LIFECYCLE GREENHOUSE GAS EMISSIONS AND ENERGY BALANCES OF SUGARCANE MOLASSES-BASED BIOETHANOL IN KENYA

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Abstract

Many countries have promoted biofuels to address energy security, environmental concerns as well as to improve the socio-economic well-being of rural people. This paper evaluates lifecycle net greenhouse gas (GHG) emissions, energy consumption and energy balances in the production chain of sugarcane molasses-based bioethanol in Kenya. Sugarcane molasses-based bioethanol production involves sugarcane cultivation, cane milling, bioethanol conversion, co-generation and wastewater treatment. The study used economic allocation to partition GHG emissions and energy inputs between sugar and molasses. The lifecycle GHG emissions were estimated at 270.87 gCO_{2eq} per litre of bioethanol produced. The total energy consumption was evaluated to be 22.39 MJ per litre of bioethanol produced. The energy balances calculated values per litre of bioethanol were; net energy value (NEV) = -1.19 MJ, net renewable energy value (NREV) = 19.75MJ and net energy ratio (NER) = 14.62. The negative value of NEV indicates that to produce a litre of bioethanol require greater energy than its energy content. The high positive values of NREV and NER indicate a low amount of fossil fuels are required to produce a litre of bioethanol. Sensitivity analysis on the effects of bioethanol yield and price of molasses on GHG emissions and NER was performed. The study found GHG emissions and NER to be sensitive to bioethanol yield and price of molasses. The results of this study were compared to results of molasses based bioethanol obtained in other countries.

Key words: Sugarcane molasses-based bioethanol, greenhouse gas emissions, energy balances, life cycle assessment, Kenya.

1.0 Introduction

Climate change, increasing demand for food and energy, environment and poverty concerns have led to a search for alternative sources of energy that would be economically productive, socially justifiable, environmentally sound and ecologically sustainable (Srinivasa *et al.* 2010). These requirements have led to increased global interest in the production and utilization of biofuels. Biofuel crops that accrue economic benefits to the rural poor while providing access to clean and green energy at both local and national level would likely meet the above requirements (Srinivasa *et al.* 2010). Also, a study by Demirbas (2008) indicates reasons to promote biofuels include energy security, environmental concerns, foreign exchange savings and socio-economic well-being of rural dwellers. Research findings in developing and developed countries have indicated that biofuels could be a dominant renewable source of energy while mitigating climate change (Srinivasa *et al*. 2010). Many countries have supported their fossil fuel supplies and consumption by blending biofuels with fossil fuels whose resources are being depleted year after year (Srinivasa *et al*. 2010).

Bioethanol is the most common biofuel, accounting for more than 90% of total biofuel usage (IEA, 2007). It can be produced from any feedstock that contains a high amount of sugar such as sugarcane, sweet sorghum and sugar beet or materials that can be converted into sugar such as maize (corn), cassava, wheat, etc., by the fermentation of carbohydrates (OFID/IIASA, 2009). Bioethanol can also be produced from lignocelluloses materials such as agricultural and forest residues, short-rotation forestry (e.g. poplar, willow) and perennial grasses (e.g. Miscanthus, switch grass) (IEA-ETSAP & IRENA, 2013). The technology to produce bioethanol from lignocelluloses feedstock is yet to become economically competitive. Bioethanol has traditionally been used for the production of alcohol but is increasing being blended with gasoline in various proportions to produce gasohol. Low level bioethanol blends such as E10 (10 percent bioethanol and 90 percent gasoline) can be used in conventional vehicles without engine modifications while high level blends such as E85 (85 percent bioethanol and 15 percent gasoline) can be used in specially motorized vehicles with engine modification such as flexible fuel vehicles (FFVs) (OFID/IIASA, 2009; Balat *et al*, 2008). Bioethanol blending increases octane levels and reduces carbon monoxide emission. Bioethanol is also presently being used as a household fuel to replace liquid petroleum gas (LPG). Bioethanol gel burns in the same way as LPG i.e. almost same heat content and with non-sooty yellow flame.

Life cycle assessment studies for molasses-based bioethanol have been undertaken in countries such as Mexico (Garcia *et al*, 2011), Thailand (Nguyen *et al.*, 2008), Nepal (Khatiwada & Silveira, 2009; Khatiwada & Silveira, 2011), Tanzania (Eshton, 2012; Eshton & Katima, 2012; Eshton & Katima, 2015), Indonesia (Venkata, 2013; Khatiwada *et al.*, 2016) and India (Soam *et al.*, 2015). There are variations within these LCA studies with regards to the definition of system boundaries, functional units and allocation methods used for accounting for co-products, and therefore the results obtained vary. Further, these results may not be replicated for example for a country like Kenya due to such factors such as geographical differences, difference in farming practices and conversion technologies. In the LCA analysis, the study considered the material and energy inputs inventory from sugarcane farming, transportation, sugar milling and ethanol production from molasses.

Starting early 1980's, Kenya produced bioethanol and blended it with petrol to produce gasohol. This programme was abandoned fifteen years later. The record oil prices of the 1970s and 1980s made the government initiate the gasohol policy. The policy mandated a 10% bioethanol blend but due to production limitation, this was only achieved in the Nairobi market. Nairobi is the capital city of Kenya. Agro-Chemical and Food Company (ACFC) based in Muhoroni (Western Kenya) produced all of the bioethanol used in the programme from sugarcane molasses. Thus it had to be transported to Nairobi, a distance of more than 350 km away. The gasohol programme became uneconomical due to a number of factors, including a drop in global oil prices, a surge in the price of bioethanol for alcoholic consumption in exports markets and a deterioration of bioethanol production. To bring gasohol to the same retail price as petrol, the Government had to reduce the customs tariff on gasohol. Even with this subsidy, the production of gasohol was still not viable and the gasohol programme ceased. A significant part of the bioethanol was now going for portable use as liquor for human consumption and the surplus to industrial use. The alcohol beverage markets are in Kenya, Uganda and Democratic Republic of Congo (DRC).

The molasses based bioethanol system consists generally of three main areas - sugarcane farming, sugar milling and bioethanol conversion. Land preparation, planting, crop management and harvesting are the basic steps involved in sugarcane farming. At Mumias Sugar Company, all these farming activities are labour dependent except land preparation which is mechanized. Sugarcane is a perennial crop and is therefore replanted after 2-4 harvests, hence the use of terminologies plant crop and ratoon crop. Harvesting of the plant crop is done after 18 months when the cane has reached maturity and the ratoon crops are harvested after every year. During harvesting, cane stalks are cut and delivered to the sugar mill whereas the trash (leaves and tops) and the root system are left in the fields. Leaving the trash in the fields conserve soil organic matter and moisture which is a good soil management practice for sustainable agriculture (Gabra, 1995).

