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LIFE CYCLE ASSESSMENT OF AGRICULTURAL RESIDUES UTILIZATION FOR BIOGAS DEPLOYMENT

Suzanne Alsamaq*[1] Charles Kingdom[1]
[1]Department of Mechanical, Automotive and Manufacturing Engineering, Faculty of Engineering and Computing, Coventry University, Priory Street, Coventry, CV1 5FB, United Kingdom

Nasir Anka Garba[2]
[2]Department of Geography, Environmental Science and Disaster Management, Coventry University, Priory Street, Coventry, CV1 5FB, United Kingdom

ABSTRACT

Production of biogas from energy crops, agricultural residues, and municipal waste is becoming increasingly important in order to reduce greenhouse gas (GHG) emissions and enhance the security of global energy supply. The environmental performance of biogas production from agricultural residues and its utilization as an alternative to fossil natural gas was evaluated and quantified in this study using a life cycle assessment (LCA) approach. The 'cradle-to-grave' LCA of a biogas production system was conducted in accordance with the ISO 14044 standards, using GaBi 4 computer software and life cycle inventory (LCI) data from the ecoinvent v2.0 database using the CML2001 method. The functional unit was the anaerobic digestion of 1 ton of agricultural residue mixture to produce biogas with the digestate as a process co-product. The environmental profile was analysed in terms of abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), photochemical ozone creation (POCP), freshwater aquatic ecotoxicity potential (FAETP), and terrestrial ecotoxicity potential (TETP). Results showed that using biogas as a replacement for natural gas can directly help in offsetting the environmental impacts associated with the production and use of fossil natural gas – ADP (-44.93 kg Sb-Equiv.); AP (-16.99 kg SO_2-Equiv.); EP (-1.93 kg Phosphate-Equiv.); GWP (-10329.4 kg CO_2-Equiv.); ODP (-0.0007 kg R11-Equiv.); HTP (-2695.38 kg DCB-Equiv.); POCP (-1.44 kg Ethene-Equiv.); FAETP (-73.0778 kg DCB-Equiv.); and TETP (-55.58 kg DCB-Equiv.). Using biogas obtained through anaerobic digestion of agricultural crops such as corn stover and rice straw can be very beneficial when compared to fossil natural gas derived energy.

Keywords:
Biogas, life cycle assessment (LCA), agricultural residues, GaBi Software, ecoinvent environmental impact

INTRODUCTION

Biofuels from renewable biomass are attracting intense interest from government, industry and researchers worldwide as potential substitute for conventional fossil fuels. A wide range of biomass sources such as annual energy crops (e.g. corn, wheat and soybean), perennial energy crops (e.g. switchgrass, miscanthus, and willow), and agricultural residues (e.g. rice and wheat straw, and corn stover), can be utilized for production of gaseous, liquid and solid biofuels which can both help reduce fossil fuel consumption and greenhouse gas (GHG) emissions (Buratti *et al*., 2013). First generation biofuels primarily derived from food crops such as corn, wheat and sugarcane have been promoted over the past decades. However, the rapidly increasing production and use for first generation biofuels have led to intense debates on the sustainability of biofuels worldwide especially the potential conflict between food and fuel production (Ekman *et al*., 2013). To counter these criticisms on food and fuel competition, agricultural residues are therefore gaining attraction as the promising resources for biofuels production as substitutes to conventional fossil fuels and first generation biofuels derived from food crops (Sims *et al*., 2008). Biogas production through anaerobic digestion process is a promising way to achieve energy and environmental benefits at both the local and global level (Chen *et al*., 2013). Biogas plants can provide an alternative renewable energy source and mitigate environmental emissions from fossil fuels (Zhang *et al*., 2013). Biogas replaces fossil fuels with clean methane, which reduces not only the release of greenhouse gases, but also other detrimental emissions and the multiple utilization of digestate, a by-product of anaerobic production of biogas (i.e., substitution for such materials as fertilizers, pesticides, and feed additives) facilitates more efficient use of organic waste or plant nutrients in daily agricultural practice (Rehl and Müller, 2011). A number of studies have evaluated the environmental benefits of small and large scale biogas production projects from different types of feedstocks (e.g., Zhang *et al*., 2013; Chen *et al*., 2013) biogas utilization (e.g., Patterson *et al*., 2011), and potential by-products with reuse (e.g., Rehl and Müller, 2011). However, few studies focused on emissions mitigation of biogas production from agricultural residues, especially when digestate (by-product of a biogas production system) is utilized as a substitute to conventional mineral fertilizer. The purpose of this paper is to undertake a holistic life cycle environmental assessment of typical biogas production system from agricultural residues with comprehensive digestate utilization as an alternative to mineral fertilizer.

