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Evaluation of a Bioethanol Based on Sweet Sorghum Stalk Juice in Kenya Throughout Its Life Cycle

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Abstract
A lot of nations have been pushing for biofuels as a way to cut down on fossil fuel use and emissions of greenhouse gases (GHG). The rapid growth and drought resilience of sweet sorghum have made it a promising feedstock for bioethanol production. This research looks at the energy and greenhouse gas (GHG) outputs of making bioethanol in Kenya from sweet sorghum stalk juice. Growing the crop, grinding the grain, converting it to bioethanol, and then co-generating are the steps involved in making bioethanol. According to the research, for every liter of bioethanol generated, the greenhouse gas emissions amount to 424.19 gCO2eq. The overall energy required to create one liter of bioethanol was determined to be 10.08 MJ. Net energy value (NEV) = 11.12 MJ, net renewable energy value (NREV) = 19.68 MJ, and net energy ratio (NER) = 13.6 were the results achieved for energy balances per liter of bioethanol in the research. A positive result for NEV suggests that the amount of energy needed to create one liter of bioethanol is lower than the energy content of the fuel itself. A small quantity of fossil fuels is needed to make one liter of bioethanol, as seen by the strong positive values of NREV and NER. Using mass allocation, the research separated the energy inputs and greenhouse gas emissions for each phase of the sweet sorghum lifecycle. We ran a sensitivity analysis to see how different amounts of stalk, juice, and bioethanol affected our greenhouse gas emissions and our NEV. Results showed that greenhouse gas emissions were stalk yield sensitive and NER was bioethanol yield sensitive.

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

1.0 Introduction
The sweet potato (Sorghum bicolor (L) Moench) is a member of the same family as rice, wheat, millet, and maize; it is a C4 plant that matures quickly. According to Muok et al. (2010), the sweet sorghum plant may reach a height of 0.6 to 5 meters, and its stems contain juicy and delicious pith. Grain, stalk juice, stalk fiber, and leaves are the three main parts of the sweet sorghum plant that may be collected and used to make useful products. Like

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sugarcane, sweet sorghum grows a stalk with a high concentration of fermentable sugar and, like grain sorghum, a big panicle of grain. Therefore, sweet sorghum may provide energy, feed products, and food all at once.

Flour made from sweet sorghum grain may be used to make bread and other baked goods. The grain has several potential uses, including as a feedstock for biofuel production and as a direct feed for animals. The sweet sorghum stalk may be used to extract juice, which is ideal for fermentation due to its high glucose and fructose content. In addition to using the juice as a sweetener in many different foods, it may be condensed and refined into a food-grade syrup for making gluten-free beer. The fermentation process yields bioethanol, a byproduct that has many potential uses after purification, including in the food, medicinal, and industrial flavoring industries. The manufacturing process may be enhanced by using sweet sorghum fiber in power co-generation, which can provide both steam and electricity. Many of the chemicals and polymers made from sweet sorghum fiber may replace those made from feedstocks used in fossil fuel production. The fibers of sweet sorghum may be used to make paper, textiles, and composite construction materials.

Researchers have shown that sweet sorghum can withstand more salt and drought than sugarcane (Almodares & Hadi, 2009; Gnansounou et al., 2005; Sutherland, 2002; Rooney et al., 2007). The higher biomass yields of sweet sorghum persist even under these challenging circumstances (Wu et al., 2010; Rooney et al., 2007; Mamma et al., 1996; Türe et al., 1997). According to Almodares and Hadi (2009), sweet sorghum uses less water and fertilizer to generate a substantial amount of biomass compared to sugarcane. According to Wu et al. (2010) and Mamma et al. (1995), sweet sorghum yields fermentable sugars that are equivalent to sugarcane. In comparison to sugarcane, sweet sorghum juice ferments more easily to bioethanol (Almodares & Hadi, 2009). Additionally, sweet sorghum can withstand a wide range of temperatures (Smith & Burton, 1993). According to research conducted by Curt et al. (1995) and Gnansounou et al. (2005), sweet sorghum is thought to have originated in tropical climates. (Smith & Burton, 1993; Tεre et al., 1997; Curt et al., 1998; Gnansounou et al., 2005) Temperate climates are also favorable for sweet sorghum cultivation.

