LIFECYCLE ASSESSMENT OF SWEET SORGHUM STALK JUICE-BASED BIOETHANOL IN KENYA

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Abstract

Biofuels have been promoted in many countries for reducing greenhouse gas (GHG) emissions and fossil fuel consumption. Sweet sorghum has gained traction as a viable bioethanol feedstock due to its short maturity period as well as being drought resistance. This study evaluates greenhouse gas (GHG) emissions and energy inputs in the production of sweet sorghum stalk juice-based bioethanol in Kenya. The bioethanol production stages include cultivation, milling, bioethanol conversion and co-generation. The study estimated the GHG emissions to be 424.19 gCO_{2eq} per litre of bioethanol produced. The total energy consumption was calculated to be 10.08 MJ per litre of bioethanol produced. For energy balances per litre of bioethanol, the study obtained; net energy value (NEV) = 11.12 MJ, net renewable energy value (NREV) = 19.68 MJ and net energy ratio (NER) = 13.6. The positive value of NEV indicates that the total energy consumption to produce a litre of bioethanol is less than its energy content. The high positive values of NREV and NER indicate low amount of fossil fuels are required to produce a litre of bioethanol. The study used mass allocation to partition GHG emissions and energy inputs at each stage/operation of the sweet sorghum lifecycle. Sensitivity analysis on the effects of stalk, juice and bioethanol yields on GHG emissions and NEV was performed. The study found GHG emissions to be sensitive to stalk yield and NER to be sensitive to bioethanol yield.

Keywords: Sweet sorghum stalk juice, bioethanol, energy balances, greenhouse gas emissions, life cycle assessment, Kenya

1.0 Introduction

Sweet *Sorghum bicolor* (L) Moench) is rapidly-maturing, C_4 plant of the same familywith maize, wheat, millet and rice. The sweet sorghum plant grows to about 0.6 to 5 metres and the stem has sweet and juicy pith (Muok *et al.*, 2010). Three basic components can be harvested from the sweet sorghum plant and be used to produce valuable produce i.e. grain, juice from the stalk, fibre from stalk and leaves. Sweet sorghum produces a stalk containing high concentration of fermentable sugar comparable to that of sugarcane and a large panicle of grain similar to that of grain sorghum. Sweet sorghum can thus simultaneously produce energy, food and feed products.

Sweet sorghum grain can be ground into flour and used for baking into bread or other human food products. The grain can also be used directly as an animal feed as well as a feedstock for biofuel production. The juice from the sweet sorghum stalk can be extracted and since it has high concentration of glucose and fructose it is suitable for fermentation. The juice can also be purified and concentrated to produce food quality syrup for production of gluten free beer and as a sweetener in a variety of food products. Bioethanol is the key product of fermentation which can be purified and used for the manufacture of food flavoring, pharmaceutical and industrial products. Sweet sorghum fibre can be used for power co-generation to provide steam and power for the production process. Chemicals and polymers can be produced from the components of sweet sorghum fibre, many of which can replace comparable items produced from fossil fuel feedstocks. Paper products, textile products and composite building materials can be produced from sweet sorghum fibre.

Sweet sorghum compared to sugarcane has a higher tolerance to salt and drought (Almodares & Hadi, 2009; Gnansounou *et al*,, 2005; Sutherland, 2002; Rooney *et al.*, 2007). Even under these conditions, sweet sorghum produces greater amounts of biomass (Wu *et al.*, 2010; Rooney *et al.*, 2007; Mamma *et al.*, 1996; Türe *et al.*, 1997). Sweet sorghum requires less water than sugarcane and requires less fertilizer to produce significant biomass (Almodares & Hadi, 2009). Sweet sorghum produces a comparable amount of fermentable sugars to sugarcane (Wu *et al.*, 2010, Mamma *et al.*, 1995). The sweet sorghum juice is also more suitable for fermentation to bioethanol than sugarcane (Almodares & Hadi, 2009). Sweet sorghum is also highly adaptable to different climates (Smith & Burton, 1993). Sweet sorghum is believed to have originally developed in tropical regions (Curt *et al.,* 1995; Gnansounou et al., 2005). Sweet sorghum also grows well in temperate climate (Smith & Burton, 1993; Tùre *et al.*, 1997; Curt *et al.*, 1998; Gnansounou *et al.*, 2005).

At maturity, up to 75 percent of the sweet sorghum plant biomass is contained in the stalk, 10-15 percent in the leaves, up to 7 percent in the grains and approximately 10 percent in the roots (Grassi, 2001). Sweet sorghum grain yields are typically 3-7 t/ha (Almodares & Hadi, 2009) and mature grain contain approximately 17 percent water, 10 percent protein, approximately 4 percent lipids, 75 percent carbohydrates, 2.2 percent fibre and 1.5 percent ash (Grassi, 2001). Sweet sorghum stalk yields are typically 50 – 100 t/ha per year (Woods, 2000; Sutherland, 2002; Almodares & Hadi, 2009). Stalk composition also varies but sugar compositions are 12-21 percent (Almodares & Hadi, 2009). The majority of soluble sugar in the stalk is sucrose but has significant amounts of glucose and fructose. The amount of sugars in the juice varies according to the cultivar, harvesting season, plant maturity and other agronomic factors (Mamma *et al.,* 1996). The typical composition of sugars in sweet sorghum is 53-85 percent sucrose, 9-33 percent glucose, and 6-21 percent fructose (Serna-Saldivar *et al.*, 2012). Sweet sorghum juice contains a significant amount of fermentable sugars, but about 20 percent of these sugars can be lost in three days at room temperature because of contaminating bacteria (Wu *et al.*, 2010). In the same study, sucrose in the sweet sorghum stalk completely disappeared after five days. Study by Woods (2000) reported 7-13 percent sugar in the stalk, 12-17 percent fibre and moisture at around 75 percent.

