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ENVIRONMENTAL BENEFITS OF VALORISING CATTLE MANURE FOR HOUSEHOLD COOKING ENERGY IN UGANDA

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SUMMARY: This study employed the Life Cycle Assessment (LCA) methodology to evaluate the environmental impacts of utilizing cattle manure as a substrate for biogas generation for cooking energy in Uganda. Results of the study showed that biogas energy systems based of cattle manure has potential environmental benefits in comparison to charcoal produced from natural forests. Under baseline scenario, without recycling of slurry as fertilizer, the biogas system leads to total environmental impacts of over 80% less than that of charcoal system. When slurry is utilized as substitute mineral fertilizers, the environmental impact of biogas system was found to be less than that of charcoal by close to 95%. The study further showed that that use of biogas could lead to considerable reduction on human health impacts compared to charcoal. In conclusion, utilization of cattle manure for biogas production has potential benefit of reducing the environmental impacts due to charcoal production and use in Uganda.

1. INTRODUCTION

Developing countries heavily rely on solid fuels for domestic applications such as cooking and heating. Most common solid fuels include firewood, charcoal, coal and agricultural residues (IEA, 2013). When used in the indoor environment, they lead to air pollution, which is a major health risk factor to women and children living in developing countries (Lim et al., 2013). Charcoal in particular is popular among urban users in developing countries because of their higher energy density and lower emissions than firewood (Mwampamba, 2007). However, its production, transportation and use results in environmental pressures ranging from deforestation, loss of biodiversity and emissions during pyrolysis and combustion.

Actually, it is estimated that emissions of greenhouse gases from charcoal production from tropical ecosystems amount to 71.2 and 1.3 million tones of CO₂ and CH₄, respectively (Chidumayo and Gumbo, 2013). Use of charcoal could therefore significantly contribute to the global warming phenomenon as well as lead to impacts on human health and the ecosystem. Consequently, other technologies are currently being explored to supplement or substitute extensive use of charcoal in

developing countries. Amongst these technologies is the domestic biogas energy system (Okello et al., 2013b). Domestic biogas technologies have of recent past attracted a lot of interest from policy makers in developing countries including Uganda. Currently, there is a deliberate effort by the Ugandan government and development partners to promote the technology to meet household energy requirements (Sengendo et al., 2010). For example, in the Renewable Energy Policy for Uganda (MEMD, 2007), the Ugandan government aims at installing 100,000 domestic biogas digesters by the year 2017. The domestic biogas technology provides opportunities for integration with crop production, since slurry is known to be a very good organic fertilizer (Okello et al., 2013b; Walekhwa et al., 2014). Use of slurry as a fertilizer could result in savings of energy, resources and emission along the supply chain of mineral fertilizers.

The potential to mitigate atmospheric methane emission from decaying cattle manure is another important advantage of the biogas technology. This is because utilization of biogas for cooking converts methane that could be released to the atmosphere into CO₂, a gas with a global warming potential of about 25 times less than that of CH₄ (Bruun et al., 2014). Nevertheless, methane emissions still occur along the biogas supply chains, for example, due to leakages of biogas from the digesters (Bruun et al., 2014; Khoiyangbam et al., 2004). Emissions of pollutants also occur during combustion phase of biogas and other processes such as production of cattle feeds as well as cattle rearing. Despite the increased interest in domestic biogas technology in Uganda, there is very limited information on the environmental benefits of employing the technology as a cooking fuel from a life cycle perspective. This study was therefore carried out to provide knowledge about the potential environmental benefits of using domestic biogas system as a cooking fuel in Uganda. The objective of this study was to model and quantify the life cycle environmental impacts of the domestic biogas energy systems in Uganda using the life cycle assessment (LCA) methodology. Charcoal, which is widely used for cooking in the country was taken as the reference system.

2. METHODOLOGY

The Life Cycle Assessment (LCA) methodology was employed to assess the environmental impact of the domestic biogas cooking system with the charcoal cooking as a reference system. The LCA methodology is an objective method for determining energy and material use, and release of wastes to the environment by a product, service or an activity (Klöpffer, 2006). Currently, the International Organization for Standardization (ISO) has developed standards to guide LCA studies.

