ENVIRONMENTAL IMPACT ASSESSMENT OF BIOETHANOL PRODUCTION FROM SUGARCANE MOLASSES IN KENYA

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Abstract
Environmental concerns and the increasing demand for transportation energy have led to increased production and utilization of biofuels worldwide. Biofuels are perceived to provide clean and green energy. Globally, bioethanol is the most widely used biofuel. This study considered the production of bioethanol from sugarcane molasses. The production of bioethanol from molasses does not pose threat to food security as molasses is a by-product in the manufacture of sugar from the sugarcane. This study aimed to determine the environmental impacts associated with production bioethanol from sugarcane molasses in Kenya from a lifecycle perspective. The environmental impact categories evaluated included Global Warming (GHG emissions), Acidification, Eutrophication, Human Toxicity, Ecotoxicity and Photochemical oxidant Formation. Data was collected in all stages of the life cycle of bioethanol production. These include sugarcane cultivation, harvesting, transportation, cane milling, bioethanol conversion and wastewater treatment. The data was collected during field visits at Mumias Sugar Company and Spectre International. In the study, an inventory analysis was performed which involved quantification of emissions from each stage using models and emission factors from literature. Emissions were also obtained from Ecoinvent databases for the major processes as well as their supporting processes. Economic allocation was used to partition emissions and resources between molasses and sugar. A life cycle impact assessment (LCIA) was performed in Chain Management by Life Cycle Assessment (CMLCA) software. The characterization method that was used to calculate the environmental impacts of bioethanol was the CML-IA. Low values of Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Human Toxicity Potential (HTP) and Photochemical Ozone Creation Potential (POCP) were obtained in this study. Emissions emitted due to fossil fuel use, production and use of agrochemicals were found to be the major contributors to environmental impact. The study recommends use of cane trash, bagasse and stillage as supplement fertilizer and boiler fuel. This will reduce dependency on fossil fuels and chemical fertilizers which impacts negatively on the environment.

Key words: Sugarcane molasses-bioethanol system, environmental impacts, life cycle assessment, Kenya

1.0 Introduction

Biofuels development has received increased attention globally in recent times as they are perceived to be cleaner and cheaper fossil fuel alternatives towards mitigating climate change, expanding the fuel energy resource mix and fostering rural development (Gheewala et al. 2013). This has led to increased production and utilization of biofuels worldwide. It should also be noted that 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, environmentally friendly and ecologically sustainable (Srinivasa et al., 2010). These requirements have led to increased global interest in the exploration, production and utilization of biofuels. Biofuel crops that provide economic benefits to the rural poor while providing access to clean and green energy at both local and national level would likely meet the aforementioned requirements (Srinivasa *et al*., 2010). Demirbas (2008) had also indicated the reasons to promote biofuels which include: energy security, environmental concerns, foreign exchange savings and socio-economic well-being of the rural population. Research findings in both developing and developed countries have shown that biofuels could be a dominant renewable source of energy that mitigates climate change (Srinivasa et al., 2010). Many developed and developing nations have supported their fossil fuel supplies and consumption by blending biofuels with fossil fuels whose resources are continuously being depleted (Srinivasa et al., 2010). The combination of improving energy security, need to reduce greenhouse gas (GHG) emissions to mitigate climate change and providing support to rural economies has been motivating biofuel development in several countries. Biofuels have potential to provide socioeconomic benefits as presence of industrial plants in rural areas create employment, encourage other economic activities and also influence other related industries (Gilio & Moraes, 2016; Moraes et al., 2016). Globally, biofuels expansion is mainly to address energy security, poverty alleviation and economic development. Biofuel impacts can be positive or negative depending on several factors such as the feedstock, the environmental/socio-economic context of biofuel production, and the policy instruments in place during biofuel production, use and trade (Gasparatos *et al.* 2015).

In the early 1980's, Kenya blended bioethanol with petrol under the Gasohol programme (GTZ & GoK, 2008). The record high oil prices of 1970s and 1980s made the Kenya government to initiate the gasohol policy. The policy mandated a 10% bioethanol blend with petrol, but due to production limitation, this was only achieved in Nairobi which was about 280 km from the plant where bioethanol was being produced, the Agro-Chemical and Food Company (ACFC), in Western part of Kenya. The gasohol programme became uneconomical due to a number of factors that included a drop in global oil prices, a surge in the price of bioethanol due to demand in export markets and reduced production of bioethanol. To bring gasohol to the same retail price as petrol, the Government reduced customs tariff on gasohol. Even with this subsidy, production of bioethanol was still not viable. The gasohol programme ceased but the bioethanol continued to be used for production of industrial alcohol. Two other bioethanol plants were later established in Kenya i.e. Spectre International and Mumias Sugar Company. The integrated production of sugar, bioethanol and power by Mumias Sugar Company is a more efficient and sustainable model of production.