Grassi (2001) found that when sweet sorghum reaches maturity, the stalk contains up to 75% of the plant's biomass, the leaves 10-15%, the grains up to 7%, and the roots about 10%. Grassi (2001) reports that mature sweet sorghum grain has around 17% water, 10% protein, 4% lipids, 75% carbs, 2.2% fiber, and 1.5 percent ash, with normal yields ranging from 3 to 7 t/ha (Almodares & Hadi, 2009). According to Woods (2000), Sutherland (2002), and Almodares & Hadi (2009), sweet sorghum stalk yields are usually 50 to 100 t/ha annually. Similarly, the sugar content of stalks ranges from 12 to 21 percent (Almodares & Hadi, 2009). Although there is a fair amount of fructose and glucose in the stalk, sucrose makes up the

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bulk of the soluble sugar. Varieties of the crop, timing of harvest, degree of plant development, and other agronomic considerations affect the sugar content of the juice (Mamma et al., 1996). Sweet sorghum typically has 53% sucrose, 9–33% glucose, and 6%–21% fructose as its sugar content (Serna-Saldivar et al., 2012). Although there are a lot of fermentable sugars in sweet sorghum juice, almost 20% of them might be lost within three days at room temperature due to pathogenic microbes (Wu et al., 2010). Five days after being added to the sweet sorghum stalk, the sucrose in that experiment evaporated entirely. The stalk included 7–13% sugar, 12–17% fiber, and around 75% moisture, according to research by Woods (2000).

Sweet sorghum may thrive in mild environments, but it really comes into its own when the temperature is high (Almodares & Hadi, 2009). Because of its short maturation time and resistance to drought, sweet sorghum may be harvested twice a year. According to research (Sutherland, 2002; Almodares & Hadi, 2009), sweet sorghum needs 30-67 percent less water than sugarcane for optimum development, while producing equivalent yields. Smith and Burton (1993) found that sweet sorghum grows to a higher biomass yield in temperate climates, with an irrigated crop producing 90 t/ha and a non-irrigated crop yielding 65 t/ha.
It has been claimed that bioethanol yields of about 3100 L/ha may be achieved using sweet sorghum stalk juice (Mamma et al., 1995; Wu et al., 2010; Smith & Burton, 1993; Almodares & Hadi, 2009). The stalk yielded 2500-3200 kg/ha in trials conducted by Nan and Ma (1989).

According to Dogget (1998), sweet sorghum may thrive in a wide variety of climates, from the tropics to the temperate zones located between 400 degrees north and 400 degrees south of the equator. It requires an ideal rainfall range of 550 to 800 mm, temperatures between 12 to 370 °C, and an altitude range of 900 to 2500 m to flourish (Srinivasa et al., 2012). Due to its C4 status and extreme adaptability to a broad variety of climates, it may be cultivated on marginal areas without interfering with other crops that are susceptible to weather extremes (Khawanja et al., 2014). Sweet sorghum has tremendous potential because to its dual harvesting of panicle for food grain and stalk for fuel and folding (Woods, J., 2001). A biofuel called bioethanol may be made from stalk juice by fermenting it and then burning the stalk fiber in boilers to generate steam and power. A sustainable sugar-rich crop that produces a variety of goods, sweet sorghum has shown promise as a biofuel source (Rooney et al.,2007; Prasad et al.,2007; Zhang et al.,2010; Linton et al.,2011; Yu et al.,2012). As the plant matures, the stems of sweet sorghum types store a lot of sugar.
According to GTZ and MOE (2008), sweet sorghum is known for its efficient photosynthetic processes and high sugar-yielding biomass. To ensure food security, sweet sorghum is mostly cultivated in agriculturally low potential regions of Kenya. The first crop, or seed crop, of sweet sorghum is allowed to mature when the crop is cultivated for bioethanol production.