These are the ISO 14040 and ISO 14044 standards, which provides principles and framework, and the requirements and guidelines for LCA studies, respectively (Finkbeiner et al., 2006). These standards require that LCA studies are executed in four generic phases involving: (1) definition of the goal and scope, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment, and (4) life cycle interpretation.

2.1 Goal and scope of the study

The goal of the study was to evaluate the environmental impacts of the small-scale domestic biogas systems used for cooking in Uganda, with the charcoal systems as the reference. The scope of the study is from cradle-to-gate. It included assessment of environmental impacts during acquisition of material raw materials, processing, transportation and use. Environmental benefits resulting from the recycling of slurry, the by-product of the biogas system as a fertilizer for crop production was also evaluated. Detailed descriptions of the scopes of the energy systems evaluated are given in Sections 2.1.1 and 2.1.2.

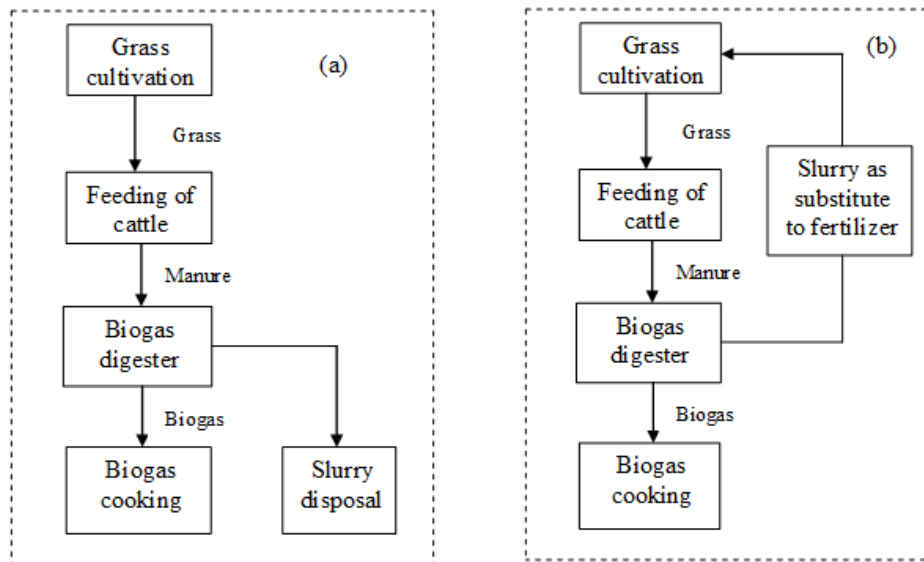


Figure 1. System boundary of the biogas systems (a) Scenario A, (b) Scenario B.

2.1.1 Description and scope of the biogas system

Biogas is mixture of gases composed of methane, carbon dioxide and traces of other gases, and is produced by anaerobic fermentation of organic matter. The methane component of biogas is combustible and can be used to generate energy for a variety of applications. Biogas is produced in an airtight container called digesters, of which three different designs are available in Uganda; namely, the fixed-dome, floating-dome and bag digester designs.

The biogas system involves use of manure generated by cattle as substrate for biogas production. The fixed-dome biogas digester, in which both the gas and the substrate occupy the same chamber is the most commonly used in Uganda technology for biogas production in Uganda. The digester is built underground, and usually range in volume from 6 to 16 m³ (Okello et al., 2013b; Walekhwa et al., 2009). Two scenarios of the biogas system were evaluated. In Scenario A, which is the baseline, grass is cultivated and used to feed cattle. This scenario models the common practice, in which slurry is released to the environment without utilizing its potential as a fertilizer. Illustration of the system boundary for the baseline scenario is given by Figure 1 (a). Scenario B on the other hand maintains all the upstream processes, but differs from Scenario A, in that slurry is used as a substitute to inorganic fertilizer. Material flow and scope of Scenario B is illustrated using the LCA diagram given in Figure 1 (b).

In both scenarios, use of feed supplements, acaricides, and veterinary drugs for cattle treatment and maintenance were excluded from the scope of the study due to lack of relevant data. It was also assumed that most of the environmental impacts of the biogas system occur during the use phase; therefore, impacts due to infrastructure development were excluded from the scope of the study.

