Environmental, social and health benefits of alternative renewable energy sources. Case study for household biogas digesters in rural areas

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Abbreviations

LPG – Liquefied Petroleum Gas
FW – Firewood
LCA – Life Cycle Assessment
BMFG – Biogas from Mineral Fertilized Grass
BOFG – Biogas from Organic Fertilized Grass
PM – Particulate Matter
Mtoe - Million tons of oil equivalent
MF – Mineral Fertilizer
FT – Fertilizer Transport
DF – Digestate Fertilizer
Cu – Cultivation
GC – Grass Chopped
HD – Household Digestion
OF – Organic Fertilizer
LPG_T – LPG Transport
FW_A – Firewood Acquisition
LPG_A – LPG Acquisition
TE – Thermal Efficiency
CC – Climate Change
HTnCE – Human Toxicity, non-Cancer Effects
PhOF – Photochemical Ozone Formation
PA – Acidification
FE – Freshwater Eutrophication
FET – Freshwater Eco-toxicity
LU – Land Use
WRD – Water Resource Depletion
MFRRD – Mineral, Fossil, Renewable Resource Depletion
TD – Dedicated Time

Abstract

In rural areas of Colombia, liquefied petroleum gas (LPG) is the preferred option available for cooking. However, the poorest households rely on firewood (FW) to meet their daily cooking needs, because is the most accessible and affordable energy source. This high level of dependence on traditional solid fuels and the use of non-optimized cook stoves results in high health, environmental, economic and social costs on developing countries' households. This study aimed at assessing the environmental and health benefits of implementing grass-fed household biogas digesters in rural areas of Colombia, through Life Cycle Assessment (LCA) methodology. Functional Unit was the annual demand of cooking energy by a typical family in those rural areas, which means 2,400 MJ of useful heat. There were evaluated two sources of biogas obtained from *Pennisetum* grass: Biogas from minerally fertilized grass (BMFG) and from organically fertilized one (BOFG). Results showed that FW had the highest impacts from fuels assessed, while the lowest impacts were found with BOFG, showing half of LCA total impacts compared with LPG and more than two orders of magnitude lower in non-methane volatile organic compounds and particulate matter ($PM_{2.5eq}$) emitted compared with FW. Therefore, BOFG appears as an environmentally feasible alternative for cooking, which allowed the reduction LCA impacts among most of the categories assessed, as the fuel purchase expenses and of the wood collection time. Moreover, health impacts including the indoor emissions exposure showed also more than two orders of magnitude less impact compared with FW. It can be concluded that household digesters could improve the living standard of rural families.

Keywords

Cooking energy, Life Cycle Assessment (LCA), Indoor air pollution, Household digester, developing countries, Pennisetum grasses.

1. Introduction

The share of solid fuels in total residential sector final energy demand in developing countries remains significant, in the range of 75% in 1990 to 60% in 2011. In contrast, the share of liquid or gaseous fuels (kerosene, LPG, biogas and natural gas) is increasing steadily from 15% in 1990 to 20% in 2011. In contrast to developing countries, the share of modern fuels in total residential sector final energy demand is increasing steadily from 68% in 1990 to 79% in 2011 in OECD countries (Malla and Timilsina, 2014).

According to the World Bank, solid fuels such as biomass (firewood, charcoal, manure, agricultural residues) and coal are often the primary sources of energy for cooking in rural areas of developing countries (World Bank, 2015). Liquefied Petroleum Gas (LPG), and in a less extend biogas, have an increase use as energy source in rural areas, meanwhile electricity is mainly used for lighting and electrical-electronic devices rather than for cooking, and have restrictions in non-interconnected areas. Colombia has large-scale programs to support the adoption of LPG in rural areas, which represents around 40% of the energy supply mix. However, firewood (FW) and charcoal continue to be the higher used fuels with a 49% (Global Alliance for Clean Cookstoves, 2012).

Although the use of biomass itself is not a concern, when natural resources are not harvested sustainably, and conversion technologies are inefficient, could cause adverse consequences for health, the environment, and economic development arose (IEA, 2006). Nearly 3 billion people in the world cook or heat their homes with solid fuels like FW or other biomass, resulting in indoor and outdoor air pollution that cause widespread health impacts (World Bank, 2018).

FW has been considered the fuel with the highest negative impact on health in Latin America and Caribbean due to its high particulate matter ($PM_{2.5eq}$) and Carbon Monoxide (CO) emissions. Others of the greatest impacts are the time used by women and children for collecting wood and the exposure to polluted air inside homes, due to defective or expired devices (inadequate air circulation). In the absence of efficient use of FW programs, the appliances consume a considerable amount of FW to satisfy their requirements (ECLAC, 2009). Furthermore, it may be a specific relevant factor regarding the deforestation problem. However, it is now widely accepted that the land-use changes caused by the expansion of agricultural activities is the main cause of deforestation rather than the use of FW for energy, as was believed in the past (Ekouevi and Tuntivate, 2012).

Two complementary approaches can improve this situation: promoting more efficient and sustainable use of traditional biomass, and encouraging people to use modern cooking technologies (IEA, 2006). Although biogas constitutes one of the main alternatives with application in rural areas of developing countries, its participation differs among countries from one another. The implementation of domestic digesters for biogas production in Latin America and Caribbean was stimulated after the energy crisis in the 1970s, but the amount installed is still less than in Asia (Garfí et al., 2016). Of the 35 Mtoe of biogas consumed worldwide in 2018, around 27% correspond to China, while Latin America and the Caribbean remain below 3% of the share (IEA, 2020).