Although sweet sorghum is well adapted to temperate climates, growth is maximized at high temperature (Almodares & Hadi, 2009). Sweet sorghum is drought resistant and has short maturity period that allow two harvests a year. Studies report for optimal growth that sweet sorghum requires between 30-67 percent less water than sugarcane for comparable yields (Sutherland, 2002; Almodares & Hadi, 2009). Study by Smith & Burton (1993) concluded that sweet sorghum produces more biomass in temperate climate yielding 90 t/ha for the irrigated crop and 65 t/ha for non-irrigated crop. Bioethanol can be produced from sweet sorghum stalk juice (Mamma *et al.*, 1995; Wu *et al.*, 2010) and has been reported to produce bioethanol yields of around 3100 L/ha (Smith & Burton, 1993; Almodares & Hadi, 2009). Trials by Nan and Ma (1989) achieved 2500-3200kg/ha from the stalk.

Sweet sorghum is well adapted to environmental conditions ranging from tropical to temperate conditions within 40^0N and 40^0S of the equator (Dogget, H., 1998). It can be grown at altitude range of 900 to 2500 metres, temperatures of 12 to 37^0C and an optimum rainfall of 550 to 800 mm (Srinivasa *et al.*, 2012). Since it is highly adapted to a wide range of climatic conditions including marginal lands as it is C_4 crop, it can be grown without competition with the other weather sensitive crops (Khawanja *et al.*, 2014). The potential of sweet sorghum is enormous because the panicle is harvested to obtain grain used as food while the stalk is harvested for both folder and fuel production (Woods, J., 2001). Fuel production includes bioethanol biofuel production from the stalk juice through fermentation and combustion of stalk fibre in boilers to produce steam and electricity. Sweet sorghum is one of the renewable sugar rich crops identified to be promising in production of biofuels as it yields multiple products (Rooney et al.,2007; Prasad et al., 2007; Zhang et al., 2010; Linton et al., 2011; Yu et al.,2012). Sweet sorghum varieties accumulate a high amount of sugars in the stem during maturation. Sweet sorghum is characterized by a high biomass sugar-yielding and photosynthetic efficiency (GTZ & MOE, 2008). Sweet sorghum is mainly grown in agriculturally low potential areas in Kenya where it plays a key role in ensuring food security. When sweet sorghum is grown for bioethanol production, the seed crop (1st crop) is left to grow to maturity. This allows the grain to be harvested for food and this ensures food security, eliminating competition between food and biofuels. Sweet sorghum is best propagated through the seeds. The seeds are cultivated in rows spaced 50-60 cm apart with hill to hill spacing of 12-15 cm (Rao *et al.*, 2008). Pre-emergence herbicides are applied at most one day after sowing. Later weed control done until the crop is 35-40 days. The crop matures after 4 months and this is established when a black spot appears on the grain at the lower end. The sweet sorghum stalks can be harvested for juice when the brix reaches 16-18% (Muok *et al.*, 2010). Harvesting stage of sweet sorghum stalk is an important aspect of the content of sugar for production of bioethanol (Oyier *et al.*, 2017). The sugar content initially decreases as the sweet sorghum crop grows but increases during maturation. Bioethanol potential for the various sweet sorghum cultivars is determined by the amount of juice extracted and also the brix content.

Globally, there are efforts to promote production of biofuels from the sweet sorghum stalk (Sokan-Adega, A., Ana, G., 2015). For example in Australia sweet sorghum is grown and the stalks are taken to biorefinery distillery plant to produce bioethanol while in USA it is used for bioethanol and fodder production (Ratnavathi et al., 2011). Study by de Vries (2010) indicate that sweet sorghum in China is one of the most sustainable ecosystems for renewable fuel production as it provide the most efficient use of land, water, nitrogen and energy resources. Study by Muok et al,.(2010) indicate that sweet sorghum has the widest suitability area from western, central, eastern coastal regions estimated at 263, 965 km^2 or 46.4% of the total Kenya surface area. Zoning off protected areas, wildlife conflict areas, wetlands and animal movement paths, the suitable area reduces to 185,822 km^2 or 32.6% of the total Kenya surface area. Kenya has a high production potential of sweet sorghum but has remained under utilized (Muui *et al.*, 2013).

2.0 Methodology

2.1 Scope of study and System Boundary

The methodology used to conduct this LCA follows the ISO 14040/14044 (2006) guidelines. The study used primary data collected during field visits as well as secondary data from literature. Data for cultivation operations (land preparation, planting, crop management and harvesting) were obtained using a structured questionnaire during a field visit at Kenya Agriculture and Livestock Research Organization. The study assumed two crops (seed and ratoon) harvest in a year. Data for biorefinery operations (milling operation and bioethanol production) for the sweet sorghum stalk juice were obtained from literature. The reason for this being that there is no sweet sorghum biorefinery processing plant in Kenya or within the East African region. Data was entered for registration in excel spreadsheets and to further calculate GHG emissions and energy consumption. The study estimates the GHG emissions and energy balances of bioethanol production from sweet sorghum stalk juice. The functional unit is defined as one litre (1L) of bioethanol produced. The results are calculated based on sweet sorghum stalk yield of 55.88 ton per ha in one year. The study assumes one year cycle period with one seed crop and one ratoon crop.