Allocation was necessary in the biogas systems, in which cattle rearing results in production of milk for sale or consumption by households and manure used for biogas production. It was assumed that 10% of environmental impacts resulting from grass production and cattle keeping are associated with energy production and dairy products account for the remaining 90%.

2.1.2 Description and scope of the charcoal system

Charcoal was taken as the reference system because it is the most commonly used technology for cooking in urban areas of Uganda. It is mainly produced from woody biomass harvested from natural forests. Charcoal is produced using the pyrolysis process in traditional earth mound kilns. It

is produced far away from the point of consumption; therefore, it is transported to point of use in trucks. The *Kenya Ceramic Jiko* (KCJ) stove was used for modeling the cooking process with charcoal. Disposal of ash resulting from charcoal combustion was excluded from the scope of the study, since it was assumed not to contribute significantly to environmental impacts. The geographical scope of the study was the district of Gulu, located in northern Uganda.

2.2 Life cycle inventory

The Life Cycle Inventory (LCI) of the LCA aims at quantification and compilation of the inputs and outputs of a given product through its entire life cycle. This can be based on primary as well as secondary data. For this study, a functional unit of 1 MJ of heat effectively used for cooking was taken into consideration when developing the LCI. Detailed description of the LCI phase of this study is given in Section 3.

2.3 Life cycle impact assessment

Eco-indicator 99 (Frishknecht and Jungbluth, 2007), a damage oriented approach for impact assessment was used in this study. The analysis included 11 environmental impacts, categorised under three endpoint impact categories of human health (carcinogens, respiratory organics and inorganics, climate change, radiation, ozone layer, ecotoxicity and acidification/eutrophication), ecosystem quality (land use) and resources (minerals and fossil fuels). The LCA Software SimaPro version 7.3.3 was used to aid analysis and of the data.

2.4 Life cycle interpretation

Interpretation of LCA results was performed through contribution analysis to identify environmental hotspots of the bioenergy supply chains. Also comparative plots of single score of impacts for each technology were done in order to understand the relative environmental impacts of the technologies.

3. LIFE CYCLE INVENTORY ANALYSIS

Life cycle inventory data for this study were mainly from secondary sources, and were realised from a detailed review of available literature. In cases where data could not be obtained under Ugandan conditions, effort was made to ensure that the data used were for similar technologies to those evaluated in this study. In addition, the ecoinvent version 2.1 database used to provide data such as emissions from transportation and fertilizer production processes.

3.1 Life cycle inventory analysis of the charcoal system

The charcoal system was modelled based on the current system of charcoal production, which involves harvesting of wood from natural forest, followed by pyrolysis in the traditional earth-mound kilns. The charcoal produced is packed in polythene bags and transported using trucks to the urban areas for cooking using charcoal stoves. All the harvesting and charcoal production operations are carried out manually using simple tools, such as axes and machetes.

Wood harvesting stage involves selective logging of the above-ground portion of the vegetation; therefore, could result in variation in carbon stock. Estimated of carbon stock flux due to wood harvesting of -1.43 t C per tonne of charcoal produced from native vegetation on a 15 year coppice was assumed based on a study by Bailis, (2005).

Not all the above ground biomass harvested is converted into charcoal. Small branches and leaves that is not suitable for charcoal production is burnt in open fire in the forest, or in some cases collected and used as firewood for cooking. It was therefore assumed that unsuitable wood, estimated to be about 10% of the mass of the total harvested biomass is burnt in open air. This results in air emissions that was estimated to be equivalent to open fire burning under savannah conditions (Akagi et al., 2011).