Sustainable development addresses humanity's aspirations for a better life. The Sustainable Development Goals (SDGs) ensure a better and sustainable future for all, balancing the economic, social and environmental development (Fonseca & Carvalho, 2019). Production of bioethanol from the sugarcane molasses aim to achieve SDG7 (Access to clean and affordable energy). SDG7 is an essential component of achieving other SDGs such as SDG1 (No poverty), SDG2 (Zero hunger), SDG3 (Good health and well-being), SDG8 (Decent work and economic growth) and SDG13 (Climate action) (Fonseca et al., 2020). Bioethanol production from sugarcane molasses can promote economic development and enhance rural livelihoods as it will avail opportunities for employment for local population, especially among the youth and women (Olivia & Mihaila, 2016, Sakai *et al*., 2020). This will be made possible when small scale farmers are involved in cultivation of sugarcane and the sugar factories and/or molasses plants are located in rural areas. Bioethanol production is associated with reduced GHG emissions; therefore it has potential to minimize climate change (Belboom et al., 2015, Numjuncharoen et al., 2015, Khatiwada et al. 2016). Increased production of bioethanol from sugarcane molasses will be in line with one of the Kenya Government's Big 4 Agenda on manufacturing, through agro-processing.

There is rising concern on environmental impacts caused by the expansion of biomass resources production and use as energy (Wu et al., 2018). Biofuels production release emissions to air, water and soil. For example emissions to air include NO_x, SO_x, CO, CO_2, CH_4, VOC, NH_3 and particulate matter which are impacted at each stage of biofuel production, distribution, and usage (EPA, 2018). Information on contribution of a biofuel to the environmental burden of a country is required to ensure its sustainable production. This study therefore evaluated some of the environmental impacts associated with the production of bioethanol from the sugarcane molasses. These impacts were used to identify and determine environmental implications in producing of the bioethanol. The environment impact categories evaluated were global warming (climate change), acidification, eutrophication, human toxicity, ecotoxicity and photochemical ozone formation to assess the environmental burden of bioethanol production from sugarcane molasses in Kenya.

2.0 Materials and Methods

The study determined environmental impacts caused by emissions emitted in the production of bioethanol from sugarcane molasses. The study identified, quantified and evaluated resources consumed, and the emissions and wastes released to the environment. The methodology used to carry out the life cycle assessment (LCA) is the one described by ISO 14040 (2006) and ISO 14044 (2006). Data was collected from Mumias Sugar Company and Spectre International Company.

2.1 Goal and Scope Definition

The goal of the study was to evaluate environmental impact potentials associated with bioethanol production from the sugarcane molasses in Kenya. The impact categories assessed were Global Warming (GHG emissions), Acidification, Eutrophication, Human Toxicity, Ecotoxicity and Photochemical Ozone Formation. The scope of study was "cradle to gate" covering all stages in the life cycle of bioethanol production. The functional unit of production of bioethanol in this study was defined as one litre (1 L) of anhydrous bioethanol produced.

2.2 System Boundary and Data Sources

The system boundary for the sugarcane molasses bioethanol system is as indicated in Figure 1. The life cycle of molasses bioethanol system starts with land preparation carried out using agricultural machineries through conventional methods (ploughing, harrowing and furrowing). Land preparation was found to consume 30 L/ha of diesel and required a human labour of 12 man-days/ha. Before planting of the cane, 30 tonnes of the cane seed are treated with Confidor pesticide (172 millilitres) and Follicur fungicide (2 litres) diluted in about 600 litres of water. This amount of seed cane can be planted in 5 ha. During planting, NPK Blend 1 fertilizer (250 kg/ha) was applied. The NPK content of the Blend 1 fertilizer for planting is 12:30:7. All planting activities were manual requiring human labour of 12 man-days/ha. In ratoon management, NPK Blend 2 fertilizer (250 kg/ha) was applied. The NPK content of the Blend 2 fertilizer for crop management is 26:0:20. Herbicides (Krismat & Dual Gold) are also applied once a year. The human labour for crop management was found to be 12 man-days/ha.