The system boundary for the processes considered in this study to carry out the LCA for the sweet sorghum stalk juice-based bioethanol is depicted in Figure 1. The Study considers the following processes: Production of farm inputs, farming, transport of sweet sorghum stalk, stalk milling, juice conversion to bioethanol and cogeneration. This study did not consider the fossil fuel energy embodied in farm and industrial equipment. 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. The embodied energy is dispersed over the life time of the equipment and thus its effect is negligible. In their studies, 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.

2.2 Definition of Net Energy Balances

Net energy value (NEV), net renewable energy value (NREV) and net energy yield ratio (NER) is used to evaluate the energy balances of bioethanol in the entire production chain. The net energy balances of bioethanol are calculated as follows;

(i) $NEV = Energy\ content\ of\ bioethanol - Total\ energy\ input$

(ii) $NREV = Energy\ content\ of\ bioethanol - Fossil\ fuel\ input$

(iii) $NER = \ Energy\ content\ of\ bioethanol/Fossil\ fuel\ input$

This study used the net energy value (NEV), the net renewable energy value (NREV) and the net energy yield ratio (NER) to assess the energy performance of bioethanol. Positive value of NREV and NER indicates that low amount of fossil fuels are required to produce a particular amount of bioethanol as per the functional unit or vice versa. Positive value of NEV indicate that the total energy consumption (both fossil and renewables) to produce the bioethanol is lower than its final energy content or vice versa.

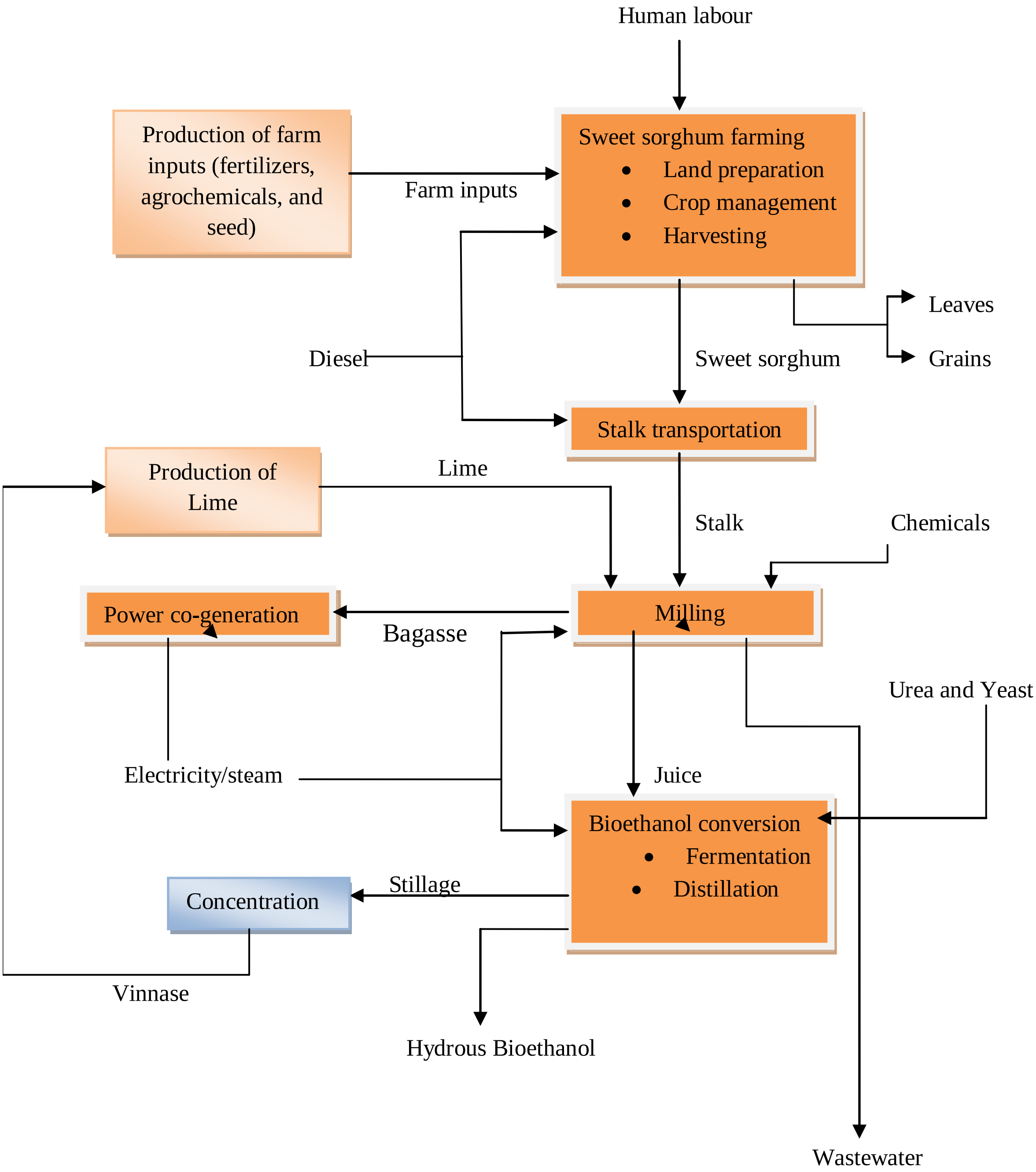

Fig. 1: System boundary for sweet sorghum stalk juice based bioethanol

2.3 Allocation

In a multi-product biofuel system, allocation allows partitioning of energy and environmental burdens between the major product and co-products when carrying out life cycle assessment (LCA). With allocation, input energy, material flows and emissions are distributed among the product and co-product(s) (ISO 14044: 2006). The allocation of energy and environmental emissions for each additional co-product can be determined by economic value, mass, energy content, or substitution. Economic allocation considers the amount and market price of products and co-products. Allocation to biofuel would be strongly influenced by price variations in co-product markets (Borjesson, 2009; Reijinders & Huijbregts, 2009). Subsidies towards fuels and co-products distort relative prices (Gnansounou *et al.*, 2009; Reijinders & Huijbrebts, 2009). Allocation by mass considers the relative mass of the biofuel and co-products while allocation by energy content accounts for the energy content value in the biofuel and co-products. The advantage of the latter is that heating values are constant and easily determined. The possible disadvantage of this allocation is that a given co-product may have high calorific content but a low market price.