NOMENCLATURE

ADP	Abiotic Depletion Potential
AP	Acidification Potential
CML	Center of Environmental Science o Leiden University
DCB-Equiv.	Dichlorobenzene Equivalent
EP	Eutrophication Potential
FAETP	Freshwater Aquatic Ecotoxicity Potential
GHG	Greenhouse Gas
GWP	Global Warming Potential,
HTP	Human Toxicity Potential
ISO 14044	International Organization of Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ODP	Ozone Layer Depletion Potential
POCP	Photochemical Ozone Creation
R11-Equiv.	Trichlorofluoromethane Equivalent
TETP	Terrestrial Ecotoxicity Potential

METHDOLOGY

LCA methodology

LCA as a decision making tool has been widely used to quantify and evaluate the environmental impacts of products through all stages in their life cycle. It has also been widely used for evaluating the environmental burdens of bioenergy systems (González-García *et al*., 2013; Boulamanti *et al.*, 2013; Poeschl *et al.*, 2012; Rehl and Muller 2011; Rehl *et al.*, 2012). The International Organization for Standardization (ISO) has described the framework of LCA in four steps including the goal and scope definition of the assessment, life cycle inventory (LCI) analysis which includes identification and quantification of environmental loads involved, life cycle impact assessment (LCIA) which also involves evaluating the potential environmental impacts of these loads and interpretation of the assessment results. In this research work, LCA of biogas production from agricultural residues was conducted. The LCA was performed according to the ISO 14044 standards (ISO 2006), using GaBi 4 as software (Eyerer 2006). The following sections describe the LCA methods and the results obtained, according to the scheme provided by the ISO standards.

Goal and scope definition

The goal of this study is to assess from ‘‘cradle-to-grave’’ the environmental performance of comprehensive production and utilization of biogas and digestate from agricultural residues as potential alternatives to fossil natural gas and mineral fertilizer, respectively. The target audiences are stakeholders, policy makers and the scientific community involved in environmental assessment of energy from biomass through anaerobic digestion.

The scope of the assessment (Life Cycle Inventory – LCI) include impacts and credits occurring during residue collection, transportation of residue, conversion of residue to biogas in an anaerobic digestion plant, and the use of the biogas and digestate to substitute conventional natural gas and mineral (chemical) fertilizer, respectively. These are taken into account in the system boundary as shown in Fig. 1. The final utilisation of biogas is combustion in a power plant for the production of electric power.

Functional unit

The functional unit used for evaluating the environmental performance of the biogas production system is 1 ton of dry residue input from common agricultural crops (maize, millet, sorghum, rice and wheat). The biogas production system is modelled using LCI data from the ecoinvent database (Ecoinvent v2.0) (Ecoinvent 2007) in the commercial GaBi 4 LCA software (Eyerer 2006).

System boundary and reference system

The chain of processes covers all the phases from agricultural residue collection from the field to the final utilisation of biogas to produce energy. Digestate utilization is included in the boundaries. The system boundary is summarised in Fig. 1. The reference system is conventional natural gas that is most likely to be displaced for producing electricity and the alternative use of digestate (organic fertilizer) to displace mineral fertilizer (Rehl *et al*., 2012).