Table 1. Life cycle inventory of the charcoal system

<i>Process</i>	<i>Inputs and outputs</i>	<i>Quantity per MJ of heat</i>	<i>Unit</i>
Wood harvesting	<i>Input</i>		
	Natural forest vegetation (dry)	2.9630	kg
	<i>Output</i>		
	Net CO ₂ flux due to direct land use change	-5.83E-04	kg
	Dry wood for charcoal	2.66667	kg
	Wood waste (10%) of total	2.96E-01	kg
	<i>Emissions from open air wood waste combustions</i>		
	CO ₂	5.00E-01	kg
	CO	1.87E-02	kg
	NO _x	1.16E-03	kg
	NH ₃	1.54E-04	kg
	N ₂ O	0.00E+00	
	SO ₂	1.42E-04	kg
	NM ₂ VOC	1.40E-02	kg
	CH ₄	5.75E-04	kg
	PM _{2.5}	2.12E-03	kg
Charcoal production (pyrolysis) in earth mound kilns, 12.5% efficiency	<i>Inputs</i>		
	Dry wood	2.66667	kg
	<i>Outputs</i>		
	Charcoal	0.33333	kg
	<i>Emissions</i>		
	CO ₂	6.01E-01	kg
	CO	7.43E-02	kg
	NO _x	2.10E-05	kg
	NO	1.87E-05	kg
	N ₂ O	5.00E-06	kg
	SO ₂	0.00E+00	
	NM ₂ VOC	3.09E-02	kg
	CH ₄	1.49E-02	kg
	PM (TSP)	1.01E-02	kg
Transport	<i>Inputs</i>		
	16 t truck	1.00E-02	
Charcoal combustion, Ceramic Jiko stove, (10% efficiency), 15% efficiency	<i>Inputs</i>		
	Charcoal (equivalent to 5.56MJ heat)	3.33E-01	kg
	<i>Output</i>		
	Heat (product)	1.00	MJ
	<i>Emissions (Per MJ heat effective)</i>		
	CO ₂	6.96E-01	kg
	CO	6.57E-02	kg
	NO _x	3.33E-05	kg
	N ₂ O	0.00E+00	
	SO ₂	0.00E+00	
	NM ₂ VOC	3.40E-03	kg
	CH ₄	4.17E-03	kg
	PM _{2.5}	1.32E-03	kg

Carbonization was assumed to be in traditional earth-mound kilns. It is the most commonly used technology for charcoal production in Uganda as well as other sub-Saharan African countries. It involves stacking the harvested wood in piles and covering with soil to limit the oxygen supply during pyrolysis. The efficiency of the process ranges from about 10 to 15% (Knöpfle, 2004; Okello et al., 2013b). The worst-case scenario of 10 % efficiency of charcoal recovery was used for

modeling charcoal production in this study. Carbonization process results in emissions of gases such as CO₂, CO, CH₄, NMVOC and particulates. Emission factors for charcoal production in earth-mound kilns were obtained from Pennise et al., (2001).

Charcoal is then packed in polythene bags and transported using trucks to the urban area where it is used for cooking. It was assumed that a 16 tonne truck is used for transportation and estimates of emission from the truck were based on the ecoinvent 2.1 process. An average charcoal collection distance of 40 km was assumed.

Use of charcoal is by combustion in charcoal stoves, resulting in emissions of pollutants and greenhouses gases such as CO₂, CO, CH₄, NMVOC and particulates (Bhattacharya et al., 2002).

Level of emissions depends on the design of the stove. The *Kenya Ceramic Jiko* is a commonly used charcoal stove in Uganda and was therefore used in modeling the combustion process.

Emission factors for the KCJ stove was obtained from Jetter et al., (2012). Stove thermal efficiency at cold start of 15% (Oketch, 2012) was assumed, and the calorific value of charcoal was assumed to be 30.8 MJ kg⁻¹ (Bhattacharya et al., 2002). The LCI for a functional unit of 1 MJ heat energy effectively used for cooking using the charcoal system was calculated and results were presented in Table 1.

3.2 Inventory of biogas system

Cattle manure is the most commonly used substrate for biogas production in Uganda. In this study, the biogas system was modelled from the stage of Napier Grass (*Pennisetum Purpureum*) cultivation, which is used as feeds to cattle kept under zero-grazing. Manure generated by the cattle is mixed with water in a ratio of 1:1 by volume and a fixed amount is fed into the bio-digester on a daily basis. Dilution of manure with water enhances gravitational flow of substrate through the system; therefore, avoiding need for mechanical pumping operations. Gas from the storage chamber of the digester is conveyed through pipes and used for cooking using biogas burners.