This study use mass allocation to partition the GHG emissions and energy inputs at each stage/operation of the sweet sorghum lifecycle. The stages/operations of the sweet sorghum lifecycle include farming, milling and conversion of stalk juice to bioethanol. For each stage/operation, the masses of the product and co-products are considered individually and expressed as the percentage of the total mass of all the outputs. The GHG emissions and energy inputs at each stage/operation are then allocated according to the percentage mass of the main product. The major product from farming is the sweet sorghum stalk (55.88 ton/ha) and the co-products are grain (8.38 ton/ha) and leaf (4.47 ton/ha). This calculated translates to mass allocation of 81.3%, 12.2% and 6.6% for the stalk, grain and leaf respectively. In milling, the major product is juice (960 kg/t stalk) and the co-products are bagasse (458.8 kg/t stalk) and mud (24 kg/t stalk). This translates to mass allocation of 66.7%, 31.6% and 1.7% for juice, bagasse and mud respectively. In case of bioethanol production, the major product is bioethanol and the co-product is stillage (0.52 kg/L bioethanol). The mass of one litre of bioethanol is 0.79 kg. This calculated translates to a mass allocation of 60.3% for bioethanol and 39.7% for stillage.

2.4 Sweet Sorghum Farming, Harvesting and Transport

Sweet sorghum farming operations start with land preparation prior to planting. Land preparation is done using agriculture machinery which use 40.9 litres/ha of diesel. Land preparation methods include ploughing, harrowing and furrowing. Before planting, 2.4 litres/ha of a pre-emergence herbicide Dual Gold is applied though not mandatory. In planting 6 kg of sweet sorghum seeds are used. During planting, NPK Mavuno fertilizer (120 kg/ha) is applied. Mavuno fertilizer NPK content is 10:26:10. This translates into 12 kg/ha N fertilizer, 31.2 kg/ha P_2O_5 fertilizer and 12 kg/ha K_2O fertilizer. In crop management, Mavuno top dress fertilizer (120 kg/ha) is applied. The NPK content of this fertilizer is 26:0:0 which translates to 31.2 kg/ha N fertilizer and no P_2O_5 or K_2O fertilizers. During crop management, weeding is done manually with no use of herbicides requiring a human labour of 12 man-days/ha.

Sweet sorghum harvesting is done 4 months after seed planting. Harvesting is done manually by first cutting the panicle so as to separate the grain from the stalk. The sweet sorghum stalk is then cut and leaves removed. The assumption of the study is that the leaves are left on the farm and used as organic fertilizer to improve the fertility of the soil. The study adopts a stalk yield of 55.88 ton per ha for the seed and ratoon crops reported by Rural Industries Research & Development Corporation, RIRDC (2013). Sweet sorghum harvesting requires a human labour of 87 man-days/ha. The study assumes the sweet sorghum is transported using either tractors whose carrying capacity is 25 ton per trip or large trucks with carrying capacity of 27 ton 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 assumed to be 30 km. Taking an average value of fuel economy to be 1.8 km/L, the fuel used for sweet sorghum transportation per ha is 35.9 L. The data collected from the field for sweet sorghum farming are presented in Table 1.

The emission and energy coefficients for cane cultivation are as shown in Table 2. This study adopts a human labour emission coefficient of 5.59 kgCO_{2eq}/man-days (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 from 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 like 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 17.2% while that of renewable was 82.8%, obtained from International Energy Agency Energy Statistics (IEA, 2014)..

2.5 Sweet Sorghum Stalk Milling and Bioethanol Conversion

Sweet sorghum stalk milling involves passing the stalks through a series of three roller mills to extract juice. In milling process the inputs are electricity, steam, chemicals and the sweet sorghum stalks. The outputs include juice, mud, bagasse and wastewater. The bagasse is combusted in boilers to generate steam and electricity to be used in the plant. The excess electricity is sold to the national grid. The chemicals used include flocculants and lime which assist in clarification of the juice. The wastewater is treated in waste stabilization ponds. Data for sweet sorghum milling are presented in Table 3. This study assumes all the bagasse produced is combusted in boilers to produce steam.

In the conversion of bioethanol from the sweet sorghum juice, the inputs are the clarified juice, steam, electricity, yeast, urea and sodium hydroxide. The juice is fermented with yeast (in presence of nutrients like urea) yielding dilute bioethanol at 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. Stillage, the by-product that remains can be concentrated and combusted together with bagasse in specially designed boilers. The inputs and outputs during the conversion of juice to bioethanol are presented in Table 4. The emission and energy coefficients for milling and bioethanol production phases are presented in Table 5.