Sugarcane was harvested 18 months after planting and then once a year for three ratoons. For this study, average sugarcane yield was taken to be 65 t/ha. During harvesting cane stalks are cut removing the leaves and tops (cane trash). The cane trash is lined in the fields along the root stumps to be used as organic fertilizer. Human labour for harvesting the cane was found to be 40 man-days/ha. Sugarcane was transported using either tractors with carrying capacity of 25 tonne per trip or large trucks with carrying capacity of 27 tonne per trip. Fuel economy for the tractors was found to be 1.6 km/L and that of the large trucks to be 2 km/L. The average turn round distance (factory-farm-factory) was found to be 44 km. Taking an average value of fuel economy of 1.8 km/L, the fuel used for sugarcane transportation per ha was calculated to be 60.5 L.

Processes involved in cane milling were cane preparation, clarification, boiling, seeding and centrifuging to obtain crystal sugar. The by-products were molasses, filter cake, and bagasse. The inputs in cane milling were steam, electricity and chemicals. The filter cake assist in cane extraction in the diffuser and bagasse was combusted in boilers producing steam used as process energy in the plant. The chemicals used include sulphur, flocculants and lime. The sulphur bleaches the sugar, flocculants and lime assist in clarification of the sugar juice. The study found that one tonne of sugarcane yields about 100 kg sugar, 370 kg bagasse, 30 kg molasses and 40 kg filter cake.

In the distillery plant, the molasses was first diluted and then hydrolyzed with sulphuric acid to make it fermentable. The molasses was then fermented with yeast (in presence of nutrients like urea) yielding dilute bioethanol at a concentration of about 9.5% in water. The fermented mash was passed through distillation yielding concentrated bioethanol of 95% (w/w) in water. Vinnase, the by-product that remains of molasses after extracting the alcohol was dewatered up to 40-50% and mixed with bagasse in the ratio of 95:5 and combusted in specially designed boilers. The wastewater for this phase was treated in waste stabilization ponds. The inventory data collected during the field visits at Mumias Sugar Company and Spectre International is presented in Table 1. .

2.3 Allocation Procedure

In the life cycle analysis methodology, allocations are proportionally made to share the accountability for life cycle resource consumption and environmental burdens when two or more co-products are being produced (ISO 14040, 2006, ISO 14044, 2006). Sugar, molasses and bagasse are the three main products in the cane industry, but the bagasse is consumed internally to generate heat and power for use in the operation of the plant. Allocation of co-products that are re-used is not recommended (Nguyen & Gheewala, 2008; Khatiwada & Silveira, 2011). In this study, economic allocation was used to partition the resource consumption and environmental burdens between sugar and molasses. The molasses is a low value product compared to sugar, thus this allocation methodology would encourage its use for bioethanol production (Khatiwada *et al*., 2016). In 2014, the average market price of sugar was about US $ 988 (KSB 2014). This study adopted the findings of Gopal & Kammen (2009) on what was found on sugar and molasses prices in Brazil, India and Indonesia. In their study, the price of sugar was found to be 5.5 times higher than that of molasses. Based on this, the price of molasses was calculated to be US $ 180/tonne of molasses. Equation 1 is used in this study to calculate the allocation ratio. The calculated partitioning ratios of sugar and molasses are presented in Table 2.

$$Allocation = \frac{Yield\ of\ sugar * Price\ of\ sugar}{Yield\ \boldsymbol{of}\ molasses * Price\ of\ molasses} \quad \text{.........................Eqn 1}$$