Cane preparation using a shredder, juice extraction in a diffuser, Clarification using a rotary drum filter, concentration to syrup in evaporators and crystallization to sugar crystals in vacuum pans are the steps in sugarcane milling. The molasses, filter cake, spent wash (stillage) and bagasse are all by-products in cane milling. The filter cake is taken back to the diffuser, the stillage is taken to the wastewater treatment plant, and the bagasse is taken to the three roller mills to extract remaining juice and then burnt in boilers to produce steam. The steam is used as a source of energy for processing and for power generation. The molasses is used as a feedstock for bioethanol production.

Bioethanol conversion process starts with fermenting molasses with yeast to yield dilute alcohol. Hydrolysis is performed with 4 %(w/w) sulphuric acid (H_2SO_4) to make the product fermentable. This is then distilled to obtain 95% alcohol, which on dehydration yield 99.5% fuel-grade alcohol. Mumias Sugar Company produces 95% alcohol. The by-product of distillation is stillage, which is concentrated and mixed with bagasse in the ratio of 95:5 and is combusted in specially designed boilers. The bagasse based co-generation plant in Mumias Sugar Company was designed to generate 35 MW of electricity, 10 MW for internal consumption by the factory and 25 MW for export to the national grid. The co-generation plant is based on conventional steam power cycle involving direct combustion of bagasse in the boiler to raise steam. Part of the steam generated used in the sugar plant processes and equipment and the power generated used internally with the excess power exported to the national grid. For each tonne of sugarcane crushed, 0.27 tonnes of bagasse is used to produce process energy (steam and electricity). Therefore, not all bagasse is combusted in boilers; the surplus bagasse is transported by trucks and dumped in the plantations to decompose. The wastewater from milling is treated in waste stabilization ponds. Effluent from sugar milling activities by Mumias Sugar factory is treated through a system of six stabilization ponds before being discharged into the river.

The goal of this study was to evaluate GHG emissions and energy balances of sugarcane molasses-based bioethanol in Kenya. The Study considered the life cycle energy and greenhouse gas emissions of bioethanol production from sugarcane molasses and focuses on resource utilization and climate change impact. The study estimated the GHG emissions and the energy balances in bioethanol production from a life cycle perspective. The Life Cycle Assessment (LCA) is a well-developed scientific approach for evaluating the sustainability of products and services (Khatiwada, 2012). The study compiled an inventory of material inputs, material outputs, energy consumption and emissions released so as to evaluate the net GHG emissions and energy balances. The quantification of the GHG emissions and energy balances was intended to assist policy makers and stakeholders in biofuel industry to make meaningful decisions. The study aims to identify if the sugarcane molasses is suitable as an alternative source of renewable energy.

2.0 Methodology

2.1 Data Sources

The methodology used for conducting this LCA is based on the guidelines of ISO series (ISO 14040/44, 2006). Data in this study were obtained during field visits to Mumias Sugar Company (MSC) and Spectre International. Interviews were conducted one on one with senior and technical personnel of various departments in the two firms to obtain required data using a structured questionnaire. Appendix I shows the personnel interviewed and Appendix 2 shows part of the questionnaire used in data collection. Where data was lacking, it was obtained from literature. While Mumias Sugar Company is involved in sugarcane farming, cane milling, bioethanol conversion from molasses and power cogeneration, Spectre

International is only involved in bioethanol conversion from molasses obtained from sugar producing plants. Thus the bioethanol distillery plant at MSC is annexed to the sugar mill but that of Spectre International is an autonomous distillery. The Excel spreadsheets were used for data registration and to calculate emissions, energy consumption and energy balances. Emission and energy factors (or coefficients) used to calculate emissions and energy consumption respectively were obtained from literature. The functional unit of production of bioethanol from sugarcane molasses is defined as one litre (1 L) of hydrous bioethanol produced. The results are calculated on average sugarcane yield of 65 ton/ha/yr. GHG emissions, energy consumption and energy balances are estimated for I L of bioethanol production.

2.2 GHG Emissions Calculation

The study calculated the following GHG emissions for the sugarcane molasses bioethanol system;

- Emissions due to production of farm inputs (fertilizers, herbicides, fungicides) and industrial chemicals.
    - Study used emission factors and models from literature [Khatiwada et al. (2016), Macedo et al. (2008)].
- Emissions due application of fertilizers and crop residues
    - study used models from IPCC (1996) & IPCC (2006) for direct and indirect N_2O emissions
    - study used emission factors from literature (Agri. Footprint 2.0, 2015) for heavy metals
- Emissions due to burning of diesel (tillage & transport)
    - study used models from IPCC (1996) & IPCC (2006)
- Emissions due to inputs and outputs in industrial phase (milling, bioethanol conversion, power co-generation, wastewater treatment)
    - study used emission factors from literature [Khatiwada et al.(2016), Macedo et al. (2008) & Eshton (2012)]
    - study used data from Ecoinvent database

2.3 Energy Consumption and Energy Balances Calculation

The study calculated the following energy consumption for the sugarcane molasses bioethanol system;

- Energy consumption in the production of farm inputs (Fertilizers, herbicides, fungicides) and industrial chemicals.
    - study used energy coefficients from literature [Khatiwada et al.(2016) & Macedo et al. (2008)]
- Energy consumption due to burning of diesel in tillage and transportation of farm outputs
    - study used energy coefficient from IPCC (1996)
- Energy equivalent of agricultural labour
    - study used energy content cited by Nguyen et al.(2008)

- Energy consumption in industrial phase (milling, bioethanol conversion, power co-generation, wastewater treatment)
    - study used energy coefficients from literature [Khatiwada et al.(2016), Macedo et al. (2008), Kumar et al.(2015), Ramjeawon (2009) & Eshton (2012)]

Energy balances deal with the saving of non-renewable fossil fuels compared to bioethanol in the entire production chain. The net energy value (NEV), the net renewable energy value (NREV) and the net energy yield ratio (NER) were used to evaluate the energy balances of bioethanol. The net energy value (NEV) of bioethanol was calculated as follows:

$$\mathrm{NEV} = \mathrm{E_F} - \mathrm{E_T}$$

Where $\mathrm{E_F}$ is the energy content of bioethanol and $\mathrm{E_T}$is the total energy inputs or consumption.