On the other hand, natural and cultivated grasslands represent 67% of the world's cultivated areas, being one of the least expensive and most common biomass in rural areas (FAO, 2014). Grasslands in Colombia are productive throughout the year and their growth rates rely mainly on water availability. *Pennisetum sp*. grasses are the most prevalent in the region and *green elephant* genotypes are recommended under non-irrigated conditions or limited rain, between 600 and 1,500 mm annually (Murillo-Solano et al., 2014).

Moreover, *Pennisetum* grasses are one of the energy crops with the highest specific methane yield worldwide (Nallathambi Gunaseelan, 1997). Its specific methane yields range from 104 to 310 mL_{CH4} g^{-1}_{VS} for harvesting ages between 60 and 360 days, where young tissues produced more methane than the old tissues (Chynoweth et al., 1993; Surendra and Khanal, 2015; Thaemngoen et al., 2020). In tropical countries, harvesting ages between 30 and 60 days are common (Chanpla et al., 2017; Lounglawan et al., 2014). Previous studies evidenced that anaerobic digestion of King Grass (*Pennisetum purpureum cv. king grass*) in domestic digesters could generate a specific methane yield of 347 mL_{CH4} g^{-1}_{VS}, and area-specific methane yield of 9,773 Nm^3_{CH4} ha^{-1} y^{-1} with optimal harvest age of 44 days (Pizarro-Loaiza et al., 2020).

The annual demand of cooking energy by a typical family in rural areas of

Colombia is estimated in 2,400 MJ, equivalent to 6,000 MJ of LPG with a thermal efficiency of 40%. About 13 million people using LPG, as cooking fuel, have an annual consumption per house unit of 132 kg_{LPG} (GASNOVA, 2019). Previous studies, also shown that cooking energy for a typical family in Colombian rural zones, with biogas produced by anaerobic digestion of grass, would require 154 m^2 of *King Grass* crop, that can be easily assumed by this type of housing (Pizarro-Loaiza et al., 2020).

Few studies have assessed the environmental benefits of household and small-scale farms digesters in rural areas of developing countries. Although they showed that household digesters led to environmental benefits most of them only focus on climate change or outdoor environmental impacts (Garfí et al., 2019; Vu et al., 2015; Wang et al., 2018). Studies of Sfez et al. (2017) as well as Lansche and Müller (2017) consider the indoor air pollution, but they focus on the substitution of dung cakes, the traditional biomass for cooking in African or Asian developing countries.

Life Cycle Assessment (LCA) is becoming the recommended tool (ISO, 2006) to conduct environmental assessment. LCA has widespread applications in supply chain management, policy analysis, identification of effective improvement strategies for the environmental performance of products, and avoid load shifting between different environmental problems. However, most of current LCAs only consider outdoor exposure to chemical concentrations present in the environment, while indoor proximity exposure to emitting sources in confined spaces has not yet been integrated (Rosenbaum et al., 2015).

Since the impacts of FW combustion on human health have received considerable attention in Latin America and Caribbean, due to the long periods of exposure to indoor concentrations and house designs (World Bank, 2018), the indoor air pollutant exposure must be quantified , in addition of the emitter

The aim of this study was to assess the environmental benefits of implementing a grass-fed household biogas digester fed with *king grass* grown in rural areas of Colombia using mineral fertilizer (BMFG) and organic fertilizer (BOFG). The use of biogas was compared with the available cooking fuels in the area, FW and LPG. LCA methodology was used to assess the environmental impact. Moreover, the indoor environment exposure was considered in the method of calculation for human toxicity category, representing the health impacts.

2. Material and methods

2.1. Methodology

To assess the environmental benefits of implementing a king grass-fed household biogas system in rural areas of Colombia, substituting the available cooking fuels, FW, and LPG, the environmental impacts of the different cooking fuel options were estimated and compared using a LCA methodology according with the ISO-14044 (ISO, 2006).

There were two biogas-based options proposed, which use king grass as household digester feedstock. In the first one, the grass was fertilized with mineral fertilizer (BMFG) and the other one fertilized with organic fertilizer (BOFG). In both cases, the digestate from de household biogas system was used to fertilize the crop fields closing the nutrient cycle and reducing the inorganic fertilization requirements.

The main aspects considered were: *i)* environmental inventory, which included energy and resources consumption, emissions and wastes; *ii)* environmental impacts and critical environmental stages for BMFG and BOFG; *iii)* comparison of environmental impacts between the present and proposed biogas-based cooking fuels; and *iv)* benefits of the best biogas-based scenario vs current scenario in rural Colombia (50% FW + 50% LPG, considering that isolated Colombian rural households do not exclusively use a single fuel, but a combination of fuels instead).

Figure 1 shows the process and the detailed system considered in the four cooking fuel scenarios analysed: Biogas BMFG, Biogas BOFG, FW, and LPG.