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Because of this, grain may be collected for human consumption, guaranteeing food security while also removing biofuels from the food chain. When it comes to sweet sorghum, the seeds work best for propagation. Rows of 50-60 cm apart and 12-15 cm between hills are used for seed cultivation (Rao et al., 2008). It is recommended to use pre-emergence herbicides no later than one day after sowing. After the crop is 35–40 days old, weeds are controlled. A black speck on the bottom end of the grain indicates that the crop is ripe, which occurs after four months. According to Muok et al. (2010), the stalks of sweet sorghum may be picked for their juice whenever the brix level reaches 16-18%. The sugar content for bioethanol production is a key feature of the sweet sorghum stalk harvesting stage (Oyier et al.,

that year (2017). As a sweet sorghum crop matures, its sugar content rises after falling at the beginning of its growth. The volume of juice extracted and the brix concentration define the bioethanol potential for the different sweet sorghum varieties.

2 Sweet sorghum stalk biofuel production is being pursued on a global scale (Sokan-Adega, A., Ana, G., 2015). The stalks of sweet sorghum, for instance, are harvested in Australia and sent to a biorefinery distillery plant to make bioethanol, but in the United States, they are used for both bioethanol production and fodder (Ratnavathi et al., 2011). According to research by de Vries (2010), sweet sorghum in China offers the best use of energy, nitrogen, water, and land, making it one of the most sustainable ecosystems for renewable fuel generation. Based on an estimate of 263, 965 km2, or 46.4% of Kenya's total surface area, a study conducted by Muok et al. (2010) found that the western, central, and eastern coastal areas are the most suitable for growing sweet sorghum. After excluding places where animals are in danger, wetlands, protected areas, and migration routes, the remaining 185,822 km2 (or 32.6% of Kenya's total surface area) are appropriate. Sweet sorghum cultivation in Kenya is underutilized despite the country's great potential (Muui et al., 2013).

2.0 Methodology

2.1 Scope of study and System Boundary

3 Methods for this LCA were based on those specified in ISO 14040/14044 (2006). Both secondary data culled from existing literature and primary data gathered during site visits made up the study's data set. While on site at the Kenya Agriculture and Livestock Research Organization, we used a standardized questionnaire to collect data on cultivation processes, including soil preparation, planting, crop management, and harvesting. It was presumed in the research that two crops, ratoon and seed, be harvested annually.

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Literature reviews were conducted to gather data for the biorefinery operations including the milling operation and bioethanol production as they pertain to the sweet sorghum stalk juice. The lack of a biorefinery processing facility for sweet sorghum in Kenya and the rest of East Africa is the main cause for this. Information was input into Excel spreadsheets for the purpose of registration and to derive further calculations for greenhouse gas emissions and energy use. The greenhouse gas emissions and energy balances of producing bioethanol from sweet sorghum stalk juice are estimated in the research. The bioethanol yield per functional unit is one liter (1L). A yield of 55.88 tons per hectare of sweet sorghum stalks in a single year is used to compute the findings. The research is based on the premise that a seed crop and a ratoon crop are harvested once every twelve months.

As shown in Figure 1, the processes that were evaluated in this research to conduct the life cycle assessment (LCA) for the bioethanol produced from sweet sorghum stalk juice have a defined system boundary. Production of agricultural inputs, cultivation, transportation of sweet sorghum stalk, milling of the stalk, conversion of juice to bioethanol, and cogeneration are all included in the study. The research failed to take into account the energy contained in agriculture and industrial equipment that is powered by fossil fuels. In their life cycle assessment (LCA) studies, Dunn et al. (2011) and Izursa et al. (2012) discovered that the amount of fossil fuel energy included in agricultural equipment was little. The impact of embedded energy is minimal since it is spread out across the lifetime of the equipment. Embedded energy in agricultural and industrial equipment should not be considered, according to research by Seabra et al. (2011), Silalertruksa and Gheewala (2009), and Garcia et al. (2011).