The net renewable energy value (NREV) was calculated as follows:

$$\mathrm{NREV} = \mathrm{E_F} - \mathrm{NE_T}$$

Where $\mathrm{E_F}$the energy content of bioethanol and $\mathrm{NE_T}$ is the fossil fuel input.

The net energy yield ratio (NER) was calculated as follows:

$$\text{Net energy yield ratio(NER)} = \frac{\text{Energy content in bioethanol}}{\text{fossil energy input}}$$

In assessing energy performance of bioethanol, this study used the net energy value (NEV), the net renewable energy value (NREV) and the net energy yield ratio (NER). Positive value of NREV and NER indicate that low amount of fossil fuels are required to produce a particular amount of bioethanol as per the functional unit. Negative value of NEV indicate that the total energy consumption (both fossil and renewables) to produce the bioethanol is higher than its final energy content.

2.4 Co-Products Allocation Procedure

Additional products other than bioethanol or biodiesel are obtained in many biofuel production systems. These additional products are referred to as co-products or by-products. Thus, to correctly evaluate the impacts of biofuels, co-products need to be taken into account. This can be done through two methodological procedures: system expansion or allocation. With allocation method input energy, material flows and output emissions are distributed among the product and co-product(s) (ISO 14044: 2006). The allocation of energy and emissions for each additional co-product can be determined by economic value, co-product mass, energy content, or substitution.

Economic allocation considers the amount and market price of products and co-products and is based on the assumption that market prices are the driver of the production process. The disadvantage of this approach is that prices are not constant and keep on changing. Allocation to biofuel would be strongly influenced by price variations in co-product markets (Borjesson, 2009; Reijinders & Huijbregts, 2008). Subsidies towards fuels and co-products distort relative prices (Gnansounou *et al.*, 2009; Reijinders & Huijbrebts, 2008). Allocation by mass and energy content account for physical properties. Mass content accounts for the relative masses of biofuels and co-products, and energy content accounts for the energy content value in biofuels and co-products. The advantage of allocation by energy content is that heating values of co-products are constant and easily determined. A possible disadvantage of this allocation is that a given co-product may have high calorific content but a low market price. In substitution allocation or "system expansion" the biofuel is considered the only product but emission or energy substituted by co-products are dedicated. This procedure is recommended by the International Organization for Standardization (ISO) [ISO 14040/44, 2006]. Substitution may be difficult to apply in many cases because one co-product can be utilized in more than one form and a choice has to be made about the type of substitution. Also, data may not be available on life-cycle emissions and substituted product energy values.

In this study, the economic allocation is chosen as the allocation methodology to partition the GHG emissions and energy inputs the upstream operations which include cane cultivation, cane transportation, and cane milling and co-generation. The yields and prices were used to calculate the allocation ratio for sugar and molasses are shown in Table 1. Equation 1 was used to calculate the allocation ratio.

Table 1: Allocation factor calculation

	Sugar	Molasses
Yield (kg/tonne)	100	30
Price (US$/tonne)	988.2	180
Allocation ratio	18.3	1

$$Allocation\,ratio = \frac{Yield\ of\ sugar * Price\ of\ sugar}{Yield\ of\ molasses * Price\ of\ molasses} \ldots\ldots\ldots\ldots\ldots\ldots$$

Equation 1

3.0 Results and Discussion

3.1 System Boundary

The processes considered in the LCA of sugarcane molasses-based bioethanol in Kenya are shown in the system boundary presented in Figure 1. The main processes include the production of farm inputs, sugarcane farming, sugarcane transport, sugarcane milling, bioethanol conversion, power cogeneration and wastewater treatment. The fossil fuel energy embodied in farm and industrial equipment was not considered in this study. Studies by Dunn *et al.* (2011), Izursa *et al.* (2012) who considered fossil fuel energy embodied in farm machinery in their LCA analysis found it to be low as cited from Venkata (2013). The embodied energy is dispersed over the life time of the equipment and thus its effect is negligible. LCA researchers, Garcia *et al.* (2011), Silalertruksa and Gheewala (2009), and Seabra *et al.* (2011) indicated that the impacts of the embodied energy in farm and industrial machinery need be neglected.