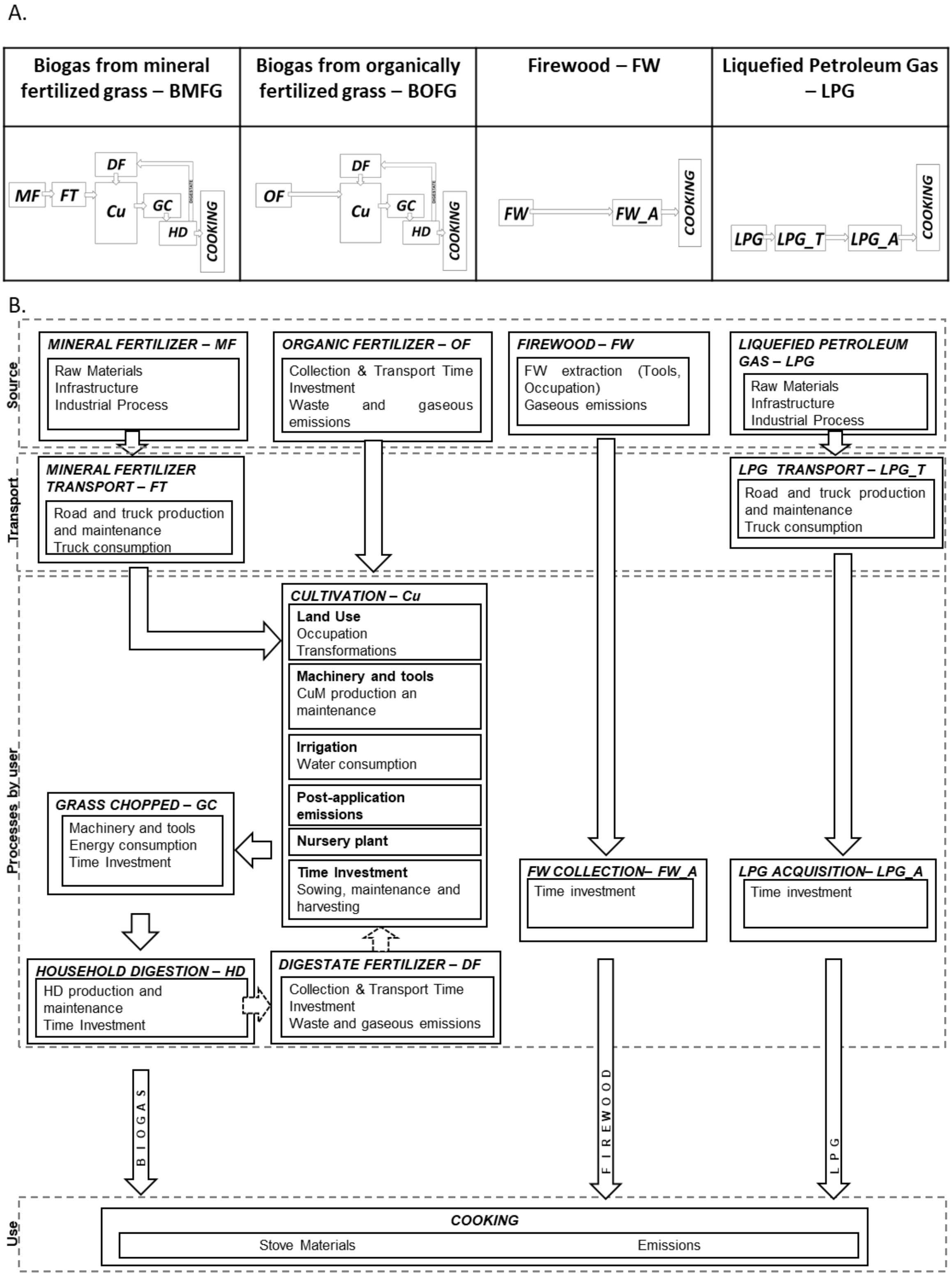

Figure 1. A. Cooking fuel scenarios evaluated and B. Process considered.

Note: MF, Mineral fertilizers production; FT, Mineral fertilizers transport; Cu, Cultivation; GC, Grass Chopped; HD, household digestion; DF, digestate fertilizer; OF, organic fertilizer; FW, firewood extraction; FW_A, firewood acquisition; LPG, LPG production; LPG_T, LPG transport; LPG_A, LPG acquisition.

The annual demand of cooking energy (2,400MJ of useful heat for cooking) by a typical family in rural Colombia was the functional unit chosen as a reference to normalize the input/output flows (ISO, 2006).

Ten midpoint impact categories following the methods proposed by ILCD (2011) and relevant for the case study conducted (excluding those categories for what no changes between scenarios were observed) were selected: Climate Change, Human Toxicity non-cancer Effects, Particulate Matter, Photochemical Ozone Formation, Acidification, Freshwater Eutrophication, Freshwater Eco-toxicity, Land Use, Water Resource Depletion and Mineral, Fossil & Renewable Resource Depletion. In addition, a non-normalized category of *Time of Dedication* was considered as a social indicator.

The SimaPro 8.0.5.13 program (PRé consultants, 2015) was used for LCA impact analysis with the required classification and characterization phases established by the ISO 14044 regulation (ISO, 2006). The equal weighting method was applied and EU27 overall environmental impact was used for normalization (ILCD, 2011). The normalization factor of the *Human Toxicity, non-Cancer Effects* category was adjusted with the integrated indoor and outdoor exposure factors for non-OECD countries, according to Rosenbaum et al. (2015).

2.2. Data collection

The description of the system (Figure 1) required a detailed data-collection process from different sources (Table 1). Primary data has been differentiated between that obtained experimentally in the field by laboratory assays, pilot-scale household digester (E) and local data previously collected by interviews to final users, providers and experts (L). Secondary data from Ecoinvent database V3.0 (Weidema et al., 2013) were used to complete the life cycle inventory (O).

Table 1. Data source used for the system stages and sub-stages. The data were split into experimental (E), local (L), and Others (O).