3.0 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 energyvalue (NEV), the netrenewable energy value (NREV) andthe net energy yield ratio (NER) to assess the energy performance of

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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.

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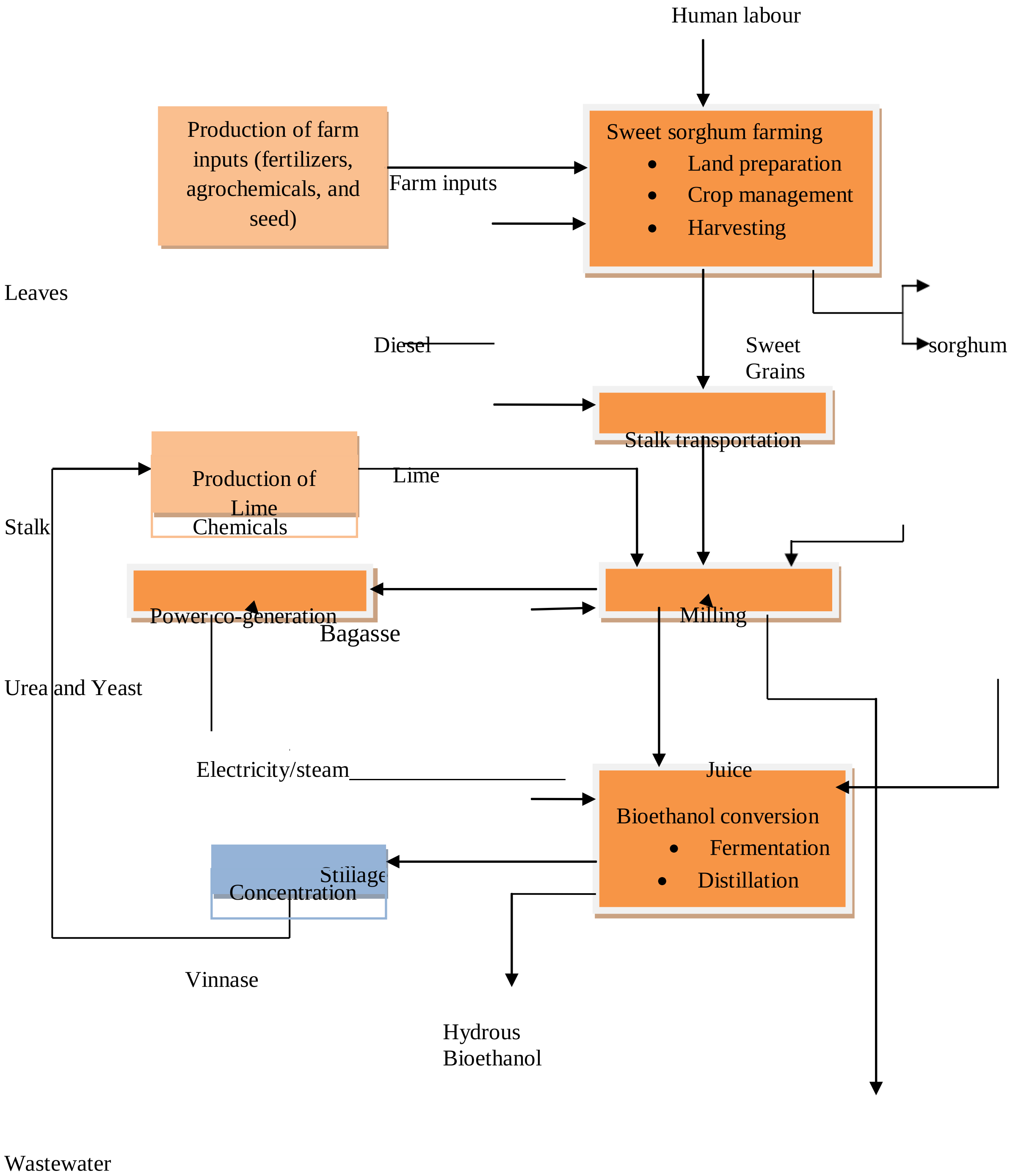