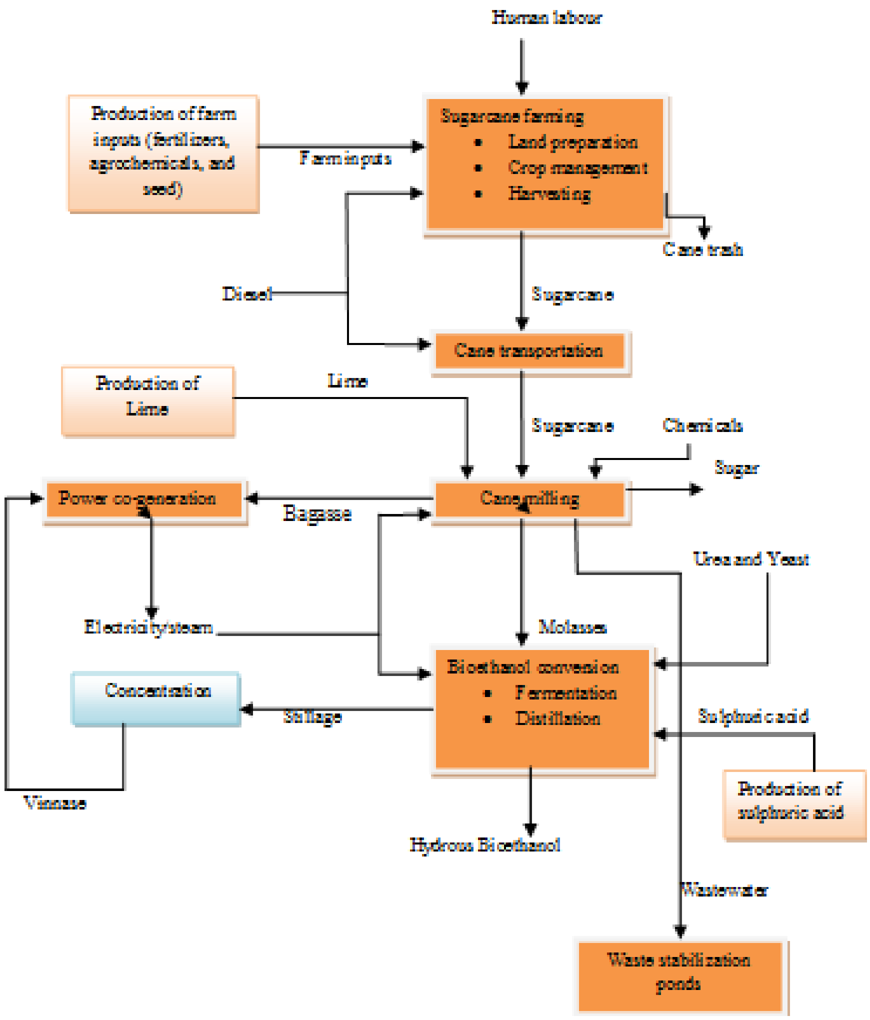

Figure 1: System boundary for sugarcane molasses based bioethanol
Source: Author

3.2 Sugarcane Farming and Harvesting

The lifecycle of sugarcane molasses-based bioethanol starts from land preparation prior to sugarcane planting. Land preparation carried out using agricultural machinery (see Appendix III) through conventional methods and was found to consume 64.6 L/ha of diesel. The conventional methods include ploughing, harrowing and furrowing. Human labour of 12 man-days/ha was also required in land preparation. Before planting, 30 tonnes of sugarcane seeds are first treated with 172 mls of Confidor pesticide and 2 litres of Follicur fungicide. This amount of seed cane can be planted in 5 ha which translates to 6 tonnes seed cane per ha. During planting, 250 kg/ha NPK Blend 1 fertilizer is applied. The NPK ratio of this Blend 1 fertilizer for planting is 12:30:7. All planting activities are manual requiring human labour of 12 man-days/ha. In crop management, 250 kg/ha NPK Blend 2 fertilizer is applied. The NPK ratio of this Blend 2 fertilizer for crop management is 26:0:20. Herbicides which include Krismat and Dual Gold are also applied once a year. The human labour for crop management was found to be 12 man-days/ha.

Sugarcane harvesting is done 18 months after field planting and then once a year for three ratoons (5 year cycle period). The yield for each of the ratoons depends on ratoon management. For this study, sugarcane yield was taken to be 65 t/ha. During harvesting, cane stalks are cut removing the leaves and tops termed as cane trash. The cane trash is lined in the fields along the root stumps to be used as organic fertilizer. Cane harvesting is done manually and requires a human labour of 40 man-days/ha. Sugarcane is transported using either tractors whose carrying capacity is 25 t per trip or large trucks with carrying capacity of 27 t per trip. Fuel economy for the tractor was found to be 1.6 km/L and that of the trucks to be 2 km/L. The turn round distance (factory-farm-factory) was found to be 44 km. Taking an average value of fuel economy to be 1.8 km/L, the fuel used for sugarcane transportation per ha is 60.5 L. The data collected from the field for sugarcane farming are presented in Table 2.

The emission and energy coefficients for cane cultivation are as shown in Table 3. This study adopts a human labour emission coefficient of 5.59 $kgCO_{2eq}$/man-day (Khatiwada *et al.* 2016). The energy equivalent of agricultural human labour was based on the Life-Style Support Energy (LSSE) method recommended by Odum (1993), cited by Nguyen *et al*. (2007). This study adopted the value 12.1 MJ/h obtained by Nguyen *et al*. (2007) for Thailand, a semi-industrialized developing country similar to Kenya. The energy input is then proportioned into fossil and non-fossil items based on Kenya primary energy consumption by fuel sources for the year 2014. Fossil fuel consumption for this year was calculated to be 17.2% while that of renewable was calculated to be 82.8%, as per data obtained from International Energy Agency Energy Statistics (IEA, 2014).

3.3 Sugarcane Milling

Sugarcane milling involves a series of process stages which include cane preparation, passing it through a diffuser to extract cane juice, clarification, boiling, seeding and centrifuging to obtain crystal sugar. In milling process, electricity, steam and chemicals are the major inputs. Sugar is the main product which is packed and transported for distribution. Molasses, filter cake, bagasse and wastewater are the by-products. The filter cake is taken to the diffuser to assist in cane extraction, the wastewater to the waste oxidation ponds for treatment, and the molasses to the distillery plant to be converted to bioethanol. The bagasse is combusted in boilers to produce process energy (steam and electricity) to be used in the plant. The excess electricity is sold to the national grid. The chemicals used include sulphur, flocculants and lime. The sulphur bleaches the sugar as well as forming sulphuric acid which together with the flocculants and lime assist in clarification. The data collected from the field found that one tonne of sugarcane yield about 10% sugar, 37% bagasse, 3% molasses and 4% filter cake. Data for sugarcane milling are presented in Table 4.

Table 2: Data for farm inputs

Item	Units	Value
Nitrogen fertilizer as N	kg/ha/yr	71
Phosphate fertilizer as P_2O_5	kg/ha/yr	15
Potash fertilizer as K_2O	kg/ha/yr	53.5
Herbicides	L/ha	3.9
Insecticides/pesticides/fungicides	L/ha	0.434
Sugarcane seeds	t/ha	6
Sugarcane yield	t/ha	65
Cane trash	t/ha	6.5
Labour (planting, crop management, harvesting)	man-days/ha	76
Diesel use for land tillage	L/ha	64.6[a]
Diesel use for transportation	L/ha	60.5

[a] Eshton (2012)

Table 3: Emission and energy coefficient of farm inputs

Particulars	Emission coefficient ($kgCO_{2eq}/kg$)	Energy coefficient (MJ/kg)
Nitrogen (N) production[a]	3.97	56.3
Phosphorus (P_2O_5) production[a]	1.3	7.5

Potash (K_2O) production[a]	0.71	7
Herbicide production[a]	25	355.6
Sugarcane seeds production[a]	0.0016	0.02
Insecticide production [b]	29	358
Diesel [c]	-	43.33

[a] Khatiwada *et al*. (2016); Venkata (2013)
[b] Macedo *et al*. (2008)
[c] IPCC (1996); IPCC (2006)

Table 4: Data for milling inputs

Item	Units	Value
Lime (CaO)	kg/t cane	1
Molasses	kg/t cane	30
Sugar	kg/t cane	100
Bagasse	kg/t cane	270
Imbibition water	m^3/t cane	0.382[a]
Filter cake	kg/t cane	40[a]
Electricity	kWh/t cane	10.67[a]
Wastewater	m^3/day	1500
Steam	kg/t cane	500[b]
Sulphur	kg/t cane	0.1
Juice flocculant	kg/t cane	0.003

[a] Eshton (2012)
[b] Ramjeawon (2008)

3.4 Bioethanol Conversion

In the distillery plant (see Appendix IV), the molasses is first pre-treated to concentrate it and then hydrolyzed with 4% (w/w) sulphuric acid to make it fermentable. The conversion of molasses to bioethanol consists of two main steps. First, molasses is fermented with yeast (in presence of nutrients like urea) yielding dilute bioethanol at a concentration of about 9.5% in water. Second, the fermented mash is passed through distillation to yield concentrated bioethanol of 95% (w/w) in water. Vinnase, the by-product that remains of molasses after extracting the alcohol, is concentrated and mixed with bagasse in the ratio of 95:5 and is combusted in specially designed boilers. The wastewater for this phase is treated in waste stabilization ponds. The conversion of molasses to bioethanol input and output data are presented in Table 5. The emission and energy coefficients for cane milling and ethanol production phases are presented in Table 6.