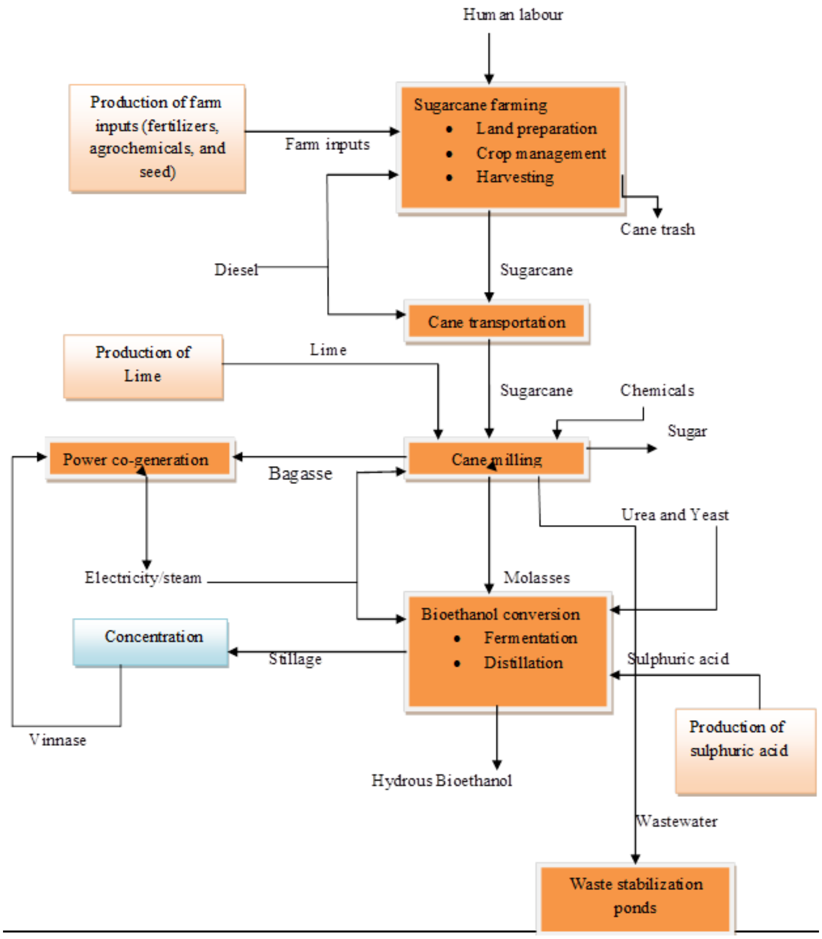

Figure 1: System boundary for sugarcane molasses based bioethanol
Source: Author

Table 1: Data for sugarcane molasses bioethanol system

Item	Units	Value
Sugarcane farming & harvesting		
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
Pesticides/fungicides	L/ha	0.434

Sugarcane seeds	t/ha	6
Sugarcane yield	t/ha	65
Cane trash	t/ha	6.5
Labour	man-days/ha	76
Diesel use for land tillage	L/ha	30
Diesel use for transport	L/ha	60.5
Sugarcane milling		
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/t cane	1500
Steam	kg/t cane	500[b]
Sulphur	kg/t cane	0.1
Juice flocculant	kg/t cane	0.003
Bioethanol conversion		
Molasses	kg/L bioeth	4
Water	L/L bioeth	6.4
Sulphuric acid	kg/L bioeth	0.0032
Urea	kg/L bioeth	0.004
Yeast	L/L bioeth	0.00004
Electricity	kWh/L bioeth	0.44[a]
Stillage	L/L bioeth	11.42
Steam	kg/L bioeth	2.25[c]

[a] Eshton (2012);
[b] Ramjeawon (2008);
[c] Khatiwada & Silveira (2009), Khatiwada & Silveira (2011)

Table 2: Economic allocation of sugar and molasses

	Sugar	**Molasses**
Yield (kg/tonne)	100	30
Price (US$/tonne)	988.2	180
Allocation ratio	18.3	1
Allocation factor (%)	94.8	5.2

Source: Author

2.4 Life Cycle Inventory Analysis

The Life Cycle Inventory (LCI) analysis involved quantification of emissions and resource extraction. The material flows, energy flows, and emissions to air, land and water were evaluated for the entire bioethanol chain. Emissions of sugarcane farming, cane milling, bioethanol conversion, wastewater treatment as well as emissions of their supporting processes were obtained from the Ecoinvent databases (Ecoinvent v2, 2010). In cultivation phase the agrochemicals used include fertilizers, herbicides, pesticides, and fungicides. Another cultivation activity is human labour. The emission factors used to determine the emissions due to production of farm inputs in cultivation phase were obtained from literature and are presented in Table 3. Emissions due to addition of nitrogen fertilizer i.e. direct and indirect soil N_2O emissions were obtained using the models described in IPCC (2006) and Agri-footprint 2.0 (2015). Emissions of heavy metals due to addition of mineral fertilizers were calculated using emission factors obtained from Agri-footprint 2.0 (2015). Emissions due to chemical inputs in cane milling and bioethanol production were calculated using emission factors presented in Table 4. The emission factors used to determine the emissions due to burning of diesel in farm machinery and in transportation are presented in Table 5. Emissions of heavy metals, inorganic and organic compounds due to burning of diesel were obtained from the Ecoinvent databases (Ecoinvent v2, 2010). The emissions due to burning of bagasse in boilers were determined using the emission factors presented Table 6.

