in CML (2010). Other environmental impact categories such as human toxicity and freshwater eco-toxicity (CML, 2010) may be relevant for some RBFs, especially those containing heavy metals or other impurities, but are not investigated further in this study.

Field application of residues will give rise to emissions to air and water, most importantly NH_3, N_2O, NO_3, PO_4, which can be estimated or modelled using various sources (e.g., IPCC, 2006; Johnes et al., 1996; Li, 2000; Li et al., 1992; Nicholson et al., 2013). Concentrations of potential soil contaminants such as heavy metals and persistent organic compounds vary widely depending on the source of the residue. Hence, estimates of leaching from these residues contributing to human- or eco-toxicity burdens requires data from residue analysis. Such impacts are localized whereas LCA takes a regional approach. Furthermore, data availability is often limited which means contaminants may remain outside the LCA system boundary.

Detailed fertilizer or nutrient budgeting manuals such as *Stallgödselkalkylen* in Sweden (EC, 2009) and national recommendations for fertilization (Jordbruksverket, 2015) estimate the fertilizer replacement value (FRV) for various organic residues, sometimes in relation to timing and technology of application, soil and crop type. A convenient nutrient budgeting tool, MANNER-NPK (Nicholson et al., 2013), estimates FRV and NH_3 and NO_3 emissions for a wide range of organic residues depending on their specific composition, and the timing, location, method and prevailing weather conditions during application. This tool was used in the case study presented below (Section 2.1.2).

2.1.2. LCA case study of decentralized anaerobic digestion and digestate reuse

2.1.2.1. Goal and scope definition. The environmental balance of two