3.2.1 Biogas system scenario A

Cultivation, weeding and harvesting of grass are typically manual operations in Uganda. Grass production was assumed to be under rain fed conditions without supplementary irrigation input. Under the baseline conditions (Scenario A), it was assumed that mineral fertilizers are applied to the grass plantation to maintain yield. The annual requirement of fertilizer for grass production was taken as 200 kg ha⁻¹ of calcium ammonium nitrate (CAN), triple superphosphate (TSP) or single superphosphate (SSP) at a rate of 300 kg ha⁻¹ and Muriate Potash (KCL) at a rate of 80 kg ha⁻¹ as recommended by Orodho, (2006). All operations were assumed to take place close to the biogas plant and therefore, vehicles were not required for transportation of materials. The grass yield was taken to be 8000 kg dry matter per hectare in accordance with Lukuyu et al., (2012).

A typical head of cattle weighing 400 kg and requiring 12 kg dry matter feed per day was assumed. Rearing of cattle results in enteric methane emissions, which in accordance with Casey and Holden, (2005) was taken to be 100 kg y⁻¹ per cattle head. Dry matter (DM) content of manure was assumed to be 15%, and biogas yield from manure is assumed to be 0.281 kg kg⁻¹ of DM. Since the digester is not fully airtight, some methane is lost during digestion through openings such as the substrate inlet pipe and slurry expansion chamber (Khoiyangbam et al., 2004). Estimated methane loss from fixed and floating dome digesters range from 5 to 15% of total methane yield (Griggs and Noguer, 2002; Pathak et al., 2009). For this study, methane emission from the CARMATEC bio-digester was estimated using the mid value of 10% leakage.

The use phase of the biogas system involves combustion of the gas in burners. Burners are of several designs, some of which are locally fabricated by Ugandan artisans and their emissions and efficiencies are expected to vary with design. For this study, it was assumed that the efficiency of

biogas burner is 55% (Sasse et al., 1991). Heating value of biogas was assumed to be 20 MJ kg⁻¹ and density as 1 kg m⁻³ (Perera et al., 2005). Combustion of biogas results in emissions such as CO₂, CH₄, NO_x and particulate matter. Emission factors from biogas burners were adopted from Afrane and Ntiamoah (2012) and Smith et al., (2000).

Slurry is the by-product of the digestion process and it flows by gravity from the expansion chamber into a storage tank. It is rich in essential plant nutrients, with the DM comprising of 1.4% nitrogen, 0.5% phosphorus, and 0.8% potassium (Pathak et al., 2009). Under Scenario A, it was assumed that the slurry is discarded without utilising it as a fertilizer, which is a common practice in Uganda.

Table 2. Life cycle inventory for the biogas system

Process	Inputs and outputs	Quantity per MJ of heat	Units
Grass cultivation	<i>Input</i>		
	N as Calcium ammonium nitrate (CAN)	3.78E-02	kg
	P as Single/triple superphosphate (Mono-calcium phosphate)	5.66E-02	kg
	K as Muriate Potash (Potassium chloride KCL)	1.51E-02	kg
	Land occupation	1.888	m ²
	<i>Output</i>		
	Grass (dry matter)	1.51	kg
Cattle Feeding	<i>Inputs</i>		
	Grass (dry matter)	1.51	kg
	Water	8.808	L
	<i>Outputs</i>		
	Enteric methane emission	3.45E-02	kg
Biogas production	Manure (dry matter)	3.59E-01	kg
	<i>Inputs</i>		
	Water	2.3933	L
	Manure (dry matter)	3.59E-01	kg
	<i>Outputs</i>		
	Methane emissions	6.00E-03	kg
	CO ₂ emissions		kg
Biogas combustion	Biogas	9.10E-02	kg
	<i>Inputs</i>		
	Biogas	9.10E-02	kg
	<i>Output (emissions kg MJ⁻¹)</i>		
	CO ₂	1.47E-01	kg
	CO	2.03E-04	kg
	NO _x	9.15E-05	kg
	N ₂ O		
	SO ₂	1.02E-05	kg
	NM VOC	6.10E-05	kg
	CH ₄	1.02E-04	kg
	PM	4.82E-06	kg
Effluent management	<i>Inputs</i>		
	Effluent (volume)	4.790	L
	<i>Outputs</i>		
	NH ₃	5.500E-04	kg
	CH ₄	3.218E-03	kg
	N ₂ O	7.467E-05	kg

3.2.1 Biogas system scenario B

Under Scenario B, all the processes in scenario A were maintained, except that slurry was modelled as substitute to mineral fertilizers by applying it in the grass fields. Application of slurry was assumed to be manually done, so does not require machinery operations. However, the slurry emits gases such as NH_3 , CH_4 and N_2O during storage and application in crop fields (Boulamanti et al., 2013).