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Fig. 1: System boundary for sweet sorghum stalk juice based bioethanol

3.1 Allocation

In a multi-product biofuel system, allocation allows partitioning of energy and environmental burdens betweenthe major product and co-products when carrying out

LCA stands for life cycle assessment. According to ISO 14044: 2006, the process of allocation involves dividing up the input energy, material flows, and emissions among the product and any co-products. Depending on factors such as mass, energy content, economic value, or replacement, the distribution of energy and environmental emissions may be adjusted for each new co-product. The quantity and selling price of goods and by-products are factors in economic allocation. According to Borjesson (2009) and Reijinders & Huijbregts (2009), biofuel allocation is heavily impacted by price fluctuations in co-product markets. Gnansounou et al. (2009) and Reijinders & Huijbrebts (2009) found that subsidies for fuels and co-products skew relative pricing. When allocating biofuel and co-products, one takes their relative masses into consideration, while another takes their energy content value into consideration. The latter has the benefit of having easily-determinable and stable heating settings. A potential drawback of this distribution is that a particular co-product can have a low market price despite its high calorific content.

This research breaks down the greenhouse gas emissions and energy inputs into their respective stages of the sweet sorghum lifecycle using mass allocation. Sweet sorghum is farmed, milled, and its stalk juice is transformed into bioethanol as part of its lifetime. At each step, we calculate the product and co-product masses as a percentage of the overall output mass for that operation. After that, the percentage mass of the final product is used to determine how much energy and greenhouse gas emissions each step or activity is responsible for. Sweet sorghum stalks (55.88 ton/ha) are the most important agricultural product, with grain (8.38 ton/ha) and leaves (4.47 ton/ha) as secondary goods. According to these calculations, the stalk should get 81.3% of the total mass, the grain should receive 12.2%, and the leaf should receive 6.6%. Juice (960 kg/t stalk) is the main byproduct of milling, with bagasse (458.8 kg/t stalk) and mud (24 kg/t stalk) as byproducts. The resulting mass allocations are as follows: 66.7% for juice, 31.6% for bagasse, and 1.7% for muck. The primary end result of bioethanol production is bioethanol, whereas stillage (0.52 kg/L bioethanol) is considered a byproduct. Bioethanol has a mass of 0.79 kilogram per liter. According to these calculations, bioethanol accounts for 60.3% of the mass, while stillage accounts for 39.7%.

3.2 Sweet Sorghum Farming, Harvesting and Transport

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4 Land preparation is the first step in growing sweet sorghum. In order to prepare the land, agricultural equipment consumes 40.9 liters of fuel per hectare. Methods such as plowing, harrowing, and furrowing are used to prepare land. While not required, 2.4 liters per hectare of the pre-emergence herbicide Dual Gold is administered before planting. There are 6 kg of sweet sorghum seeds used for sowing. Apply 120 kg/ha of NPK Mavuno fertilizer when planting. The NPK content of Mavuno fertilizer is 10:26:10. Fertilizer using nitrogen (12 kg/ha), potassium (31.2 kg/ha), and potassium (12 kg/ha) may be produced from this. The use of Mavuno top dress fertilizer at a rate of 120 kg/ha is part of crop management. This fertiliser does not include any P2O5 or K2O fertilisers and has an NPK content of 26:0:0, or 31.2 kg/ha N fertiliser. Using 12 man-days/ha of human labor, crop management include weeding without pesticides.