Table 3: Emission factors in Cultivation phase

Particulars	Value	Units
Nitrogen (N) production	3.97	$kgCO_{2eq}/kg$
Phosphorus (P_2O_5) production	1.3	$kgCO_{2eq}/kg$
Potash (K_2O) production	0.71	$kgCO_{2eq}/kg$
Herbicide production	25	$kgCO_{2eq}/kg$
Sugarcane seeds production	0.0016	$kgCO_{2eq}/kg$
Human labour	5.59	$kgCO_{2eq}$/man-day

Source: Khatiwada et al. (2016)

Table 4: Emission factors for inputs in cane milling and bioethanol production

Substance	Emission coefficient ($kgCO_{2eq}/kg$)
Lime production	0.07
Bagasse combustion	0.025
Sulphuric acid production	0.21
Urea	1.85
Yeast	0.49

Source: Khatiwada et al (2016)

Table 5: Emission factors for diesel burning

Substance	Emission factor (kg/TJ) for farm machinery	Emission factor (kg/TJ) for transportation
Nitrous oxide(air)	0.6	3.9
Methane (air)	10	3.9
Nitrogen oxides (air)	100	1200
Carbon dioxide(air)	74100	74100
Carbon monoxide (air)	20	1000
Non-methane volatile organic compounds (air)	5	200
Sulphur dioxide (air)	346.5	346.5
Particulates (air)	372	372

Source: IPCC (1996); IPCC (2006)

Table 6: Emissions factors due to burning of bagasse in boilers

Substance	EF(kg/kg bagasse)
Ammonia[air]	2.99E-06
Particulates[air]	7.71E-05
Methane[air]	7.69E-05
Carbon monoxide[air]	5.45E-05
Cadmium[air]	1.20E-09
Arsenic[air]	1.72E-09
Copper[air]	3.78E-08
Lead[air]	4.28E-08
Nitrogen oxides[air]	6.00E-04
Sulphur dioxide[air]	5.81E-06
Zinc[air]	5.15E-07
Nitrous oxide[air]	7.69E-06
Phosphorus[air]	5.15E-07
Toluene[air]	5.15E-07
Benzene[air]	2.72E-07
Chromium V[air]	6.87E-11

Source: Ecoinvent databases

2.5 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) aimed at aggregating and interpreting the results of the inventory analysis. The inventories of emissions and resources consumed were assessed in terms of impacts. The environmental impact categories assessed were global warming/climate change, acidification, eutrophication, human toxicity, ecotoxicity and photochemical ozone formation. The emissions causing each of these impact categories were expressed in terms of a reference substance and were referred to as characterization factors. The characterization factors for each impact category were used to convert an LCI analysis result to common unit of category indicator. For example, emissions of GHGs were converted to one score for climate change, and emissions of acidifying substances were converted into one score of acidification. In this study, the characterization method used to calculate the environmental impacts was the CML-IA (Van Oers, 2010). The set of characterization factors for global warming/climate change were obtained from IPCC (2007) while those for acidification, eutrophication, human toxicity, ecotoxicity and photochemical ozone formation were obtained from van Oers (2010). The life cycle impact assessment (LCIA) was performed in Chain Management by Life Cycle Assessment (CMLCA) software.

3.0 Life Cycle Inventory Analysis of the Sugarcane Molasses Bioethanol System

3.1 Global Warming/GHG Emissions

The GHG emissions results of the sugarcane molasses bioethanol system are presented in Table 7. The estimated net GHG emission is 270.88 g CO_{2eq}/L bioethanol for the complete lifecycle chain. Sugarcane production phase is the major contributor to GHG emissions emitting 78.45% of the total emissions and the industrial phase the rest. Production of agrochemicals contributes about 18.7% of the total GHG emissions with nitrogen fertilizer production and being the major contributor. Nitrogen fertilizer use contributes 25% of the total GHG emissions. Diesel use in land tillage and in transportation of cane to the sugar factory contributes 16.8% of the total GHG emissions. Sugarcane milling and wastewater treatment contribute 0.19 and 0.17%, respectively of the total GHG emissions. The emissions associated with human labour contribute 17.58% of the total GHG emissions.

Table 7: GHG emissions from sugarcane molasses based bioethanol

Process	Emissions (g CO_{2eq}/L bioethanol)	Percent
Sugarcane production	***212.5***	***78.45***
Fertilizers		
Nitrogen production	31.6	11.67
Phosphorus production	2.19	0.81
Potash production	4.26	1.57
Herbicide production	10.93	4.03
Insecticide/Pesticide production	1.41	0.52
Sugarcane seeds production	1.08	0.40
N_2O emissions (direct & indirect)	67.89	25.06
Human labour	47.62	17.58
Diesel (tillage)	23.38	8.63
Diesel (transportation)	22.14	8.17
Cane milling	***0.51***	***0.19***
Lime production	0.51	0.19