Wastewater coming from milling and bioethanol conversion processes during its treatment in oxidation stabilization ponds is a source of methane (CH_4). Citing from Eshton (2012), El-Fadel and Massoud (2001) reports 1.1 kg CH_4 emissions from treatment of any type of industrial wastewater in oxidation stabilization ponds. This study assumes this value. From field data, the cane crushing rate was 350 tc/hour and the plant running 24 hours a day, the bioethanol production per day is about 60,000 litres. This corresponds to 1.83E-02 g CH_4/L bioethanol which translates to 4.6E-01 g CO_{2eq}/L bioethanol.

Table 5: Data for inputs and outputs during bioethanol production

Item	Units	Value
Molasses	kg/L bioethanol	4
Water	L/L bioethanol	11.42[a]
Sulphuric acid	kg/L bioethanol	0.0032
Urea	kg/L bioethanol	0.004
Yeast	L/L bioethanol	0.00001
Electricity	kWh/L bioethanol	0.44[a]
Stillage	L/L bioethanol	11.42[a]
Steam	kg/L bioethanol	2.25[b]

[a] Eshton(2012)
[b] Khatiwada & Silveira (2009)

Table 6: Emission and energy coefficients for inputs in milling and ethanol production

Substance	Emission coefficient	Energy coefficient
Lime production[a]	0.07 $kgCO_{2eq}$/kg	0.1 MJ/kg
Bagasse combustion[b]	0.025 $kgCO_{2eq}$/kg	16.80 MJ/kg
Sulphuric acid production[a]	0.21 $kgCO_{2eq}$/kg	0.11 MJ/kg
Urea[a]	1.85 $kgCO_{2eq}$/kg	2.39 MJ/kg

Yeast[a]	0.49 kgCO_{2eq}/kg	17.56 MJ/kg
Electricity[b]	-	3.6 MJ/kWh
Steam[c]	-	3.12 MJ/kg

[a] Khatiwada et al (2016); Venkata (2013)
[b] Soam *et al.* (2015)
[c] Eshton (2012

3.5 Lifecycle GHG Emissions

The results of GHG emissions are presented in Table 7. The estimated net GHG emission is 270.87 gCO_{2eq}/L bioethanol for the complete lifecycle chain. As depicted in Figure 2, cane cultivation emits 70% of the total GHG emissions, and thus contributes a significant share to the total emissions. In cane cultivation, the major contributor to GHG emissions is the production and application of nitrogen fertilizers contributing 52% of cane cultivation emissions and about 37% of the total emissions. Bagasse combustion in boilers to produce energy follows cultivation, contributing 18% of the total GHG emissions.

Table 7: Lifecycle greenhouse gas emissions

Process	Emissions (gCO_{2eq}/L bioethanol)
Cane cultivation	
Fertilizers	
Nitrogen production	31.60
Phosphorus production	2.19
Potash production	4.26
Herbicide production	10.93
Insecticide/Pesticide production	1.41
Sugarcane seeds production	1.08
N_2O emissions (direct)	54.33
N_2O emissions (indirect)	13.56
Human labour	47.62
Diesel (tillage)	23.38
Cane transportation	
Diesel (transportation)	22.14
Cane milling/ Bioethanol production	
Lime production	0.51
Sulphuric acid production	0.77
Urea	7.40
Yeast	0.05

Wastewater treatment	0.46
Co-generation	
Bagasse combustion	49.19
Total emissions	270.87

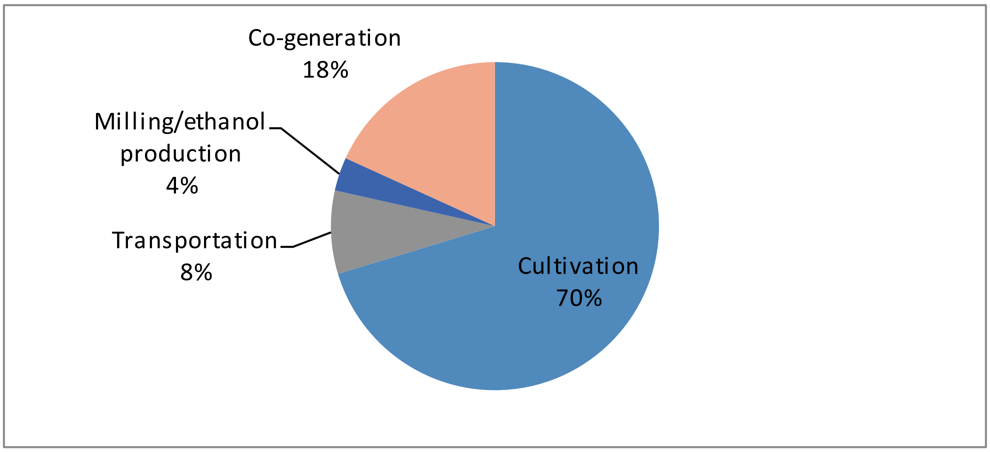

Figure 2: Net GHG emissions for sugarcane molasses based bioethanol in Kenya

3.6 Lifecycle Energy Consumption and Balances

The energy consumption and energy balances for the complete lifecycle chain of bioethanol production from molasses are presented in Table 8. It shows the calculated energy inputs in cane cultivation, cane transportation, cane milling and bioethanol conversion. The estimated total energy consumption is 22.39 MJ per litre of bioethanol produced. The renewable energy contributes 93.5% of the total energy consumption with most of the operations run with use of fuel bagasse combusted in boilers to generate steam and electricity.

The net energy value (NEV) for sugarcane molasses-based bioethanol has a slightly negative value of -1.19MJ/L bioethanol. This indicates that the total energy (fossil and renewable) required to make molasses based bioethanol is slightly more than its final energy content. The net renewable energy value (NREV) has a high positive value of 19.75MJ/L bioethanol, indicating that the amount of fossil fuels used in the production cycle of the bioethanol is quite low. The net energy ratio (NER) between energy content of the bioethanol fuel to fossil fuel is 14.62. This indicates that little fossil energy is used to produce a renewable energy. As indicated in Figure 3, cane milling leads in energy consumption at 52% of the total energy consumed, followed by bioethanol conversion at 39%. Milling has a number of processes using large quantities of steam and electricity. Fermentation and distillation processes in bioethanol conversion stage also consume large amounts of steam and electricity.