Table 1: Data for farm inputs

Item	**Units**	**Value**
Nitrogen fertilizer as N	kg/ha/yr	43.2
Phosphate fertilizer as P_2O_5	kg/ha/yr	31.2
Potash fertilizer as K_2O	kg/ha/yr	12
Herbicides	L/ha	2.4
Seeds	kg/ha	6.4
Stalk yield	t/ha	55.88[a]
Trash	t/ha	4.47[a]
Labour (planting, crop management, harvesting)	man-days/ha	87
Diesel use for land tillage	L/ha	40.9
Diesel use for transportation	L/ha	35.9

Table 1: Data for farm inputs

[a] RIRDC (2013)

Table 2: 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
Seeds production[a]	0.0016	0.02
Diesel [b]	-	43.33

[a] Khatiwada *et al.* (2016), Venkata (2013)
[b] IPCC (1996), IPCC (2006)

Table 3: Data for milling inputs and outputs

Item	**Units**	**Value** [a]
Lime (CaO)	kg/t stalk	0.7
Stalk juice	kg/t stalk	960
Bagasse	kg/t stalk	454.8
Mud and ash	kg/t stalk	24
Electricity	kWh/t stalk	13
Wastewater	m^3/day	1500
Steam	kg/t stalk	20
Juice flocculant	kg/t stalk	0.0001

[a] RIRDC(2013)

Table 4 : Data for inputs and outputs during bioethanol conversion

Item	Units	Value [a]
Juice	kg/L bioeth	12.04
Sodium hydroxide	kg/L bioeth	0.001
Urea	kg/L bioeth	0.0015
Yeast	L/L bioeth	0.005
Electricity	kWh/L bioeth	0.206
Stillage	L/L bioeth	0.52
Steam	kg/L bioeth	3.13

[a] RIRDC (2013)

Table 5: Emission and energy coefficients for inputs in milling and ethanol conversion

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] Kumar *et al.* (2015)
[c] Eshton (2012)

3.0 Results and Discussion

The stages/operations of the sweet sorghum lifecycle include cultivation and harvesting of sweet sorghum, transportation of stalk to milling plant, stalk milling to extract juice and conversion of stalk juice to bioethanol. The masses of the product and co-products in each stage/operation are considered individually and expressed as the percentage of the total mass of all the outputs. The GHG emissions and energy inputs at each stage/operation are then allocated according to the percentage mass of the main product. GHG emissions and energy balances of the overall lifecycle of sweet sorghum are presented in the following sections.

3.1 GHG Emissions

The GHG emissions of the overall lifecycle of the sweet sorghum stalk juice-based bioethanol production are presented in Table 6. The net GHG emissions are estimated at 424.19 gCO_{2eq} per litre of bioethanol. Contribution to GHG emissions by each stage/operation is depicted in Figure 2, with Cultivation leading in emissions at 56% followed by milling/co-generation at 34%, both contributing a significant share to the total emissions. Nitrogen fertilizer production and usage is the major contributor to GHG emissions in cultivation phase, contributing 45% of this phase emissions and 25% of the total emissions. Bagasse combustion in boilers for steam and electricity generation is primarily the major contributor to GHG emissions in milling/co-generation stage, contributing about 99% of these stage emissions and 34% of the total emissions. This is attributed by the assumption that all the bagasse produced is combusted in boilers. Transportation of sweet sorghum stalks to the milling plant and bioethanol conversion contribute 3% and 5% respectively of the total GHG emissions.

3.2 Energy Balances

The energy consumption and energy balances for the production of bioethanol from the sweet sorghum stalk juice are presented in Table 7. The total energy consumption of sweet sorghum stalk juice based bioethanol system in this study is 10.08 MJ per litre of bioethanol produced. The renewable energy produced by combustion of bagasse in boilers to generate steam and electricity contributes 85% of the total energy consumed. The relatively high positive value of NEV (11.12 MJ/L bioethanol) indicate that the total energy (fossil and renewable) required to make sweet sorghum stalk juice-based bioethanol is lower than its final energy. The high positive value of NREV (19.68 MJ/L bioethanol) indicates that the amount of fossil fuels used in the production cycle of the sweet sorghum stalk juice-based bioethanol is quite low.

As depicted in Figure 3, bioethanol conversion leads in energy consumption at 63% of the total energy consumed, followed by cultivation of sweet sorghum at 25%, milling at 9% and transportation at 3%. The fermentation and distillation processes during the conversion of sweet sorghum stalk juice to hydrous bioethanol require large amounts of energy (steam and electricity). Milling involves mainly extraction of juice from the sweet sorghum stalk and further clarification of the juice, and therefore requiring a relatively lower amount of energy. The study considers only the transportation of sweet sorghum stalks from the farm to the distillery plant explaining why energy consumption is low for this operation.

Table 6: Lifecycle greenhouse gas emissions

Process	**Emissions (gCO_{2eq}/L bioethanol)**
Cane cultivation	
Fertilizers	
Nitrogen production	31.1783
Phosphorus production	7.3810
Potash production	1.5489
Herbicide production	10.9079
Seeds production	0.0018
N_2O emissions (direct)	55.8119
N_2O emissions (indirect)	20.0341
Human labour	88.4083
Diesel for tillage	24.0155
Cane transportation	
Diesel for transportation	21.3431
Cane milling	
Lime production	0.4102
Bioethanol conversion	
Urea	20.5308
Yeast	0.0189
Co-generation	
Bagasse combustion	142.6013
Total emissions	424.1920

