LIFE CYCLE ANALYSIS OF BIOETHANOL PRODUCTION FROM SUGARCANE MOLASSES AND SWEET SORGHUM STALK JUICE IN KENYA

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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ACRONYMS AND ABBREVIATIONS

ACFC	Agro-Chemical and Food Company
AP	Acidification Potential
CMLCA	Chain Management by Life Cycle Assessment
CNPC	China National Petroleum Cooperation
CVM	Contingent Valuation Method
DDG	Distiller's Dry Grain
DPP	Directorate of Plant Production
EA	Energy Allocation
EF	Emission Factor
EIA	Environment Impact Assessment
ELU	Environmental Load Unit
EPA	Environment Protection Agency
EPS	Environmental Priority Strategies
ETP	Ecotoxicity Potential
ETSAP	Energy Technology System Analysis Programme
EU	European Union
FFVs	Flexible Fuel Vehicles
GAIN	Global Agricultural Information Network
GHG	Greenhouse Gases
GoK	Government of Kenya
GTZ	German Technical Cooperation
GWP	Global Warming Potential
HLPE	High Level Panel of Experts
HTP	Human Toxicity Potential
ICRISAT	International Crops Research Institute for the Semi Tropics
IEA	International Energy Agency
IIASA	International Institute for Applied Systems
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency

ISO	International Standard Organization
KALRO	Kenya Agricultural and Livestock Research Organization
KSB	Kenya Sugar Board
LCA	Life Cycle Assessment
LCI	Life Cycle Inventories Analysis
LCIA	Life Cycle Impact Assessment
LPG	Liquid Petroleum Gas
MA	Mass Allocation
MPA	Market Price Allocation
NER	Net Energy Ratio
NEV	Net Energy Value
NREV	Net Renewable Energy Value
OFID	The OPEC Fund for International Development
PERCAP-GDP(PPP)	Per Capita -Gross Domestic Product *(*at Purchasing Power Parity*)*
POCP	Photochemical Ozone Creation Potential
REN21	Renewable Energy Network for 21st century
RFA	Renewable Fuels Association
RFS	Renewable Fuels Standards
RIRDC	Rural Industries Research and Development Cooperation
UNDP	United Nation Development Programme
UNEP	United Nation Environment Programme
UNFCCC	United Nation Framework Convention on Climate Change
UNU-WIDER	United Nations University World Institute for Development Economics Research
USA	United States of America
WA	Without Allocation
WBA	World Bioenergy Association
WTP	Willingness To Pay
YOLL	Years of Life Lost

SYMBOLS AND FORMULAE

CFCs	Chlorofluorocarbons
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide equivalent
DCB	Dichlorobenzene
E10	Fuel Mixture of 10% Bioethanol and 90% Petrol
E85	Fuel Mixture of 85% Bioethanol and 15% Petrol
F_{CR}	N in Crop Residues
F_{ON}	Organic N Fertilizer Applied
$FRAC_{GASF}$	Fraction of Synthetic Fertilizer
$FRAC_{GASM}$	Fraction of Organic N Fertilizer
$FRAC_{LEACH}$	Fraction of all N in Leaching
F_{SN}	Synthetic N Fertilizer Applied
F_{SOM}	N Mineralization in Soil Organic Matter
GtC	Gigatonne Carbon
$GtCO_2eq$	Gigatonne Carbon Dioxide equivalent
H_2SO_3	Sulphurous Acid
H_2SO_4	Sulphuric Acid
ha	Hectare
HFCs	Hydrofluorocarbons
HNO_2	Nitrous Acid
HNO_4	Nitric Acid
MJ/ha	Megajoules per hectare
MTBE	Methyl Tertiary Butyl Ether
N_{md}	Number of man-days
N_2O	Nitrous Oxide
NH_3	Ammonia
NO_x	Nitrogen Oxides
PM	Particulate Matter

SO_x	Sulphur Oxides
t/ha	Tonne per hectare
tC	Tonne Carbon
VOCs	Volatile Organic Carbons
Y_C	Yield