Co-generation	***49.19***	***18.16***
Bagasse combustion	49.19	18.16
Bioethanol conversion	***8.22***	***3.03***
Sulphuric acid production	0.77	0.28
Urea	7.4	2.73
Yeast	0.05	0.02
Wastewater treatment	***0.46***	***0.17***
Effluent treatment	0.46	0.17
Total emissions	270.88	100.00

LCA of sugarcane molasses based bioethanol have been done in countries such as Indonesia (Khatiwada *et al.*, 2016), India (Soam et al., 2015), Ethiopia (Demissie & Gheewala, 2019; Gabisa *et al.*, 2019). The reported GHG emissions per litre of bioethanol in Indonesia and India are 616.5 and 696 g $CO_{2eq,}$ respectively. In Ethiopia, Demissie & Gheewala (2019) and Gabisa *et al*. (2019) reported GHG emissions of about 1506 and 1140 g CO_{2eq} per litre of bioethanol, respectively. All these previous results were higher than that obtained in this study (270.88 g CO_{2eq}). In the study by Khatiwada *et al*. (2016) in Indonesia, the use of coal as source of energy and cane burning before harvesting contributed significant GHG emissions. The high value of GHG emissions reported by Demissie & Gheewala (2019) was due to use of light fuel oil for electricity generation for the bioethanol plant, cane trash burning, cane trash and filer cake decomposition, and use of large amounts of nitrogen fertilizer (430 kg/ha) than that of this study (71 kg/ha). The high value of GHG emissions reported by Gabisa *et al*., (2019) was due to sugarcane burning before harvesting, a high fossil consumption in agriculture machinery and transport services, and consumption of lime and phosphoric acid during molasses generation. Soam *et al*., (2015) also reported a higher value of GHG emissions due to use of electricity from the grid generated from fossil fuels and also the use of fossil fuel for irrigation. In this study, no sugarcane burning prior harvesting, no use of fossil fuels in steam and electricity generation, sugarcane production is rainfed and thus no pumped irrigation which all contribute to GHG emissions.

3.2 Acidification Potential

In this study, acidification potential (AP) of the sugarcane molasses bioethanol is estimated at about 0.313 g SO_{2eq} per litre of bioethanol produced. The AP results from atmospheric emissions of NH_3, NO_x and SO_2. As shown in Figure 2, NH_3 is the major acidifying pollutant (52%), followed by NO_x (40%) and SO_2 (8%) of total AP. The major source of NH_3 and SO_2 was found to be sugarcane farming. NH_3 emissions were found to be due to application of nitrogen fertilizers while SO_2 emissions are due to use of fossil diesel for land tillage and farm outputs transportation. The major source of NO_x emissions is the use of urea in bioethanol conversion.

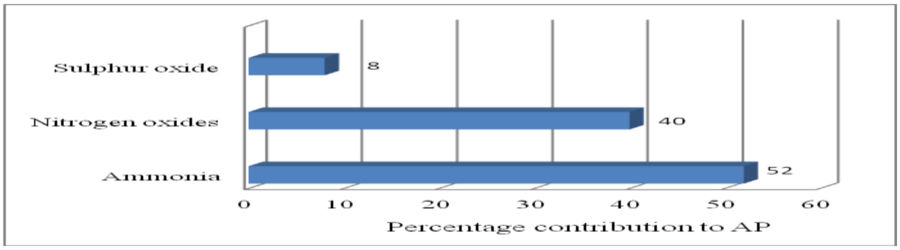

Figure 2: Acidification potential of sugarcane molasses bioethanol

The AP obtained in this study was compared to that reported by Eshton (2012) in Tanzania, Demissie & Gheewala (2019) and Gabisa *et al.* (2019) in Ethiopia who reported AP values of 11.9, 79 and 59 g SO_{2eq} per litre of bioethanol, respectively. The result of this study i.e. 0.313 g SO_{2eq} per litre of bioethanol is much lower compared to each of these studies. Eshton (2012) reported a higher AP value due to NO_x emissions from sugarcane burning before harvesting. The high AP value reported by Demissie & Gheewala (2019) is due to discharge of vinasse and consumption of high amount of light fuel oil in the bioethanol plant. Gabisa *et al.* (2019) also reported a high AP value; this due to cane trash burning, high fossil fuel use in agriculture machinery and transport services; which emit NO_x and SO_2. In this study, the source of energy is combustion of bagasse in boilers with no use of coal, and there is no sugarcane burning before harvesting. Due to no use of coal and no sugarcane burning before harvesting results in a significant reduction in AP in this study.