Four months after seed sowing is when sweet sorghum is harvested. Manual harvesting begins by slicing the panicle to release the grain from its stalk. After that, the stalk of sweet sorghum is chopped and the leaves are taken off. In order to enhance the soil's fertility, the research assumes that the leaves be left on the farm and used as organic fertilizer. According to the Rural Industries Research & Development Corporation, RIRDC (2013), the stalk yield for seed and ratoon crops is 55.88 tons per hectare. The harvesting of sweet sorghum requires 87 man-days per hectare. The research is based on the premise that big rigs or tractors with a carrying capacity of 25 or 27 tons per trip are used to deliver the sweet sorghum. The truck's fuel efficiency was determined to be 2 km/L, whereas the tractor's was 1.6 km/L. We estimated a turn-around distance of 30 km from the plant to the farm and back again. The fuel consumed for transporting sweet sorghum per hectare is 35.9 L, assuming an average fuel efficiency value of 1.8 km/L. Table 1 displays the field data acquired for sweet sorghum growing.

5 Table 2 shows the energy and emission coefficients for cane cultivation. The emission coefficient for human labor in this research is 5.59 kgCO2eq/man-days, as stated by Khatiwada et al. (2016). The LSSE approach, which was proposed by Odum (1993) and mentioned by Nguyen et al. (2007), was used

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to determine the energy equivalent of human labor in agriculture. Nguyen et al. (2007) found a value of 12.1 MJ/h for Thailand, a developing nation similar to Kenya in that it is semi-industrialized. This figure was used in this analysis. Next, we divide the input energy into fossil and non-fossil categories according to Kenya's main energy consumption by fuel sources in 2014. According to the International Energy Agency's Energy Statistics (IEA, 2014), although 82.8% of the energy used this year came from renewable sources, 17.2% came from fossil fuels.

5.0 Sweet Sorghum Stalk Milling and Bioethanol Conversion

6 To get the juice out of sweet sorghum stalks, you have to grind them using a set of three roller mills. Sugar sorghum stalks, together with power, steam, and chemicals, are the ingredients for the milling process. Fruit juice, sludge, bagasse, and effluent are the byproducts. The bagasse is burned in boilers to provide steam and power for the plant's operations. The surplus power is sold to the power grid on a national scale. To clarify the juice, chemicals like lime and flocculants are added. Ponds designed to stabilize effluent are used for this purpose. In Table 3 you can see the milling data for sweet sorghum. All of the bagasse is assumed to be burned in boilers to produce steam in this research.

Clarified sweet sorghum juice, steam, power, yeast, urea, and sodium hydroxide are the ingredients used to make bioethanol. Dilute bioethanol, with a concentration of about 9.5% in water, is produced by fermenting the juice with yeast (in the presence of nutrients like urea). Secondly, distillation is used to extract 95% (w/w) bioethanol from the fermented mash. Concentrating and burning the residual by-product, stillage, in conjunction 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.

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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

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[a] RIRDC(2013)

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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)

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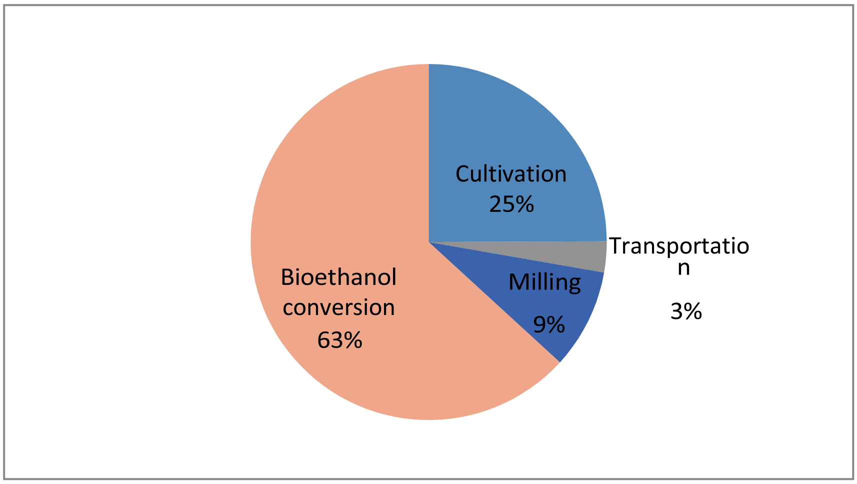

Fig. 3: Energy consumption for sweet sorghum stalk juice based bioethanol in Kenya

3.0 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 bioethanolyield 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.