STAGE	**DATA SOURCE**		
	E	**L**	**O**
MINERAL FERTILIZERS – MF			
MF Production	x	x	x[a]
MF Transport		x	x[a]
ORGANIC FERTILIZERS – OF			
OF Collection and transport	x		x[a]
OF Time investment	x		
OF Waste and gaseous emissions		x	x[a,b]
CULTIVATION – Cu			
Cu Land Use	x	x	x[a]
Cu Machinery and tools	x		x[a]
Cu Irrigation	x	x	x[a,c]
Cu Post-application emissions	x		x[a,b]
Cu Nursery plant	x	x	x[a]
Cu Time investment	x	x	
GRASS CHOPPED – GC			
GC Machinery and tools	x		x[a]
GC Energy consumption	x	x	x[a,d]
GC Time investment	x	x	
HOUSEHOLD DIGESTION – HD			
HD Production and maintenance	x	x	x[a]
HD Time investment	x	x	
FIREWOOD – FW			
FW Extraction and gaseous emissions		x	x[a,e]
FW Time investment		x	
LIQUEFIED PETROLEUM GAS – LGP			
LPG Production		x	x[a]
LPG Transport		x	x[a]
LPG Acquisition		x	
COOKING			
Emissions (include HD emissions)	x	x	x [a,e,f,g,h]
Stove Materials (Included in HD)	x	x	x[a]

Other Data source: [a]Weidema et al. (2013); [b]Nemecek et al. (2015); [c]Solano et al. (2014); [d]UPME (2018); [e]IPCC (2000); [f]IPCC (2006); [g]Rosenbaum et al. (2015); [h]Karvosenoja et al. (2008).

Data for Agricultural practices

The agricultural practices data were collected in a farm located in Cali, Colombia (3°21'50.8"N; 76°33'45.8"W) at an altitude of 1,100 meters above sea level. The area has an average annual precipitation of 1,173 mm with two rainy periods per year (April to June and October to December) and two dry periods (January to March and July to September) with a minimum rainfall in July of 44 mm, and a maximum in October, of 167 mm (Climate-Data, 2021).

The crop used as the substrate for the anaerobic digestion (*Pennisetum purpureum cv. king grass*) was previously established. For 10 months, the crop was fertilized applying digestate of the biogas household unit and compost from fruits and vegetable wastes. Later, during a similar period, the crop was fertilized with digestate of the biogas household unit and complemented with mineral fertilizers. The agronomic and methane yields were determined in Pizarro-Loaiza et al. (2020).

Data for household digestion and cooking

Design, construction and operation of the household biogas digester were obtained from experimental data. The Ecoinvent database v3.0 (Weidema et al., 2013) was also used when needed.

Household biogas digester system consisted in three (3) reactors of 1 m^3 working volume, made of polyethylene with a PVC membrane for biogas capture. Pipes for leachate drainage and recirculation as well as biogas connection to the stove were constructed on PVC since it is a common practice in the rural Colombian areas.

Data for FW emissions, combustion and indoor air pollution

Most of the data on FW combustion emissions were obtained from IPCC (2000). Particulate matter ($PM_{2,5eq}$) emissions factors and intake fractions and characterization factors of indoor concentration exposure were obtained from Karvosenoja et al. (2008) and Rosenbaum et al. (2015), respectively.

2.3. Life cycle inventory

2.3.1. Preliminary considerations

Thermal efficiency

Since the selected functional unit, 2,400 MJ useful heat for cooking, resulted from the annual demand of LPG in the studied area (GASNOVA, 2019), it is necessary to know the thermal efficiency (TE) of each of the analysed scenarios. For FW it was considered a TE of 12,5% (Boy et al., 2000) and for LPG and biogas a TE of 40% (Kaushik and Muthukumar, 2018).

Crop's fertilizers practices and methane yields

Table 2 shows the doses and typology of fertilizers applied to the crops, as well as the agronomic and methane yields obtained experimentally.

Table 2. Grass agricultural practices and methane yields

Parameter	Units	Biogas from BMFG	Biogas from BOFG
Fertilizer source & doses	NPK values[a]	833:91:50[c] + 281:50:50[d]	686:75:102[c] + 85:3:102 [e]
Agronomic Yield[b]	$t_{MS}.ha^{-1}.y^{-1}$	28.1±2,5	23.2±2,2
Volatile Solids	% VS (dry basis)	86%	86%
Specific CH_4 Yield	$ml_{CH4}\,g^{-1}{}_{VS}$	347.8	347.8

Area-specific CH_4 Yield	Nm^3_{CH4} ha^{-1} y^{-1}	9,773	8,069

Note: [a]in kg ha^{-1} y^{-1}; [b]45d harvest age; [c]100% digested grass; [d]Mineral Fertilizer; [e]Compost from fruits, vegetables and herbaceous wastes.

Electric mix

Table 3 shows the electrical mix of Colombia and the CO_2 contribution of each of the fuels, according to UPME (2018).

Table 3. Electrical mix of Colombia.

Source	Participation	CO_2 Contribution [a]
Hydro	70.4%	1.2%
Natural gas	11.7%	27.1%
Oil	9.7%	37.1%
Hard coal	7.6%	34.4%
Biomass	0.5%	0.26%
Wind	0.1%	0.01%

Note: [a] Contribution refereed to 1MJ high voltage electricity with and emission of 0,078 kg $CO_{2\ eq}$.

Personnel dedication time

The time spend for the acquisition/production of the cooking energy in each of the scenarios was estimated as follows: a) scenarios with biogas, grass crop cultivation (1,154 h.ha^{-1}), crop harvest (374 h.ha^{-1}), crop chopping (200 kg.h^{-1}), household digester feeding and general maintenance (32 h.y^{-1}); b) FW scenario, 9 kg.h^{-1} for extraction and transport on foot; c) LPG scenario, 9 h.y^{-1} dedication for acquisition and transportation in a light commercial vehicle**.**

2.3.2. Biogas scenarios

Fertilizers production and transport.

i) Compost

The inventory of inputs, outputs, and characteristics of the compost production from organic solid wastes and green pruning was provided by field managers and farmers. The considered collection method was manual and the transport on foot. Emissions from compost production have not been considered, as well as avoided emissions and carbon fixation in the soil due to the organic fertilizer application, since the current management of organic waste for its production in Colombian rural areas is on-site combustion or burial.