ABSTRACT

Biofuels development has received increased attention in recent times in the hope that they are cleaner and cheaper fossil fuel supplement towards mitigating climate change, expanding the fuel energy resource mix and fostering rural development. This has led to increased production and utilization of biofuels worldwide. In order to ensure sustainable bioethanol production in Kenya, information on its contribution to the energy security, economical development and environmental burden of the country is required. Thus, the main objective of this study was to evaluate the energy balances, production and environmental costs, and environmental impacts in the production of bioethanol from sugarcane molasses and sweet sorghum stalk juice in Kenya, from a life cycle perspective. In this study, Chain Management by Life Cycle Assessment (CMLCA) software was used to perform inventory analysis and impacts assessment for each of the bioethanol systems. The inventory analysis quantified all the emissions for each of the bioethanol systems, Fossil energy and renewable energy inputs of each bioethanol system were determined from which the energy balances were calculated. Production costs of each bioethanol system were determined from the costs of farm inputs, industrial chemicals and hiring of farm machinery. Environmental costs of each bioethanol system were determined using the Environmental Priority Strategies (EPS) model. In both the sugarcane molasses and the sweet sorghum stalk juice bioethanol systems, more than 85% of the total energy consumption was renewable energy. The calculated values for net renewable energy value (NREV) were 19.75 and 19.68 MJ per litre of bioethanol for the sugarcane molasses and the sweet sorghum stalk juice bioethanol systems, respectively. The calculated values for net energy ratio (NER) for the sugarcane molasses and the sweet sorghum stalk juice bioethanol systems were 14.62 and 13.60 respectively, for every litre of bioethanol. The high positive values of NREV and NER obtained indicated that there was less non-renewable energy input in the production of bioethanol in each case. The net energy value (NEV) of the sugarcane molasses-based bioethanol and the sweet sorghum stalk juice-based bioethanol were evaluated to be 3.88 MJ and 11.12 MJ per litre of bioethanol, respectively. The positive NEV values indicate that the energy required to produce bioethanol in both bioethanol systems is less than the energy content of bioethanol. The net greenhouse gas (GHG) emissions of the sugarcane molasses-based bioethanol and the sweet sorghum stalk juice-based bioethanol were estimated to be 270.88 and 424.19 gCO_{2eq} per litre of bioethanol, respectively. Cultivation was found to produce the highest proportion of the total GHG emissions in both bioethanol systems. Low GHG emissions were reported in this study mainly due use of biomass (bagasse and vinasse) as the source of energy (steam and electricity). Similarly, low values of acidification potential (AP) and photochemical ozone creation potential (POCP) were obtained in this study attributable to no biomass burning prior to harvesting and no use of coal as a source of energy. Lower values of human toxicity potential (HTP) were also obtained in this study attributable to no biomass burning prior to harvesting associated in emissions of heavy metals and particulates. Low ecotoxicity potential (EP) values were obtained in both

bioethanol systems, attributable to use of lower amounts of fertilizers in cultivation. The largest cost component of the total cost for both bioethanol systems was found to be in cultivation stage which was more than 75% of the total cost in each case. Further, the study found that more than 80% of the total external environmental costs in both bioethanol systems were due to fossil oil fuel use. Emissions due the use of agrochemicals (fertilizers, herbicides and pesticides) and fossil fuels (diesel and gasoline) during farming of the biocrops contribute greatly to the environmental impacts considered. Energy balances of the sugarcane molasses bioethanol system and the sweet sorghum stalk juice bioethanol system indicate low fossil energy use.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Climate change, increasing demand for food and energy, environment and poverty concerns have led to a search for alternative sources of energy that would be economically productive, socially justifiable, environmentally sound and ecologically sustainable (Srinivasa *et al*. 2010). This has led to increased global interest in the exploration, production and utilization of biofuels. Bioenergy crops that accrue economic benefits to the rural poor while providing access to clean and green energy at both local and national level would likely meet the above requirements (Srinivasa *et al*., 2010). A study by Demirbas (2008) indicates reasons to promote biofuels include energy security, environmental concerns, foreign exchange savings and socio-economic well-being of rural population. Globally, biofuels expansion is mainly to address energy security, poverty alleviation and economic development (Gheewala *et al*., 2013). Mitchell (2011) also indicated that biofuel production in Africa will increase national energy security and foreign exchange saving by reducing oil imports. Biofuels have potential to provide socioeconomic benefits as having industrial plants in rural areas create employment, encourage other economic activities and also influence other related industries (Gilio & Moraes, 2016; Moraes *et al*., 2016)