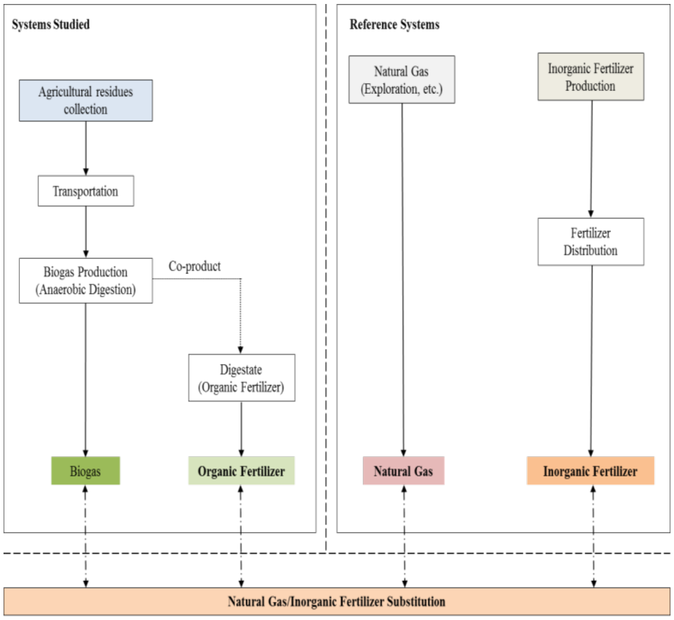

Fig. 1: Scheme of the system boundary for the collection of agricultural residues for the production of biogas for bioenergy.

Key assumptions

Baling operation with the bale size of about 1.4 m^3, 700 kg on dry basis is assumed. A transportation distance of 100 km radius from farm to the processing plant is assumed in the assessment. The baled residue is loaded and transported (delivered) from the farm to the anaerobic digestion plant using 20-28 ton heavy-duty diesel vehicles. The LCA was done based on the guidelines for LCA according to ISO 14040:2006/14044:2006 (ISO 2006). The system boundary of this LCA is cradle-to-grave (residue collection, transportation, biogas production and distribution, and use). The CML method (Guinee *et al.*, 2001) developed by the Centrum for Milieukunde in Leiden, Netherlands (CML) was chosen to assess inventory flows.

Life cycle inventory (LCI)

LCI, which is the second step of an LCA, involves the construction of the inventory analysis; systematic inventory of all energy and material flows of the biogas systems during the entire lifecycle. Data from the ecoinvent 2.0 database (Ecoinvent 2007) is used to generate the compilation and quantification of inputs and outputs for residue collection, biogas production, biogas and utilisation. The processes of the residue collection from field and anaerobic digestion are built with the inputs and outputs shown in appendix 1, linked to the production of biogas from 1 kg residue.

Life cycle impact assessment (LCIA)

The CML2001 method was used to assess inventory flows for the impact categories: abiotic resource depletion potential (ADP), global warming potential (GWP), acidification potential (AP), ozone layer depletion potential (ODP), eutrophication potential (EP), photochemical ozone creation (POCP), and human toxicity potential (HTP). Background data for the biogas system as well as the reference system were taken from the GaBi database (Eyerer 2006) which was extended by data from the ELCD database (ECLD 2007) and the ECO-Invent integrated database (Ecoinvent 2007). Biogas system modelling, data administration, classification, characterization, analysing and weighting were done with GaBi 4 software. Emissions and resource consumption by the production of buildings and machinery are all included in the assessment. The global warming impact is evaluated in terms of global warming potential (GWP) over a 100 year-time horizon and expressed in units of kg CO_2-equivalent. The impacts of the acidifying pollutants such as SO_2 and NOx emissions are measured in terms of acidification potential (AP) and expressed as kg SO_2-equivalent. The photochemical ozone creation potential (POCP) is measured relative to ethylene and is expressed as kg ethane (C_2H_4)-equivalent and the human toxicity potential (HTP) caused by the toxic substances released to air, water and soil are evaluated relative to 1,4 dichlorobenzene and expressed as kg 1,4 DB-equivalent. The analysis accounts for the emissions from residue cultivation (farm operations), biogas conversion process, and distribution to regional storage and use (equation 1).

$$e_{biogas} = e_{coll} + e_{proc} + e_{dist.} - e_{fos-saved} - e_{cpd-saved} \tag{1}$$

Where, e_{biogas} is the total emissions from the use of the biofuel; e_{coll} the emissions from the collection of residues from the field (farm); e_{proc} the emissions from processing; e_{dist} the emissions from biogas distribution; $e_{fos\text{-}saved}$ the emissions savings from natural gas substitution and; $e_{cpd\text{-}saved}$ the emissions savings from mineral fertilizer substitution.