3.7 Sensitivity Analysis

Sensitivity analysis was performed to evaluate the effect of changes in bioethanol yields and prices of molasses on GHG emissions and NER. The variation of GHG emissions with bioethanol yields and prices of molasses is presented in Figure 4. The value of GHG emission is sensitive to changes in bioethanol yield and price of molasses. Increasing bioethanol yield results in a decrease in GHG emissions. Assuming an increase of 10% bioethanol yield results into decrease of net GHG emissions from 270.87 gCO_{2eq} to 245.8 gCO_{2eq} (or 9.3% decrease) per litre of bioethanol. Increasing price of molasses results in increase of GHG emissions. Assuming an increase to 10% of the price of molasses, the net GHG emissions increase from 270.87 gCO_{2eq} to 293.7 gCO_{2eq} (or 8.4% increase) per litre of bioethanol. Figure 5 shows the variation of NER with changes in bioethanol yield and price of molasses. Bioethanol yield and price of molasses were also found to be sensitive parameters to NER. Increasing bioethanol yield results in increase of NER. For example, an increase to 10% of bioethanol yield result in increase of NER from 14.62 to 16.06 (or 9.6% increase). Bioethanol yield can be manipulated by the factory operators. Increase in price of molasses results in decrease of NER. An increase to 10% of price molasses results in decrease of NER from 14.62 to 13.17 (or 9.9% decrease). An increase in price of molasses would lead to higher allocation of resources to molasses thereby decreasing the NER. An increase in demand for bioethanol may lead to increases in price of molasses, which in turn reduces the GHG emissions saving.

Table 8: Lifecycle energy consumption

Process	**Fossil inputs (MJ/L bioethanol)**	**Renewable energy inputs (MJ/L bioethanol)**
Cane cultivation		
Fertilizer		
Nitrogen production	0.44807	
Phosphorus production	0.01261	
Potash production	0.04198	
Herbicide production	0.15540	
Insecticide/pesticide production	0.01742	
Sugarcane seeds production	0.01345	
Human labour	0.14193	0.68271
Diesel (tillage)	0.31376	
Cane transportation		

Diesel (transportation)	0.29385	
Cane milling		
Lime production	0.00073	
Electricity		0.2800
Steam		11.3700
Bioethanol conversion		
Sulphuric acid	0.00035	
Urea	0.00956	
Yeast	0.00176	
Electricity		1.58400
Steam		7.0200
Total energy	1.45086	20.9367
Total input energy	22.39	
Energy content of bioethanol	21.2	
Net energy value (NEV)	-1.19	
Net renewable energy value (NREV)	19.75	
Net energy ratio (NER)	14.62	