Net GHG

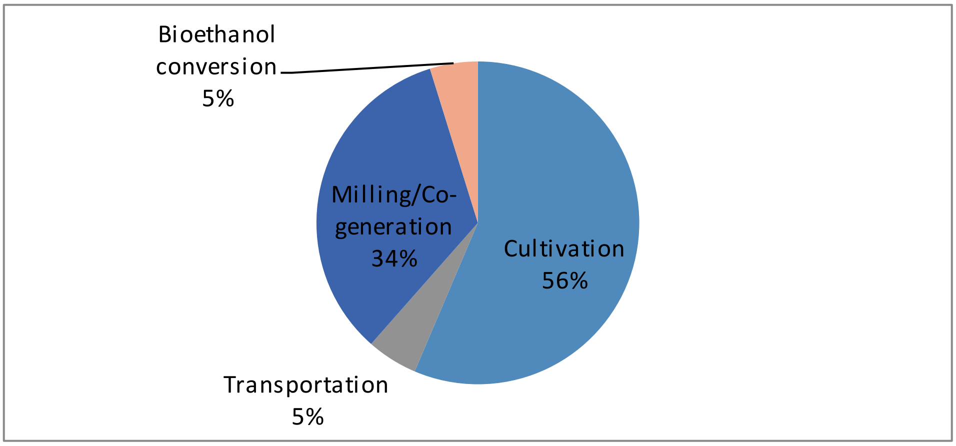

Fig. 2: Emissions for sweet sorghum stalk juice based bioethanol in Kenya

Table 7: Lifecycle energy consumption

Process	Fossil inputs (MJ/L bioethanol)	Renewable energy inputs (MJ/L bioethanol)
Cultivation		
Fertilizer		
Nitrogen production	0.44381	
Phosphorus production	0.04270	
Potash production	0.01533	
Herbicide production	0.15572	
Seeds production	0.00002	
Human labour	0.26449	1.27221
Diesel for tillage	0.32338	
Stalk Transportation		
Diesel for transportation	0.28383	
Milling		
Lime production	0.00058	
Electricity		0.39150
Steam		0.52200
Bioethanol conversion		
Urea	0.02711	
Yeast	0.00066	
Electricity		0.44718
Steam		5.88866
Total energy	1.55763	8.52155
Total input energy	10.08	
Energy output of bioethanol	21.2	
Net energy value (NEV)	11.12	
Net renewable energy value (NREV)	19.68	
Net energy ratio (NER)	13.6	

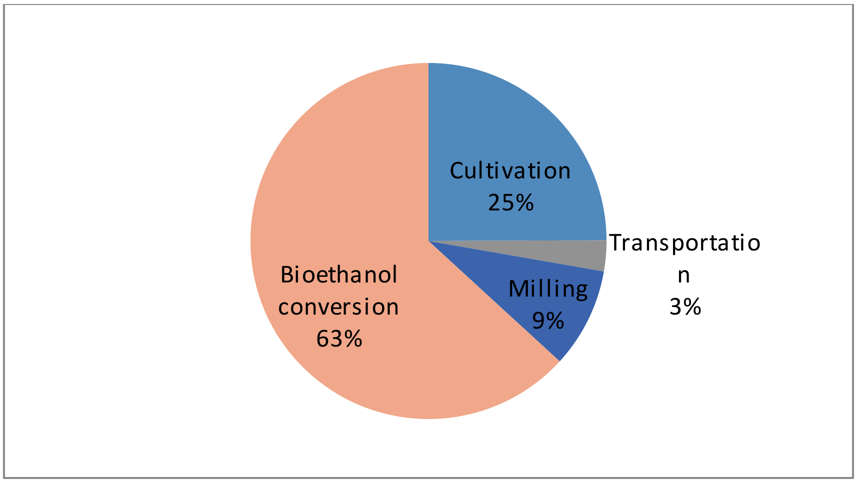

Fig. 3: Energy consumption for sweet sorghum stalk juice based bioethanol in Kenya

3.3 Sensitivity Analysis

Sensitivity analysis was performed to evaluate the effect of changes in the yields of sweet sorghum stalk, stalk juice and bioethanol on GHG emissions and NEV. The variation of GHG emissions with 50% increases in stalk yield, juice yield and bioethanol yield is depicted in Figure 4. Stalk yield was found to be a sensitive parameter to GHG emissions but juice yield and bioethanol yield were not. Increase of the stalk yield to 50% results in increase of net GHG emissions from 424.19 gCO_{2eq} to 442.58 gCO_{2eq} (or 4.3%) per litre of bioethanol produced. The variation of NEV with 50% increase in amount of stalk yield, stalk juice yield and bioethanol yield are presented in Figure 5. Bioethanol yield was found to be sensitive to NEV but stalk and juice yields were not. Increasing bioethanol yield results in decrease in NEV. Increase of bioethanol yield to 50% results in decrease of NEV from 11.12 to 10.15 MJ (or 8.7%) per litre of bioethanol produced.