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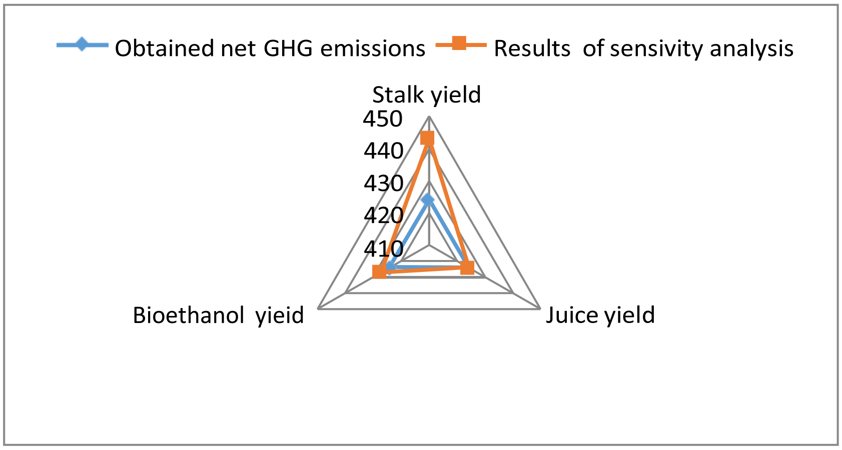

Figure 4: Sensitivity analysis of GHG emissions

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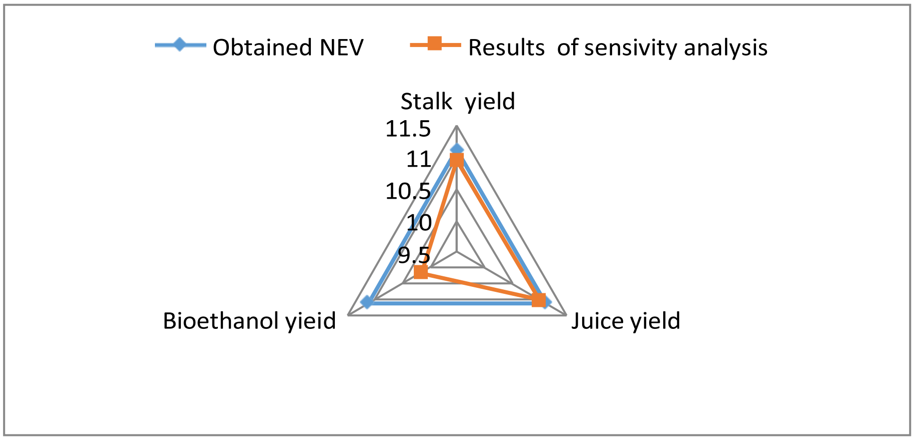

Figure 5: Sensitivity analysis of NEV

4.0 Conclusion

Researchers in Kenya determined that for every liter of bioethanol generated, the total lifetime greenhouse gas emissions from sweet sorghum stalk juice accounted for 424.19 gCO2eq. The majority of greenhouse gas emissions occur during the cultivation phase, with milling and co-generation following closely behind. The cultivation phase is primarily characterized by the production and utilization of nitrogen fertilizer. The overall energy usage for producing one liter of bioethanol was determined to be 10.08 MJ, with 15% coming from fossil fuels and 85% from renewable sources. Per liter of bioethanol generated, the projected net energy value (NEV) is 11.12 MJ, the net renewable energy value (NREV) is 19.68 MJ, and the net energy ratio (NER) is 13.6. Renewable energy sources may be generated with minimal input of fossil fuels, as shown by the comparatively high positive value of NEV. Reduced greenhouse gas emissions are a direct outcome of the low levels of non-renewable inputs needed to make bioethanol in Kenya from sweet sorghum stalk juice, as shown by the high positive values of NREV and NER. Researchers discovered that stalk yield affected greenhouse gas emissions and bioethanol output affected NEV.

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