3.3 Eutrophication Potential

Eutrophication is due to nutrient enrichment in both aquatic and terrestrial ecosystems. The calculated eutrophication potential (EP) of the sugarcane molasses based bioethanol is 0.18 g PO_4^{3-} per litre of bioethanol produced. In this study, emissions of NO_x, NH_3, and N_2O emitted to air, Total-N and Total-P emitted to water contributing to eutrophication impact. Figure 3 presents the contribution of each of these emissions to the total EP, i.e., Total-N (57%), Total-P (10%), NH_3 (17%), NO_x (13%) and N_2O (3%). The NH_3, Total-N and Total-P emissions are due to application of fertilizers in sugarcane farming. Largest proportion of NO_x emissions in bioethanol conversion results from use of urea fertilizer to propagate yeast organisms for ethanol fermentation.

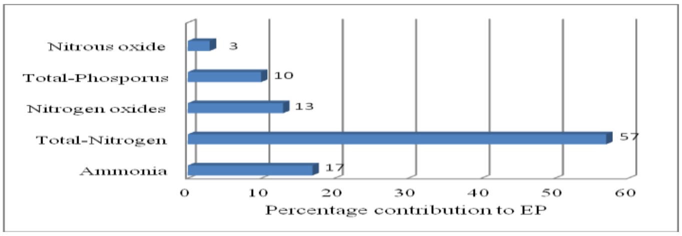

Figure 3: Eutrophication potential of sugarcane molasses bioethanol

The eutrophication impact potential calculated in this study was much lower compared to that reported by Eshton (2012) and that of Silalertruksa and Gheewala (2009) who reported EP values of 4.57 and 19.67 g PO_4^{3-} eq per litre of bioethanol, respectively. The higher values of EP reported by Eshton (2012) and that by Silalertruksa and Gheewala (2009) are due to use of larger quantities of nitrogen and phosphate fertilizers than in this study. Fertilizer application in Eshton (2012), Silalertruksa and Gheewala (2009) and this study were 260, 256 and 86 kg/ha, respectively. The much higher EP value in Silalertruksa and Gheewala (2009) was due to treatment of spent wash in waste stabilization ponds resulting in COD emissions which cause eutrophication.

3.4 Human Toxicity Potential

Human toxicity is due to a long time exposure to toxic substances or chemicals that have potential to cause negative human health effects. This study estimated the human toxicity potential (HTP) for sugarcane molasses based bioethanol in Kenya at about 47 g 1, 4 DCB eq per litre of bioethanol. Here, HTP is due to emissions of heavy metals and benzene to air and soil. The heavy metals include Cd, Zn, Pb, As and Ni. Figure 4 shows the contribution of each of these emissions to the total HTP. The heavy metals emissions were due to use of fertilizers, herbicides and pesticides. The HTP result obtained in this study was compared with those reported by Eshton (2012) and Gabisa *et al*. (2019), which were 105 and 93.07 g 1, 4-DCB eq per litre of bioethanol respectively. The HTP value reported by Eshton (2012) was much higher due to sugarcane burning before harvesting which result in emissions of heavy metals and particulates which contribute significantly to human toxicity. The HTP reported by Gabisa *et al.* (2019) was higher than that obtained in this study due to addition use of diesel for mechanical harvesting. Production and use of diesel emit emissions that result to human toxicity. In this study, sugarcane harvesting is manual.

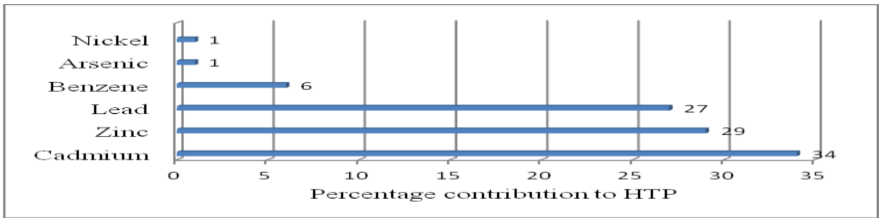

Figure 4: Human toxicity potential of sugarcane molasses bioethanol

3.5 Ecotoxicity Potential

In this study, ecotoxicity (ET) of sugarcane molasses based bioethanol was estimated to be 5.75 g 1, 4 DCB eq per litre of bioethanol. As shown in Figure 5, ecotoxicity was found to be due to emissions of heavy metals and Atrazine. Zinc emissions were found to contribute to about 93% of the total ET. The emissions causing ecotoxicity were due to use of fertilizers, herbicides and pesticides.