Total emissions of NH_3 , CH_4 and N_2O during storage and application were assumed to be 229.9 g m^{-3} , 1344.6 g m^{-3} and 31.2 g m^{-3} , respectively (Amon et al., 2006). It was assumed that negligible loss in mass of the substrate occurs during digestion (Pathak et al., 2009). Therefore, the volume DM content of slurry was assumed to be equivalent to that of the initial substrate material fed into the digester. Inventory analysis for both Scenarios A and B of the biogas systems were developed and presented in Table 2.

4. RESULTS AND DISCUSSIONS

4.1 Characterization results

Characterisation results for Scenarios A and B of the biogas systems in comparison to the reference system are presented in Table 3. The results show that Scenario A of the biogas system had lower impact categories of carcinogens, respiratory organics and inorganics, and climate change. However, charcoal showed better performance in terms of the radiation and ecotoxicity impact categories which were $6.85\text{E-}12$ and $5.19\text{E-}13$ disability adjusted life years (DALY), respectively. A summary of results of the Scenario A is presented in Figure 2 (a), which shows that charcoal had better performance than charcoal in four of the 11 impact categories evaluated.

Table 3 also shows characterisation results of Scenario B of the biogas system. It can be observed that under Scenario B, the biogas system shows better performance in all impact categories than the charcoal system, except the Eutrophication/Acidification potential. When compared to Scenario A, this result suggests that using slurry as a substitute to mineral fertilizers leads to a significant reduction in environmental impacts of the biogas system. Figure 2 (a) and (b) are graphical illustrations of the relative contribution of Scenarios A and B of the biogas system compared to charcoal system. It shows that by recycling manure as substitute to inorganic fertilizers, biogas system has potential to benefit the environment in ten out of the eleven impact categories evaluated.

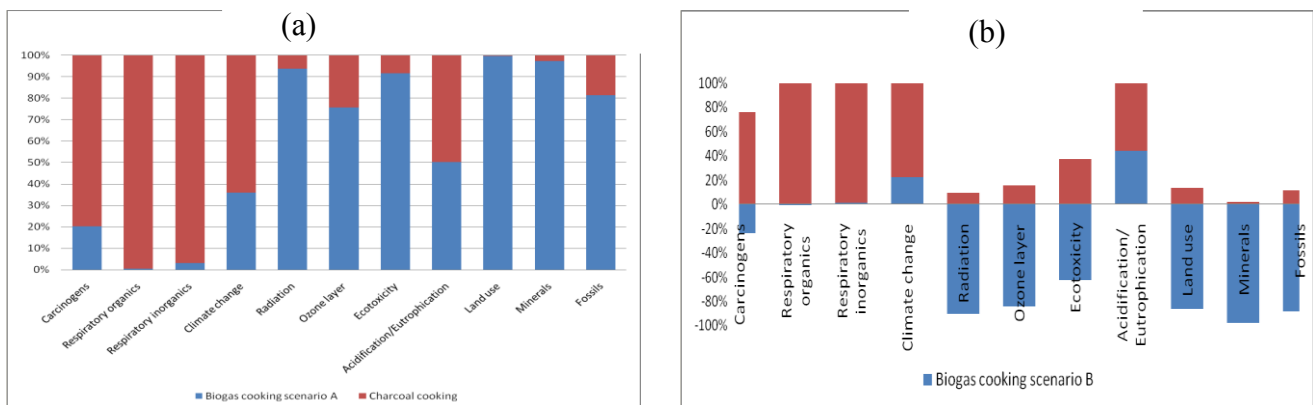


Figure 2. Characterization results in percentage showing relative contributions to environmental impacts (a) biogas scenario A and charcoal, (b) biogas Scenario B and charcoal.

Table 3. Characterization results of biogas and charcoal cooking systems.