In principle, plant residues, due to their relatively low density and low moisture content, do not usually produce particularly high emissions and properly handled compost piles do not usually generate large amounts of methane because they remain in aerobic conditions and an appropriate moisture content. In any case CO_2 emissions could be considered biogenic and therefore not accounted for. In the same way, CH_4 emissions could be considered but they will still below the emissions for the current local practices for manage residues.

ii) Mineral fertilizer production

Data on the manufacture of mineral fertilizers was obtained from the Ecoinvent database v3.0 (Weidema et al., 2013), including the production infrastructure, transport of raw materials, synthesis of the chemical components required, and the deposition or treatment of waste generated, according to Nemecek et al., (2015).

iii) Mineral fertilizer transport

In Colombia, fertilizers are mostly imported through seaports (500 km in a lorry of >32 t EURO 3), being the European Union, Russia and Canada the main providers. Final users of cooking energy with biogas are at least 30 km from main municipalities and light commercial vehicles, the most common transport source. As mentioned above, only outward journeys were included in the inventory.

Cultivation

i) Land use and occupation

The transformation from not used grassland to grass plantation, was considered because grass could be cultivated in areas without agriculture exploitation. In the case of BOFG transformation to pasture and meadow organic, and the same occupation was considered. For BMFG transformation to pasture and meadow intensive, and its respective occupation was applied. In both scenarios, grass exploitation is considered to be for 30 years, thus no effect on climate change has been considered.

ii) Machinery and tools

Wheelbarrow and bowie knife were considered as the tools for the hand cultivation of grass. Based on local experience, a useful lifetime was estimated in 5 years with 5% dedication.

Soil emissions

Emissions from soil were calculated considering nitrogen and phosphorous contributions made by the fertilizer, compost or mineral fertilizer, while the N and P concentrations absorbed by the grass, as measured were obtained experimentally. Air emissions of NH_3, N_2O, and NO_x, and water emissions of NO_3^- and PO_4^{3-} were accounted following the methodologies described by Montemayor et al. (2019) and Torrellas et al. (2018). CO_2 emissions were also estimated for the urea application according to Nemecek et al. (2015) and Weidema et al. (2013).

Grass Chopped

An amount of 15 kg of Agricultural machinery with unspecified production (Weidema et al., 2013) was considered for the entire 10 years lifetime, processing 266 annual tons of grasses. A ton of grass demands 0.118 kWh for the chopped process.

Household digester

A household digester with biogas connection to a gas stove was considered for 10 years of useful lifetime. Following the design, the biogas supply requires 3 plastic tanks of 1 m^3 with a covering membrane each and the hydraulic connections and valves in PVC. Additionally, a polyethylene pipe for biogas and a gas stove were included. Table 4 present the inputs for this step.

Table 4 List of inputs included in household digester for the entire 10 years lifetime.

Input	Value
Polyvinylchloride, suspension polymerised {RER}	22 kg
Polypropylene, granulate {RER}	150 kg
Polyethylene, high density, granulate {RER}	5 kg
Steel, chromium steel 18/8 {RER}	3 kg

Nylon 6-6 {RER}	2 kg
Copper tube 15 mm, 1 mm thickness EU-15 S	0.2 kg
Electricity	8 kWh

2.3.3. LPG scenario

LPG Production

The LPG manufacture data was obtained from the Ecoinvent database v3.0 (Weidema et al., 2013), including the production infrastructure, transport of raw materials, synthesis of chemical components required, and deposition or treatment of generated wastes (Nemecek et al., 2015).

LPG transport

In Colombia, LPG is mostly transported through pipelines. However, rural zones with limited access to cooking energy, require 500 km in a lorry of >32 t MAL EURO 3 and 50 km in a light commercial vehicle between the producer or the storage facility and the house.

LPG bottle

Five years of a useful lifetime was considered for the 20 kg bottle of LPG. Table 5 presents the inputs considered for this step.

Table 5. Inputs for production and maintenance of LPG bottle.

Ecoinvent processes	**Value**

Energy and auxiliary inputs, metal working factory {RER}| with heating from heavy fuel oil	13.5 kg
Steel, low-alloyed, hot rolled {RER}| production	13.5 kg
Polyethylene, high density, granulate {RER}| production	0.2 kg
Steel, chromium steel 18/8 {RER}| steel production, electric, chromium steel 18/8	0.3 kg

2.3.4. FW scenario

For the FW extraction was considered a wheelbarrow with a lifetime of 5 years and a 10% dedication, a bowie knife, and an axe, both with a lifetime of 2 years.

2.3.5. Cooking

Cooking emissions

Table 6 presents the emissions considered for this process.

Table 6. Cooking emissions by fuel for functional unit (2,400 MJ useful heat).