RESULTS AND DISCUSSIONS

The overall LCA (environmental performance) of agricultural residues based biogas and fertilizer were calculated in GaBi LCA software by comparing the benefits that would be obtained from substitution of the conventional natural gas and chemical fertilizer, respectively. The results of the analysis per functional unit (1 ton of agricultural residue processed) for ADP, AP, EP, GWP, ODP, HTP, POCP, FAETP and TETP are depicted in Table 1.

Table 1: Environmental emissions savings for biogas production and utilization from 1 ton agricultural residues

Impact Category	Unit	Amount
ADP	kg Sb-Equiv.	-44.9338
AP	kg SO_2-Equiv.	-16.9939
EP	kg Phosphate-Equiv.	-1.92822
GWP	kg CO_2-Equiv.	-10329.4
ODP	kg R11-Equiv.	-0.0007
HTP	kg DCB-Equiv.	-2695.38
POCP	kg Ethene-Equiv.	-1.43929
FAETP	kg DCB-Equiv.	-73.0778
TETP	kg DCB-Equiv.	-55.5836

Table 2 shows the life cycle environmental performance of agricultural residues based biogas and fertilizer as compared to the conventional natural gas and chemical fertilizer that are being substituted. The results revealed that there is a huge potential savings could be obtained per ton of dry agricultural residues. The result shows that per ton of dry agricultural residues, GWP yielded the highest reduction (i.e., 10329 kg CO_2-Equiv.), followed by HTP (i.e., 2696 kg DCB-Equiv.).

Similarly, the results showed that agricultural residues based biogas resulted in substantial net reduction ADP, AP, EP FAETP, and TETP i.e., reducing around 44.93 kg Sb-Equiv., 17 kg SO2-Equiv., 1.9 kg Phosphate-Equiv., 73 kg DCB-Equiv., and 55.6 kg DCB-Equiv. per ton of dry agricultural residues, respectively.

If any government was to commit to a policy and incentive (for the domestic production of biogas), that would initiate and facilitate the development of biogas production from agricultural residues, that would help substantially in climate change mitigation.

CONCLUSIONS

An LCA of agricultural residues utilization for biogas production was conducted using a cradle to grave LCA methodology. The LCA results revealed that agricultural residues utilization for biogas production would lead to high environmental benefits in terms of ADP, AP, GWP, EP, HTP, ODP, FAETP, and TETP.

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APPENDIX

Amount of Agriculture residues collection at farm

Agricultural residues collection, at farm		
Inputs	**Amount**	**Unit**
Baling [work processes]	5.7143	pcs.
Loading bales [work processes]	5.7143	pcs.
Transport, lorry 20-28t, fleet average [Street]	0.7716	tkm
Outputs		
Residue, at farm [plant production]	1000	kg
Biogas anaerobic digestion process, at plant		
Inputs	**Amount**	**Unit**
Anaerobic digestion plant covered, agriculture [fuels]	4.82E-04	pcs.
Electricity, low voltage, at grid [supply mix]	301.94398	MJ
Residue, at farm [plant production]	1000	kg
Transport, lorry 3.5-20t, fleet average [Street]	27.276	tkm
Treatment, sewage grass refinery, to wastewater treatment, class 3 [wastewater treatment]	6.0949	m^3
Heat, natural gas, at boiler condensing modulating >100kW [heating systems]	393.53	MJ
Outputs		
Biogas [Biomass fuels]	595.2	kg
Digested matter from agricultural anaerobic digestion [organic fertiliser]	989.0	kg