Impact category	Unit	Biogas cooking scenario A	Biogas cooking scenario A	Charcoal cooking
Carcinogens	DALY	8.59E-09	-1.05E-08	3.39E-8
Respiratory organics	DALY	2.29E-10	1.83E-10	6.21E-8
Respiratory inorganics	DALY	8.18E-08	3.17E-08	2.66E-6
Climate change	DALY	4.73E-08	2.45E-08	8.43E-8
Radiation	DALY	1.02E-10	-6.26E-11	6.85E-12
Ozone layer	DALY	1.61E-12	-2.81E-12	5.19E-13
Ecotoxicity	PAF*m2yr	0.0089	-0.0136	0.000814
Acidification/Eutrophication	PAF*m2yr	0.00988	0.0077	0.00974
Land use	PDF	0.109	-0.000368	5.82E-05
Minerals	MJ surplus	0.00148	-0.00234	4.10E-05
Fossils	MJ surplus	0.0166	-0.0285	0.00377

4.2 Contribution analysis of the biogas system

The contribution analysis was performed in order to identify hotspots of environmental impacts of the biogas systems for both scenarios A and B. Figure 3 (a) shows the contribution of the different processes to the environmental impacts of Scenario A of the biogas system. It shows that grass production stage of the biogas system had the highest environmental impacts of 0.009 EcoPoints.

This is probably due to impacts of the fertilizer requirements for grass productions, since the contribution of this process drops significantly when manure is used to substitute inorganic fertilizers as shown in Figure 3 (b). Results also indicate that the biogas production phase also has high environmental impacts, which is probably due to leakage of biogas from the biogas plant.

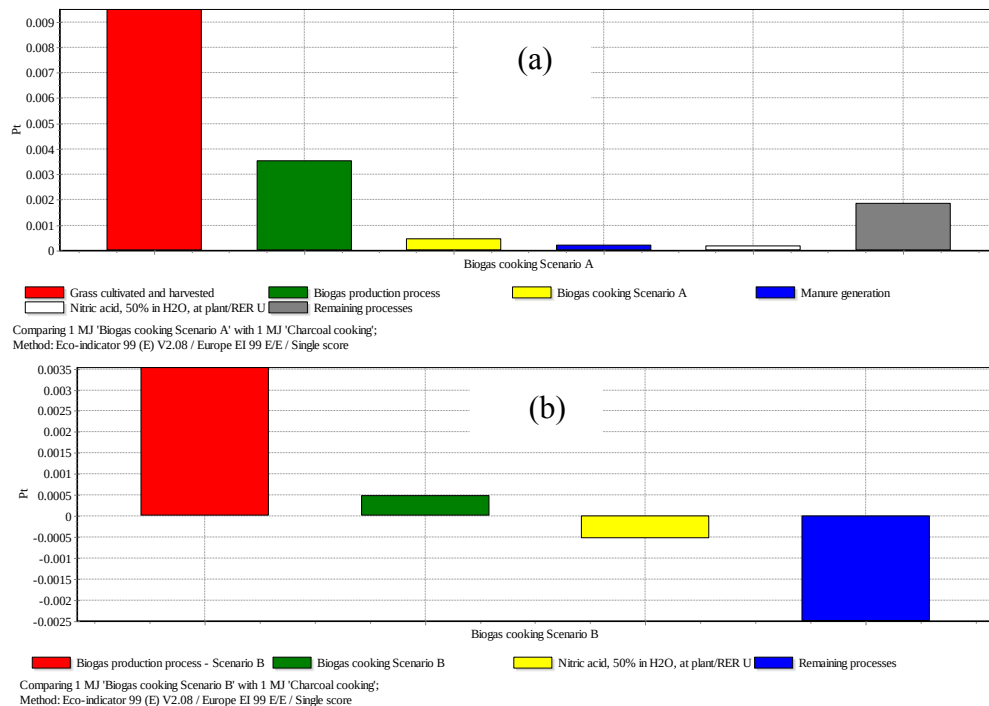


Figure 3. Contribution analysis of the biogas systems (a) Scenario A, (b) Scenario B.