Emission	Value (kg)
BMFG or BOFG*	
Methane, biogenic (5% loss of biogas 0,667 kgCH_4.m^{-3})[a]	5.0
Hydrogen sulphide (5% loss of biogas 1,4 gH_2S.m^{-3})[a]	0.0035
Dinitrogen monoxide (0,1 kg.TJ^{-1})[b]	0.0006
FW**	
Methane, biogenic (300 kg.TJ^{-1})[c]	5.75
Dinitrogen monoxide (4 kg.TJ^{-1})[c]	0.075
Nitrogen oxides (100 kg.TJ^{-1})[c]	1.9
Carbon monoxide, biogenic (5000 kg.TJ^{-1})[c]	96
NMVOC, non-methane volatile organic compounds (600 kg.TJ^{-1})[c]	11.5

$PM_{2,5eq}$ (700 kg.TJ^{-1})[d]	13.44
LPG	
Carbon dioxide, fossil (63100 kg.TJ^{-1})[b]	379
Methane (5 kg.TJ^{-1})[b]	0.03
Dinitrogen monoxide (0,1 kg.TJ^{-1})[b]	0.0006

a Vu et al. (2015); b IPCC (2006); c IPCC (2000); d Karvosenoja et al. (2008). *Mainly from digester losses; ** include FW extraction.

3. Results and Discussion

3.1. Characterization of BMFG and BOFG impacts.

The characterization of BMFG and BOFG impacts are presented in Table 7. In general, BOFG impacts were lower than those from BMFG, except in the land use and dedicated time categories, due to the highest demand of land and work for organic cultivation and lowest yields (Hakala et al., 2012).

Table 7. Characterization of BMFG and BOFG impacts per functional unit (2,400 MJ useful heat).

Impact category	**Units**	**Cooking**	**HD**	**Cu + DF**	**GC**
BMFG					
CC	kg CO_{2eq}	126.3	28.7	181.2	0.2
HTnCE	CTUh	1.25E-04	3.5E-06	1.0E-05	7.9E-08
PM	kg $PM_{2.5eq}$	0.002	0.010	0.080	0.000
PhOF	kg $NMVOC_{eq}$	0.051	0.095	1.031	0.001
PA	mol H^{+}_{eq}	0.010	0.110	1.022	0.002
FE	kg P_{eq}	1.2E-04	0.006	0.052	0.000
FET	CTUe	23.8	88.0	325.0	1.8
LU	kg C deficit	0.0	11.0	1,214.9	0.2
WRD	m^3 $water_{eq}$	-0.005	-0.905	-0.387	-0.010
MFRRD	kg Sb_{eq}	0.00031	0.00037	0.00331	0.00003
TD	h	-	32.0	35.4	5.0

BOFG					
CC	kg CO_{2eq}	126.3	28.7	97.0	0.3
HTnCE	CTUh	1.25E-04	3.5E-06	1.8E-06	9.4E-08
PM	kg $PM_{2.5eq}$	0.002	0.010	0.012	0.000
PhOF	kg $NMVOC_{eq}$	0.051	0.095	0.802	0.001
PA	mol H^+_{eq}	0.010	0.110	0.611	0.002
FE	kg P_{eq}	1.2E-04	0.006	0.017	0.000
FET	CTUe	23.8	88.0	94.2	2.2
LU	kg C deficit	0.0	11.0	1,398.6	0.2
WRD	m^3 $water_{eq}$	-0.005	-0.905	-0.045	-0.012
MFRRD	kg Sb_{eq}	0.00031	0.00037	0.00052	0.00003
TD	h	-	32.0	41.8	5.9

Where: Climate Change – CC, Human Toxicity, non-Cancer Effects – HTnCE, Particulate Matter – PM, Photochemical Ozone Formation – PhOF, Acidification – PA, Freshwater Eutrophication – FE, Freshwater Eco-toxicity – FET, Land Use – LU, Water Resource Depletion – WRD and Mineral, Fossil, Renewable Resource Depletion – MFRRD and a non-normalized category of Dedicated Time – TD; Stages acronyms are: Household Digestion – HD, Cultivation including the digestate fertilization – Cu+DF and Grass Chopped – GC.

The cultivation stage of BMFG displayed the greatest impacts. When tracing the sub-stages, most impacts come from fertilizer production, mainly urea, that is used as nitrogen source in mineral fertilization (Hakala et al., 2012; Hasler et al., 2015; Martínez-Blanco et al., 2011). Figure 2 presents the Life Cycle Impact Assessments (LCIA) from BMFG and BOFG normalized and weighted in a single score.

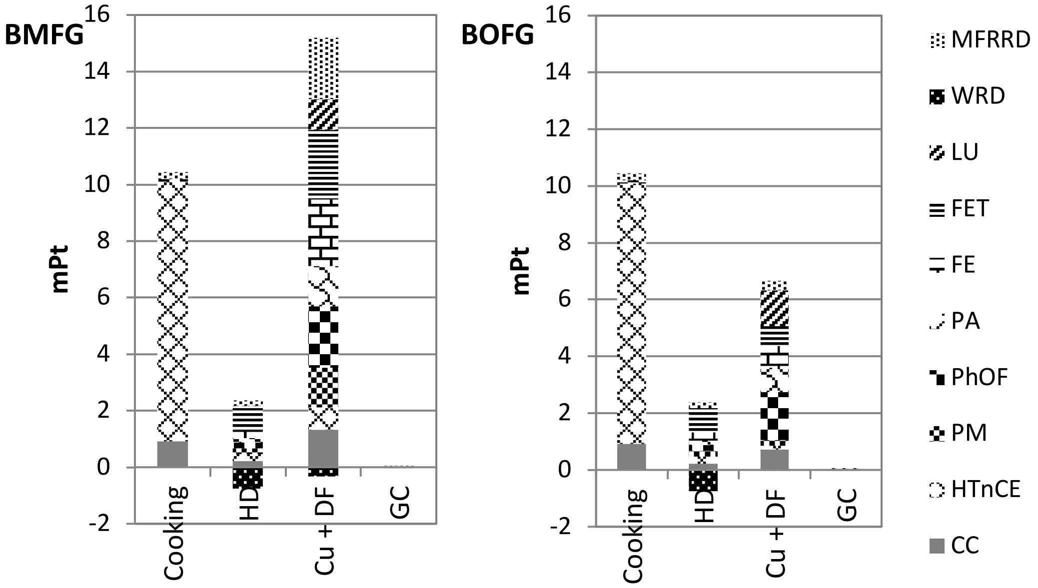

Figure 2. LCIA single score for 2,400MJ useful heat from BMFG and BOFG, respectively.