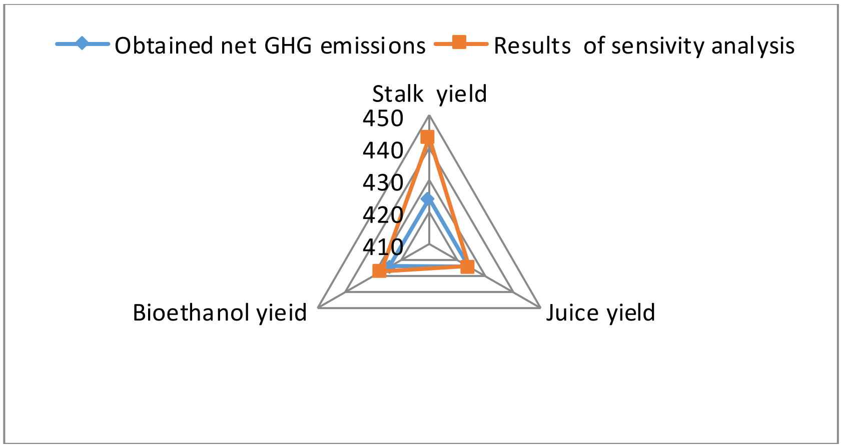

Figure 4: Sensitivity analysis of GHG emissions

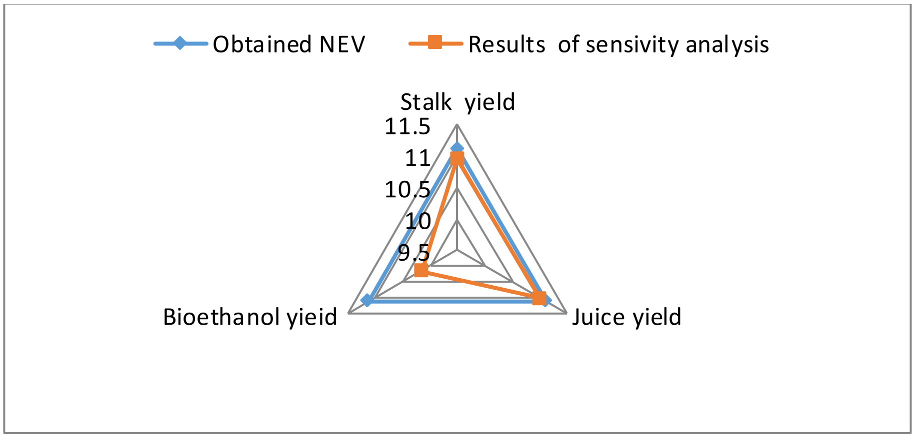

Figure 5: Sensitivity analysis of NEV

4.0 Conclusion

The calculated lifecycle GHG emissions of sweet sorghum stalk juice based bioethanol in Kenya were found to be 424.19 gCO_{2eq} per litre of bioethanol produced. Cultivation phase contributes the highest share of the total GHG emissions followed by milling/co-generation. Nitrogen fertilizer production and usage are the major contributors in the cultivation phase. The total energy consumption was found to be 10.08 MJ per litre of bioethanol with renewable and fossil energy contributing 85% and 15% respectively. The estimated net energy value (NEV) is 11.12 MJ, net renewable energy value (NREV) is 19.68 MJ and net energy ratio (NER) is 13.6 per litre of bioethanol produced. The relatively high positive value of NEV indicates that little fossil energy is required to produce a renewable energy. The high positive values of NREV and NER indicate that to produce sweet sorghum stalk juice based bioethanol in Kenya requires less non-renewable input which results in less GHG emissions. GHG emissions and NEV were found to be sensitive to stalk yield and bioethanol yield respectively.

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References

Almodares, A., Hadi, R. (2009) Production of Bioethanol from Sweet Sorghum: A Review. *African Journal of Agriculture Research* **4** (9): 772-78032

Bõrjesson, P. (2009) Good and Bad Bioethanol from a Greenhouse Gas Perspective – What Determines This? *Applied Energy* **86**: 589-94

Curt, D., Fernandez, J, Martinez, M. (1995) Productivity and Water Use Efficiency of sweet sorghum (sorghum bicolor (L) Cv. "Keller" on Relation to Water Regime. *Biomass and Bioenergy* **8** (6): 401-409.

Curt, D., Fernandez, J., Martinez, M. (1998) Productivity and Radiation Use Efficiency of Sweet Sorghum (Sorghum bicolor (L) Moench) cv. Keller in Central Spain. *Biomass and Bioenergy* **14** (2): 169-179

De Vries, S.; Van de, G; Van Ittersum, M; Giller, K.(2010) Resource Use, Efficiency and Environmental Efficiency of Nine Major Biofuels, Processed by First Generation Conversion Techniques. *Biomass and Bioenergy* **34**: 588-6

Dogget, H. (1998) Sorghum. Longmans, Greens and Co. London, UK. 2nd Edition

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.

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) (2011) 2088-2097

Gnansounou, E, Dauriat. A, Wyman, E. (2005) Refining Sweet Sorghum to Ethanol and Sugar: Economic Trade-offs in the contest of North China. *Bioresource technology* **96**(9) (2005) 985-1002.

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

Grassi, G.(2001) "Sweet Sorghum". Available at http://web.etaflorence.it/uploads/media/LaMNET /Sweet Sorghum.pdf

GTZ & MOE (2008) A Roadmap for Bio-fuels in Kenya: Opportunities and Obstacles.

IEA (2014) International Energy Agency Energy Statistics

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., 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

Khawanja, C.; Janssen, R.; Rutz, D.; Luquet, D.; Trouche, G.; Reddy, B.; Srinivasa, R.; Basavaraj, G.; Schaffert, R.; Damasceno, C.; Parella, R.; Zacharias, A.; Bushmann, R.; Rettenmaier, N,; Reinhardt, G.; Monti, A,; Zegada, W.; Amaducci, S.; Marocco, A.; Snijman, W.; Shargie, N.; Terblanche, H.; Zavara-Garcia, F.; Braconnier, S.(2014) Energy Sorghum an Alternative Energy Crop. A Handbook

Linton,J.; Miller, J.; Little, R.; Petrolia, D.; Coble, K.(2011) Economic Feasibility of Producing Sweet Sorghum as an Ethanol Feedstock in the Southeastern United States. *Biomass and Bioenergy* **35**: 3050-7

Mamma, D., Christakopoulous P, Koullas, D., Kekos, D., Macris, J., Koukios, E. (1995) An Alternative Approach to the Bioconversion of Sweet Sorghum Carbohydrates to ethanol. *Biomass and Bioenergy* **8** (20): 99-103.