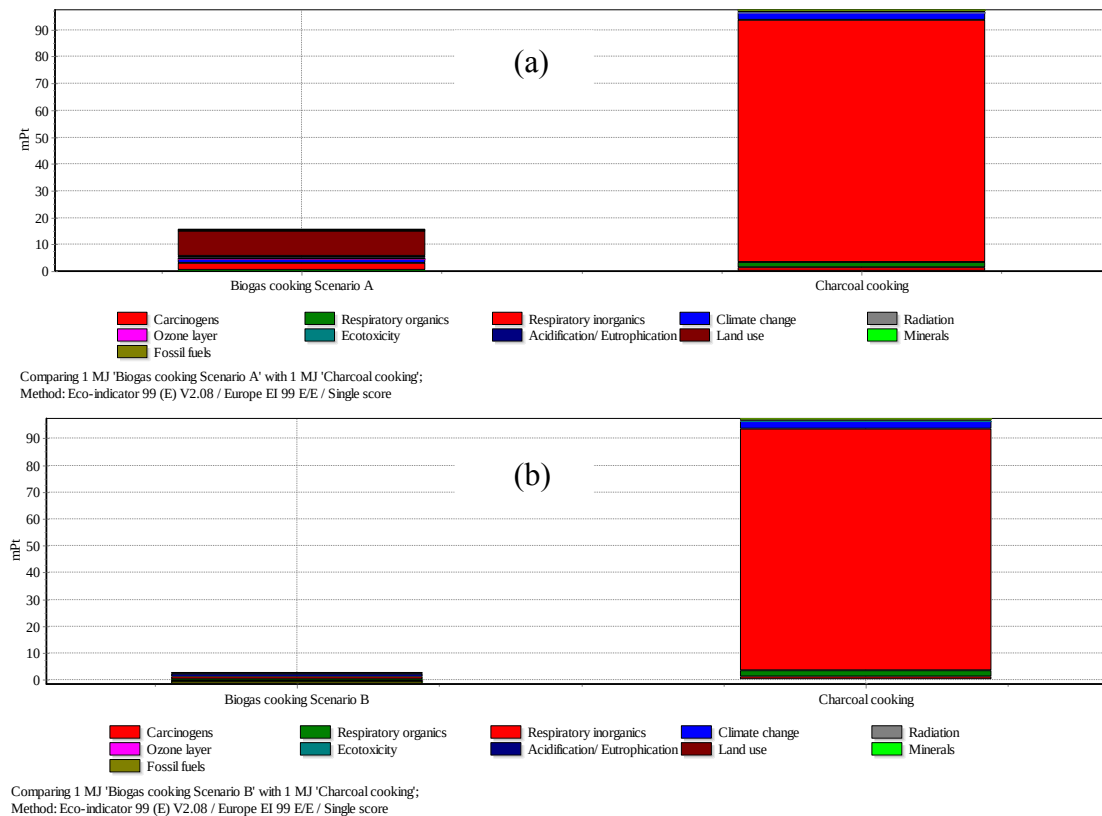


Figure 4. End point analysis of Scenario A of biogas system compared to charcoal system

4.3 Comparison of the single scores of environmental impacts

The single scores of the environmental impacts of the two scenarios of the biogas systems were evaluated in comparison with the charcoal system. Figure 4 (a) shows the single score of the Scenario A of the biogas system compared to that of charcoal. It shows that Scenario A of the biogas system results in environmental impacts of about 17 mPts, compared to charcoal system with total impact close to 100 mPts. It can therefore be observed that without recycling of slurry as fertilizer, biogas system has lower environmental impacts than charcoal system by close to 80%.

The highest impact from of the charcoal system is mainly due to respiratory inorganics, which contributes over 90% of the total impacts of the charcoal system. Use of biogas could therefore result in improved health of users as suggested by Afrane and Ntiamoah (2012).

The effect of recycling of slurry on the total environmental impact of the biogas system (Scenario B) is shown in Figure 4 (b). In comparison to Scenario A, it can be observed that use of slurry as substitute to mineral fertilizers leads to a significant reduction of the total impact of the biogas system.

5. CONCLUSIONS

The study aimed at evaluating the environmental benefits of using biogas as a cooking fuel in Uganda. Results showed that biogas has a high potential to benefit the environment compared to the charcoal system. This study demonstrated that use of slurry from biogas production as a substitute to mineral fertilizers would result in considerable improvement of the biogas system. Also use of biogas systems results in significantly lower impacts on human health compared to the charcoal system.

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