Where: Climate Change – CC, Human Toxicity, non-Cancer Effects – HTnCE, Particulate Matter – PM, Photochemical Ozone Formation – PhOF, Acidification – PA, Freshwater Eutrophication – FE, Freshwater Eco-toxicity – FET, Land Use – LU, Water Resource Depletion – WRD and Mineral, Fossil & Renewable Resource Depletion – MFRRD; stages acronyms are: Household Digestion – HD, Cultivation including the digestate fertilization – Cu+DF and Grass Chopped – GC.

According to Figure 2, the human toxicity category showed the greatest impacts with a high impact in the cooking stage. The climate change category stands out in the cooking and cultivation stages, being the impacts of climate change in BMFG scenario a 33% higher than on BOFG. This difference in environmental impacts between organic crops and mineral fertilization has been previously documented (Fagnano et al., 2011; Hakala et al., 2012). Although the agronomic yields of crops with chemical fertilization could be higher than in organic crops, their impact on climate change is greater (Hakala et al., 2012). Additionally, Fagnano et al. (2011) have shown positive effects of soil fertilization with compost from organic solid wastes on C fixation in stable soil organic matter. However, carbon fixation by the application of organic fertilizer in the BOFG was not considered in the present study.

Hence, despite that BOFG showed a greater impact on land use (15% higher) and dedicated time (10% higher), the lower impacts on the different categories analysed, mainly in the cultivation stage, suggest it is a better option among the two biogas-based options.

3.2. Biogas scenarios impacts versus FW and LPG scenarios

Figure 3 and Table 8 present a comparison of BMFG and BOFG LCIA with the present supply sources for the target population, FW, and LPG. FW displayed the highest total impacts while BOFG had the lowest life cycle impacts.

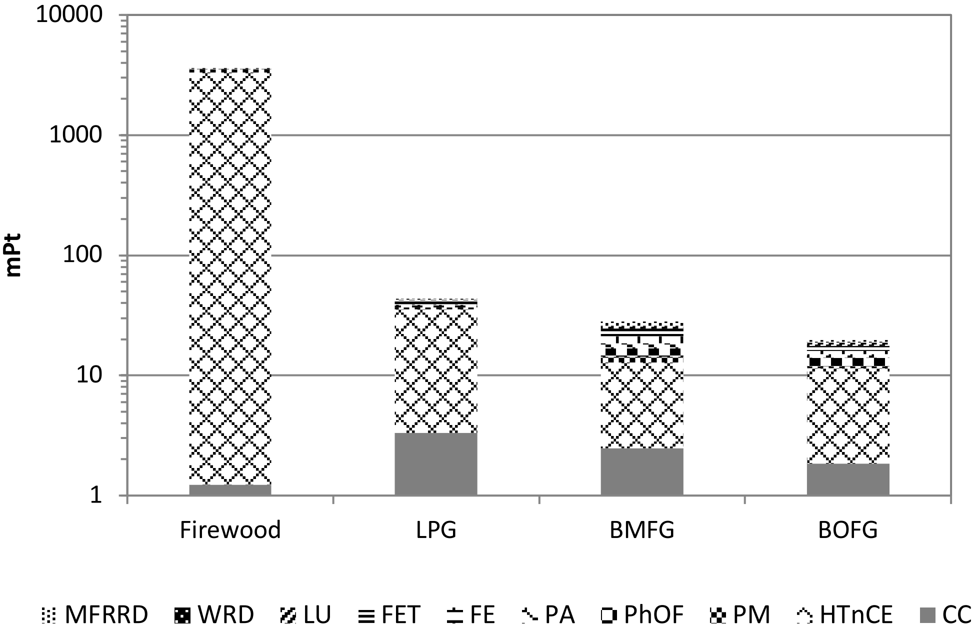

Figure 3. LCIA comparing fuels for 2,400MJ useful heat with and without indoor emissions exposure, respectively.

Where: Climate Change – CC, Human Toxicity, non-Cancer Effects – HTnCE, Particulate Matter – PM, Photochemical Ozone Formation – PhOF, Acidification – PA, Freshwater Eutrophication – FE, Freshwater

Eco-toxicity – FET, Land Use – LU, Water Resource Depletion – WRD and Mineral, Fossil & Renewable Resource Depletion – MFRRD.

Impacts of the the category of human toxicity are much greater for FW than for LPG, BMFG, and BOFG, due to health impacts from indoor emissions, aspect not always considered in LCA studies (Rosenbaum et al., 2015). In fact, they are much higher than conventionally outdoor impacts and more than two orders of magnitude lower for cooking with gas if compared to FW.

Table 8. LCIA comparing for functional unit (2,400 MJ useful heat).