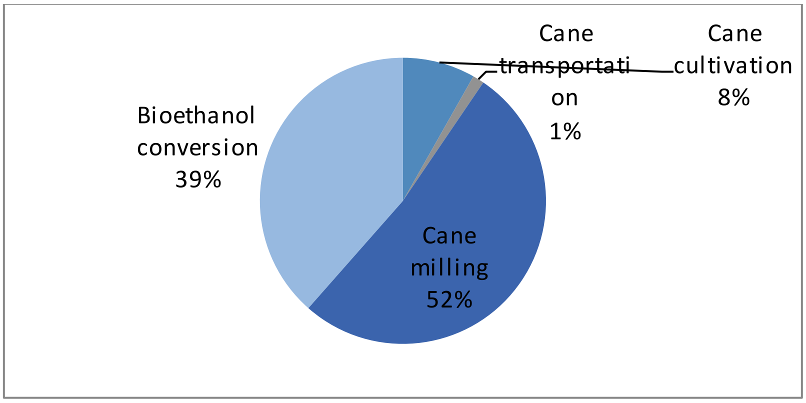

Figure 3: Energy consumption for sugarcane molasses based bioethanol in Kenya

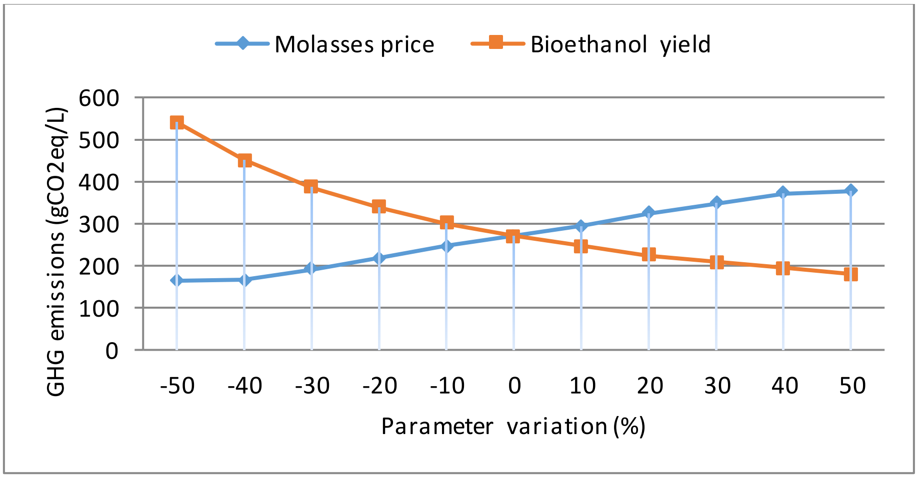

Figure 4: Sensitivity analysis of GHG emissions

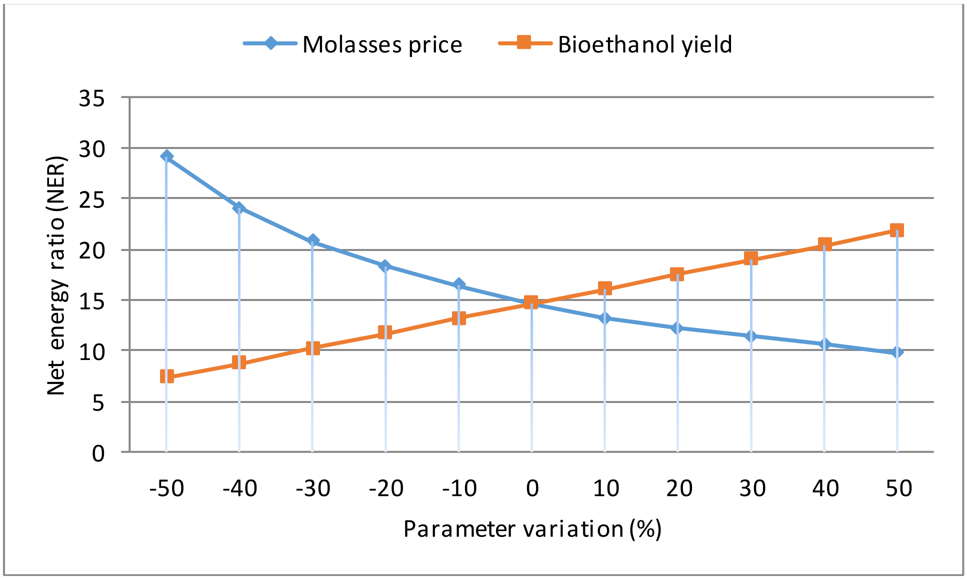

Figure 5: Sensitivity analysis of NER

3.8 Comparison with other references

LCA of molasses based bioethanol have been done in countries such as Thailand (Nguyen *et al.*, 2008), Nepal (Khatiwada & Silveira, 2009; Khatiwada & Silveira, 2011) and Tanzania (Eshton, 2012) and Indonesia (Khatiwada *et al.*, 2016). The results of the GHG emissions and energy balances by some of these studies were compared with that obtained in this study. The reported GHG emissions per litre of bioethanol: Tanzania (423.0 gCO_{2eq}), Indonesia (616.5 gCO_{2eq}), Nepal (432.5 gCO_{2eq}). These results were significantly higher than that obtained in this study (270.87 gCO_{2eq}) and they vary. Variations of these results are due to differences in farming practices,

Country	Fossil energy (MJ)	Renewable energy (MJ)	Total energy (MJ)
Nepal [a]	2.84	31.42	34.26
Indonesia [b]	3.49	24.69	28.18
Tanzania [c]	2.08	18.13	20.21
Thailand [d]	15.23	11.62	26.85
Kenya [e]	1.45	20.94	22.39

system boundaries, energy sources and geographical regions. In Indonesia, cane burning before harvesting and use of coal as source of energy results in significant GHG emissions. In Tanzania and Nepal, use of diesel in irrigation contributed significantly to GHG emissions. In addition, cane burning in Tanzania and production of biogas from wastewater in Nepal result to GHG emissions. The lower GHG emissions reported in this study are due to no cane burning before harvesting, no use of coal as source of energy, and no irrigation of sugarcane fields. Combustion of bioethanol in vehicles also contributes to GHG emissions. Unlike in the other studies, combustion of bioethanol was not in the scope of this study.

The reported energy balances from literature were: Tanzania (NEV= 0.995, NER= 10.2), Nepal (NEV= -13.06, NER=7.47), Indonesia (NEV=17.71, NER= 6.07), Thailand (NEV=2.5, NER= 6.12). The NEV for the various countries varies but that of Tanzania is very close to that obtained in this study. The NER obtained in this study indicate that less amounts of fossil fuels is required to produce one litre of bioethanol in Kenya than in Tanzania, Nepal, Thailand and Indonesia in that order. The reported total energy consumption per one litre of bioethanol for various countries including that of this study is shown in Table 9. It is observed Tanzania's total energy consumption is closer to that obtained in this study. Fossil energy use in this study is less than that reported Tanzania, Nepal, Indonesia and Thailand. In Tanzania and Nepal, higher fossil energy use attributed to diesel use in irrigation. In Thailand and Indonesia, higher fossil energy use attributed to use of coal. To note, the source of energy in these countries is primarily from renewables contributing 87-96% of the total energy consumption except Thailand.

Table 9: Energy consumption per litre bioethanol produced

[a] Khatiwada & Silveira (2009); Khatiwada & Silveira (2011)
[b] Khatiwada *et al.*(2016)
[c] Eshton, 2012
[d] Nguyen *et al.*(2008)
[e] Author

4.0 Conclusion

The net lifecycle GHG emission of molasses based bioethanol in Kenya was estimated to be 270.87 gCO_{2eq} per litre of bioethanol. Cane cultivation contributed the highest share (70%) to the total emissions with nitrogen fertilizer production and use being the major contributor. The total energy consumption was estimated to be 22.39 MJ per litre of bioethanol, 93.5 % of this being renewable energy. The net energy value (NEV), the net renewable energy value (NREV) and the net energy ratio (NER) were calculated to be -1.19 MJ, 19.75 MJ and14.62 respectively per litre of bioethanol produced. The high positive values of NREV and NER indicate that to produce molasses based bioethanol in Kenya requires less non-renewable input resulting in less GHG emissions. GHG emissions and NER were found to be sensitive to bioethanol yield and price of molasses.

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References

Balat, M., Balat, H., Cahide, O.Z. (2008) Progress in Bioethanol Processing. *Progress in Energy and Combustion Science* **34** (2008) 551-573

Blottnitz, H., Curran, A. (2007) A Review of Assessments Conducted on Bioethanol as a Transportation Fuel from a Net Energy, Greenhouse Gas, and Environmental Life-cycle Perspective. *Journal of Cleaner Production* **15** (2007) 607-619

Bŏrjesson, P. (2009) Good and Bad Bioethanol from a Greenhouse Gas Perspective – What Determines This? *Applied Energy* **86**(5): 589-943

Demirbas, A. (2008)"Biofuels Sources, Biofuel Policy, Biofuel Economy and Global Biofuel Projections". *Energy Conversion and Management* **49**, pp 2106-2116 doi : 10.1007/s 11430-009-0204-y

Dunn,J., Eason,J., Wang, M. (2011) Updated Sugarcane and Switch Grass Parameter in the Greet Model. Memo, Argonne: Argonne National Laboratory.

Eshton, B.(2012)"Evaluation of the Potential Environmental Impacts of Liquid Biofuels Production and Use in Tanzania". PhD Thesis, University of Dar es Salaam, Tanzania.

Eshton, B., Katima, J. (2012) Energy Balances of Molasses Based Bioethanol Production in Tanzania. World Resources Forum Conference on Resources and Green Energy.

Eshton, B., Katima, J. (2015) Carbon Footprints of Production and Use of Liquid Biofuels in Tanzania. *Renewable and Sustainable Energy Reviews*, Vol **42**, pp. 672-680

Gabra, M.,(1995) Sugarcane Residue Fuels – A Viable Substitute for Fuel in Tanzania Sugar Industry. *Renewable Energy for Development* **8**(2).