Mamma, D., Koullas, D., Fountoukidis, G., Kekos, D., Macris, J., Koukios, E. (1996) Bioethanol from Sweet Sorghum. Simultaneous Saccharification and Fermentation of Carbohydrates by a Mixed Microbial Culture. *Process Biochemistry* **31**(4): 377-381.

Muok, B., Nyabenge, M., Okila, B., Esilaba, A., Nandokha, T. (2010) Environmental Suitability and Agro-environmental Zoning of Kenya for Biofuel Production. PIECES, Kenya.

Muui, C.; Muasya, R.;Kirubi, D. (2013) Baseline Survey on Factors Affecting Sorghum Production and use In Eastern Kenya. *African Journal of Food, Agriculture, Nutrition and Development* **13**(1): 7339-7342

Nan, Lu , Jienxue Ma (1989). Research on Sweet Sorghum and it's Synthetic Applications. *Biomass* **20** (1-2): 129-139.

Nguyen,T., Gheewala, S., Garivait, S. (2007) Energy Balance and GHG-Abatement Cost of Cassava Utilization for Fuel Ethanol in Thailand. *Energy Policy* **35**(2007) 4585-96

Oyier, M.; Owuoche, J.; Oyoo, M.; Cheruiyot, E.; Mulianga, B.; Rono, J. (2017) Effect of Harvesting Stage on Sweet Sorghum (Sorghum Bicolor L.) Genotypes in Western Kenya. The Scientific World Journal. Available at http://doi.org/10.115/2017/8249532

Prasad, S.; Singh, A.; Jain, N.; Joshi, J. (2007) Ethanol Production from Sweet Sorghum for Utilization as Automotive Fuel in India. *Energy Fuel* **21**: 2415-20

Rao, S.S., Umakanth, A.V., Kumar, A.A., Wani, S.P., Venkateshwarlu, B., Kamal, A., Blumel, M., Reddy, Y.R., Palaniswamy, A.R., Reddy, B.V.S. (2008) Cultural Practices for Maximizing Stalk and Bioethanol Yields, International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

Ratnavathi, C.; Chakravarthy, V.; Komala, V.; Chavan, U.; Patil, J. (2011) Sweet Sorghum as Feedstock for Biofuel Production: A Review. *Sugar Technology* **13**(4): 399-407.

Reijinders, L., Huijbregts, M. (2009) Biofuels for Road Transport. A Seed to Wheel Perspective. Springer. Science & Business Media 2008.

RIRDC (2013) Sweet Sorghum: Opportunities for a New, Renewable Fuel and Food industry in Australia.

Rooney, L., Blumenthal, J., Bean, B., Mullet, E. (2007). Designing Sorghum as a Dedicated Bioenergy Feedstock. *Biofuels, Bioproducts and Biorefining* **1**(2): 147-157.

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.

Serna-Saldivar, Sergio, O., Hernandez, C., Carrillo, E., Heredia, E. (2012) "Sorghum as a Multi-Funtional Crop for the Production of Fuel Ethanol: Current Status and Future Trends In Bioethanol."Edited by M.A.P. Lima and A.P.P. Natalense, 52-74: In Tech

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

Smith, A., Burton, R. (1993) Temperate Zone Sweet Sorghum Ethanol Production Potential. *Bioresource Technology* **43** (1): 71-75

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) 307-315.

Sokan-Adeaga, A.; Ana, G. (2015) A Comprehensive Review of Biomass Resources and Biofuel Production in Nigeria: Potential and Prospects. *Reviews on Environmental Health* **30**(3): 143-162

Srinivasa, R.; Deshpande, S.; Blummel, M.; Reddy, B.; Hash, T. (2012) Characterization of Brown Midrib Mutants of Sorghum (Sorghum Bicolor (L) Moench). ICRISAT-ILRI. *The European Journal of Plant Science and Biotechnology* **6**: 71-75

Sutherland, F. (2002) New Energy Options in the Australian Sugar Industry. PROCEEDINGS-AUSTRALIAN SOCIETY OF SUGAR CANE TECHNOLOGISTS, PK Editorial Services; pp. 19-23.

Türe, Semra, Davut Uzun, Türe, I. (1997) The Potential Use of Sweet Sorghum as a Non-Polluting Source of Energy. *Energy* **22** (1): 17-19.

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

Woods, J. (2000) Integrating Sweet Sorghum and Sugarcane for Bioenergy. Modeling the Potential for Electricity and Ethanol Production in SE Zimbabwe. Kings College. Doctoral Thesis

Woods, J. (2001) The Potential for Energy Production using Sweet Sorghum in the Southern Africa. *Energy for Sustainable Development* **5**(1): 31-8.

Wu, Xiaorong, Staggenborg, S., Propheter, L., Rooney, L., Jianming Yu, Donghai Wang (2010). Features of Sweet Sorghum Juice and their Performance in Ethanol Fermentation. *Industrial Crops and Products* **31** (1): 164-170.

Yu, J.; Zhang, T.; Zhong, J.; Zhang, X.; Tan, T. (2012) Biorefinery of Sweet Sorghum Stem. *Biotechnology advances* **30**:811-6.

Zhang, C.; Xie, G.; Li, S.; Ge, L.; He, T. (2010) The Production Potential of Sweet Sorghum in China. *Applied Energy* **87**(7): 2360-8.