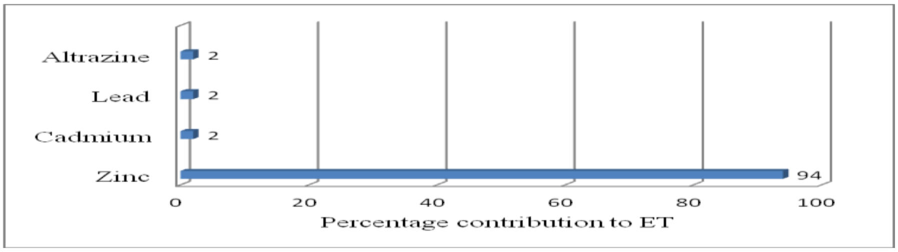

Figure 5: Ecotoxicity potential of sugarcane molasses bioethanol

This study compared ET results obtained with that obtained by Eshton (2012) in Tanzania and Demissie & Gheewala (2019) in Ethiopia. The ET result reported by Eshton (2012) was 7.35 g 1, 4 DCB eq and that by Demissie & Gheewala (2019) was 9.61 g 1, 4 DCB eq, per litre of bioethanol in each case. The ET result estimated in this study was slightly lower than that reported by Eshton (2012) and Demissie & Gheewala (2019). In the study by Eshton (2012), slightly higher ET value can be attributed to addition use of diesel for irrigation. The use of light fuel oil for electricity generation and the vinnase discharge contribute to a slightly higher ET value in Demissie & Gheewala (2019).

3.6 Photochemical Ozone Creation Potential

The calculated photochemical ozone creation potential (POCP) of sugarcane molasses bioethanol was estimated at about 2.93E-03 g ethene eq per litre of bioethanol. As shown in Figure 6, this impact is due to the following emissions; CO, SO_2, benzene, toluene, formaldehyde and acetaldehyde which contribute 30, 41, 10, 10, 4, and 2%, respectively, to the total POCP. These emissions are mainly from sugarcane farming and bioethanol conversion stage of the sugarcane molasses based bioethanol life cycle. The POCP result obtained in this study was compared with those reported in previous studies by Eshton (2012), and Silalertruksa and Gheewala (2009) who reported a POCP of 3.62 and 5.79 g ethene eq per litre of bioethanol, respectively. In each of the two studies, sugarcane burning prior to harvesting accounted to more than 90% of the total POCP. In the study by Demissie & Gheewala (2019), NO_x, SO_x and CO emissions due to cane trash burning contributed 80% of the total POCP. In this study there was no sugarcane burning before harvesting.

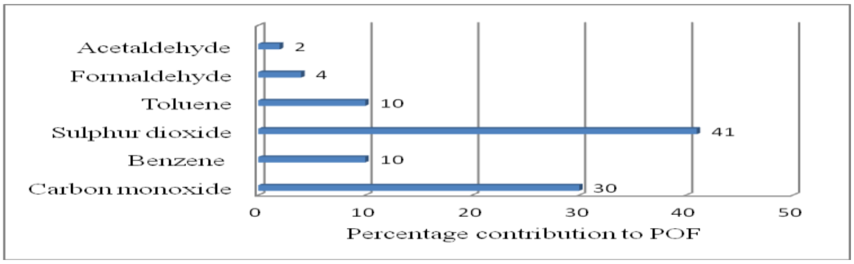

Figure 6: Photochemical ozone formation of sugarcane molasses bioethanol

4.0 Conclusions and Recommendations

4.1 Conclusions

Sugarcane molasses based bioethanol was found to have net GHG emissions of 270.88 gCO_{2eq} per litre of bioethanol. Cultivation and harvesting stages of the sugarcane production was found to contribute the highest proportion (more than 60%) of the total GHG emissions, the production and use of nitrogen fertilizers (36.7%) being the main contributor. This study obtained low net GHG emissions for the sugarcane molasses bioethanol system. Low values of Acidification Potential (0.313 g SO_{2eq}), Eutrophication Potential (0.18 g PO_4^{3-}), and Photochemical Ozone Creation Potential (2.93E-03 g ethene eq), per litre of bioethanol in each case, were also obtained in this study.

4.2 Recommendations

Maximum use of cane trash, bagasse and stillage as fertilizer supplements as well as boiler fuel is recommended. This will reduce the use of fossil fuels and chemical fertilizers, resulting in reduction of air emissions, hence reducing environmental impact mainly GHG emissions, acidification and eutrophication. There is also need to promote production of biogas since it is renewable source of energy - its production and use in bioethanol production may reduce the use of fossil fuels, and thereby reduce environmental impact.

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