Garcia, C., Fuentes, A., Hennecke, A., Riegelhaupt, E., Manzini, F. (2011) Life-Cycle Greenhouse Emissions and Energy Balances of Sugarcane Ethanol Production in Mexico. *Applied Energy* **88**(6) pp 2088-2097

Gnansounou, E., Dauriat, A., Villegas, J., Panichelli, L. (2009) Life Cycle Assessment of Biofuels. Energy and Greenhouse Gas Balances: *Bioresource Technology* **100**: 4919-4930

IEA (2007) Energy Technology Essentials: Biofuel Production. Available at www.iea.org/Textbase/techno/essential.htm

IEA (2014) International Energy Agency Energy Statistics

IEA-ETSAP & IRENA (2013) Production of Liquid Biofuels: Technology Brief. Available at www.etsap.org-www.irena.org

IPCC (1996) Climate Change 1995: The Science of Climate Change. A Report of Intergovernmental Panel on Climate Change, Cambridge, Cambridge University Press

IPCC (2006) IPCC Guidelines for National GHG Inventories. Prepared by the Natural GHG Inventories Programme.

ISO (2006) ISO Norm 14040: 2006. Life Cycle Assessment: Principles and Framework. Environmental Management

ISO (2006) ISO Norm 14044: 2006. Life Cycle Assessment: Requirements and Guidelines. Environmental Management.

Izursa,J., Amponsal, N., Hanlon, E., Capece, J. (2012) Comparative Lifecycle Analysis of Sugarcane Production on Mineral and Organic Soils in Florida in Support of Ethanol Generation. Gainesille: University of Florida.

Khatiwada, D. (2012) Assessing the Sustainability of Bioethanol Production in Different Development Contexts: A System Approach. Doctoral Thesis. KTH University, Sweden.

Khatiwada, D., Silveira, S. (2009) "Net Energy Balance of Molasses-based Ethanol: The Case of Nepal". *Renewable and Sustainable Energy Reviews*, Vol **13**, pp. 2515-2524

Khatiwada, D., Silveira, S. (2011) Greenhouse Gas Balances of Molasses-based Ethanol in Nepal. *Journal of Cleaner Production*, Vol **19**, pp. 1471-1485

Khatiwada, D., Venkata, K., Silveira, S., Johnson, F. (2016) Energy and GHG Balances of Production of Ethanol from Cane Molasses in Indonesia. *Applied Energy* **164** (2016) 756-768

Macedo, I, Seabra, J., Silva, J. (2008) "Greenhouse Gases Emissions in the Production of Ethanol from Sugarcane in Brazil: The 2005/2006 Averages and a Prediction for 2020". *Biomass and Bioenergy* **32** (7): 582-595.

Nguyen, T., Gheewala, S., Garivait, S. (2007) "Fossil Energy Savings and GHG Mitigation Potentials of Ethanol as a Gasoline Substitute in Thailand". *Energy Policy*, Vol **35**, pp.5195- 5205

Nguyen, T., Gheewala, S., Garivait, S. (2008) Full Chain Energy Analysis of Fuel Ethanol from Cane Molasses in Thailand. *Applied Energy*, Vol **85**, pp.722-735

OFID/IIASA.(2009). Biofuels and Food Security

Ramjeawon, T. (2008) "Life Cycle Assessment of Electricity Generation from Bagasse in Mauritius." *Journal of Cleaner Production*, Vol **18**, pp.1727- 1734.

Reijinders, L., Huijbregts, M. (2009) Biofuels for Road Transport. A Seed to Wheel Perspective. Springer. Science & Business Media

REN21 (2011)"Renewables 2011. Global Status Report". Renewable Energy Policy Network for the 21st Century

RFA (2011)"Building Bridges to a More Sustainable Future". Ethanol Industry Outlook. Renewable Fuels Association.

Seabra, J., Macedo, I., Chum, H., Farloni, C., Sarto, C. (2011) Lifecycle Assessment of Brazilian Sugarcane Products: GHG Emissions and Energy Use. *Biofuels, Bioproducts and Biorefining.* **5**(5): 519 – 532. doi:10.1002/bbb.289.

Silalertruska, T., Gheewala, S. (2009) Environmental Sustainability Assessment of Bioethanol Production in Thailand. *Energy* **34** (11): 1933-1946. doi: 10.1016/j.energy.2009.08.02

Soam, S., Kumar, R., Gupta, RP. Sharma, P., Tuli, Dk., Das, B.(2015)"Life Cycle Assessment of Fuel Ethanol from Sugarcane Molasses in Northern and Western India and its Impacts on Indian Biofuel Programme." *Energy* **83**(2015) pp 307-315 Available at http://dx.doi.org/10/1016/j.energy.2015.02.025

Srinivasa, R., Reddy BVS R; Blummel, M., Subbarao, GV., Chandraraj, K.,Sanjana R., Darathasarathy, R. (2010). Sweet Sorghum as Biofuel Feedstock: Can there be Food-Feed-Fuel Tradeoffs? Available at http://www.wgcrop.acidonline.org/sweet% 20 sorghum deco9.pdf

Venkata, BK.(2013) "Life Cycle Assessment and Resource Management Options for Bioethanol Production from Cane Molasses in Indonesia." Postgraduate Thesis. KTH University, Sweden.

APPENDIX I: FIELD VISITS

Company	Visit dates	Section	Position of persons interviewed
Mumias Sugar Co.	16th-23rd May 2016	Training	Training Manager
	,,	Agronomy	Agronomist
	,,	Milling	Production Manager
	,,	Harvesting	Harvesting Manager
	,,	Bioethanol conversion	Manager-Bioethanol plant
	,,	Cogeneration plant	Engineer
	,,	Out growers	Field officer
Spectre International	7th July 2016	Processing	Chemical Engineer

APPENDIX II: PART OF QUESTIONNAIRE

Land preparation	**Information and data**
Land preparation methods and activities	
Agriculture machines used	
Quantity of fuel used	
Human labour per Ha	
Planting	
Methods of planting	
Agriculture machines used	
Quantity of fuel used	
Human labour per Ha	
Type and quantity of fertilizer per Ha	
Crop Management	
Type and quantity of pesticide/ insecticide per Ha	
Type and quantity of herbicide per Ha	
Type and quantity of fertilizer per Ha	
Human labour per Ha	

APPENDIX III: PHOTO SHOWING LAND PREPARATION

APPENDIX IV: PHOTO FOR BIOETHANOL PLANT