Impact category	**Units**	**FW**	**LPG**	**Current Scenario (50%FW 50% LPG)**	**BMFG**	**BOFG**
CC	kg CO_{2eq}	167	453.7	310.35	336.5	252.3
HTnCE	CTUh	4.45E-02	4.36E-04	2.3E-02	1.39E-04	1.30E-04
PM	kg $PM_{2.5eq}$	13.4995	0.0525	6.78	0.093	0.024
PhOF	kg $NMVOC_{eq}$	13.46	0.65	7.06	1.176	0.949
PA	mol H^{+}_{eq}	1.42	0.535	0.98	1.144	0.733
FE	kg P_{eq}	0.0015	0.009	0.005	0.058	0.023
FET	CTUe	80.1	420.2	250.1	439.3	209.0
LU	kg C deficit	2,198.2	275.2	1,236.7	1,226.3	1,410.1
WRD	m^3 $water_{eq}$	-0.034	-0.475	-0.250	-1.308	-0.968
MFRRD	kg Sb_{eq}	0.0003	0.0018	0.0011	0.0040	0.0012

TD	h	163.8	9.0	86.4	72.4	79.7

Where: Climate Change – CC, Human Toxicity, non-Cancer Effects – HTnCE, Particulate Matter – PM, Photochemical Ozone Formation – PhOF, Acidification – PA, Freshwater Eutrophication – FE, Freshwater Eco-toxicity – FET, Land Use – LU, Water Resource Depletion – WRD and Mineral, Fossil, Renewable Resource Depletion – MFRRD and a non-normalized category of Dedicated Time – TD.

Despite the strong impacts on human toxicity, particulate matter, and photochemical ozone formation of FW, it has the lowest climate change potential. BOFG has 44% less impact on climate change than LPG, due to its fossil origin. Studies assessing the environmental benefits of household and small-scale farms digesters in rural areas of developing countries showed that household digesters led to environmental benefits by reducing different impact categories vs the current cooking fuels (Garfí et al., 2012, 2019; Lansche and Müller, 2017; Sfez et al., 2017; Vu et al., 2015; Wang et al., 2018).

However, most studies obtained environmental benefits from the substitution of current fuels and methane emissions withdrawn by poor waste management such as cattle manure and the replacement of mineral fertilizers by the use of digestate. In this study, the emissions avoided by the inefficient management of organic waste to produce composting were not considered. Substitution of fertilizers was not considered because the digestate is applied in a closed cycle for the feedstock fertilization and the benefits are only due to the substitution of present fuels for cooking.

3.3. Benefits of Biogas from grass digestion vs actual condition in rural Colombia (FW and LPG) including indoor air pollution

The implementation of BOFG shows an improvement for 8 out of 11 impact categories analysed when compared to the current scenario. The current impact on the Mineral, Fossil and Renewable Resource Depletion category persists. Only the Land Use and the Freshwater Eutrophication categories have an impact on BOFG greater than the current condition with an increase of 14% in the first case and 3.6 times in the second.

Tracking the BOFG sub-stages, phosphorous emissions from organic fertilization represent 74% of weight in the Freshwater Eutrophication category; 23.5% of the impact comes from the injection moulding process of building plastic materials of the biodigesters. These two contributing processes are difficult to improve in the life cycle assessment for the projected alternative as the organic fertilizers used for the substitution of mineral fertilizers tend to have a P / N ratio higher than the crop requirement (Hanserud et al., 2018). Furthermore, tropical grass crops have greater phosphorus use efficiency when applied at the appropriate time and pH conditions rather than applying a greater quantity (Mengel, 1997).

Although there is a low response of phosphorus fertilization on carbon fixation in permanent pastures (Eze et al., 2018), these crops are among the most efficient for phosphorus extraction (Dorioz et al., 2006). Moreover, the capture of phosphorus in surplus agricultural or livestock farms, by planting pastures and recycling phosphorus contained in the organic fraction of solid waste by composting, are all accepted like strategies for the phosphorus resource conservation (Reijnders, 2014). Note that these positive externalities were not quantified as benefits in the present study.

Among the environmental benefits from implementing BOFG to replace FW and LPG, the reductions between 1 and 2 orders of magnitude in the Human Toxicity, non-Cancer Effects, Particulate Matter and Photochemical Ozone Formation categories stand out. Nevertheless, the impact on Climate Change is reduced to a lesser extent, Acidification and Freshwater Eco-Toxicity.

The dedicated time was slightly reduced by 8%, because LPG requires only 9 h of dedicated time and in the current scenario it represent 50%. However, if compare BOFG with FW reduction of time achieved a 51%. BOFG has the advantage of bringing greater control and energy self-sufficiency for cooking with own pastures cultivation when compared to the collection of FW and purchase of LPG, which represents a monetary cost. These aspects become relevant in the social environment of application (Garfí et al., 2019, 2012; Lansche and Müller, 2017).

4. Conclusions

Based on Life Cycle Assessment (LCA), *Pennisetum* grass-fed household biogas digesters in rural Colombia with organic and mineral fertilized crops (BOFG and BMFG) displayed good environmental sustainability in pollutant emissions, when compared to FW and LPG. Between the fertilization type, the BOFG had a better environmental performance than BMFG in most impact categories and the best global performance among all fuels evaluated. Future research should focus on different grasses and organic substrates available in tropical climates to optimize biogas production.

The work presented covering social and health benefits, in addition to the environmental benefits shows the chance to implement household biogas digester. However, several accounting aspects could be improved, for instance specific emission factors for Latin American and Caribbean countries should be defined. The health impacts do to the poorly ventilated closed spaces, especially in relation with cooking practices in rural zones of developing countries is another relevant issue that should be also addressed.

Results will be helpful to develop public policies on economy, health and environment. Policymakers could use this research to establish investment requirements, support resource allocation and investment in full scale projects. Finally, non-governmental organizations as well as general public could be also beneficiaries of this research results.

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