Biofuels production is associated with environmental and social impacts such as greenhouse gas (GHG) emissions, water availability/pollution, deforestation, biodiversity loss, poverty alleviation, energy security, loss of access to land and food security (Gasparatos *et al.* 2015). 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). Biofuels production release emissions to air, water and soil. Examples of emissions to air include NO_x, SO_x, CO, CO_2, CH_4, VOC, NH_3 and particulate matter impacted at each stage of biofuel production, distribution, and usage (EPA, 2018). In the life cycle of a biofuel these emissions can be determined and used to evaluate the environmental and cost

performance of the biofuel (Nguyen & Gheewala, 2008). There are growing concerns about the economic, environmental and social sustainability of biofuels, as well as about their ability to actually meet the energy security expectations (Mandil & Shihab-Eldin, 2010). Research findings have indicated that biofuels could be a dominant renewable source of energy while mitigating climate change (Bessou *et al*, 2009; Srinivasa *et al*., 2010; Hanaki & Portugal-Pereira, 2018). Biofuel production must be sustainable and it must be viable in social economical, environmental and energetic terms (Aguilar-Sanchez *et al*., 2018).

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). 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). SDG1 aims to end poverty, SDG2 to end hunger and achieve food security, SDG3 to ensure healthy lives, SDG8 to promote economic growth and productive employment, and SDG13 to take urgent action to combat climate change and its impacts (Fonseca *et al*., 2020). Biofuels are anticipated to be clean and affordable sources of energy. Thus the production of bioethanol, a biofuel, will achieve SDG7 and this will go along in achieving other SDGs.

Bioenergy production and consumption promote rural economic development as it will have a positive impact on agriculture employment and livelihoods (Sakai *et al*., 2020). This is made possible when small scale farmers are involved in cultivation of the bioenergy crops, and the conversion facilities are located in rural areas (Gilio & Moraes, 2016). Bioethanol has been promoted because of its capacity to reduce GHG emissions and petroleum fuel consumption (Cai *et al*., 2013; Wang *et al*., 2012). GHG emissions reductions have been demonstrated in production of bioethanol from various bioenergy crops. A study conducted in Belgium found that the production of bioethanol from wheat could reduce GHG emissions by 91% compared with conventional gasoline (Belboom *et al*., 2015). In Thailand, a study on production of bioethanol from cassava found that GHG emissions reductions were estimated at about

58% compared to gasoline (Numjuncharoen *et al*., 2015). In Indonesia, Khatiwada *et al.* (2016) found that bioethanol production from sugarcane molasses could reduce GHG emissions by 67% compared with gasoline. Bioethanol from corn has higher emissions across the life cycle than bioethanol from other feedstocks (EPA, 2018). This study considered LCA in the production of bioethanol from sugarcane molasses and sweet sorghum stalk juice. The growing of sugarcane and sweet sorghum absorb CO_2, thus release of CO_2 emitted during bioethanol combustion will not contribute new carbon emissions as they are already part of the fixed carbon cycle. Thus bioethanol production expected to achieve a greater energy security through reduced reliance on oil as well as making a country have diversified sources of energy. Research findings have indicated that biofuels could be a dominant renewable source of energy while mitigating climate change (Bessou *et al*, 2009; Srinivasa *et al*., 2010; Hanaki & Portugal-Pereira, 2018).

Transport sector consumes about 30% of the world's total primary energy consumption and is one of the major contributors to global greenhouse gas (GHG) emissions (Khatiwada, 2013). The transport sector is a major oil consumer; accounting for 27.4% of total energy demand (IEA, 2013) and 22.9% CO_2 emissions worldwide (IEA, 2015). Increased use of fossil fuel for transportation in urban areas of developing countries has not only exacerbated problems of local air pollution but also poses energy security threats and high economic costs (Creutzig & He, 2009; Yan & Crookes, 2010). Many countries have supported their fossil fuel supplies and consumption by blending biofuels with fossil fuels whose resources are being depleted year after year (Srinivasa *et al*., 2010; Nallamothu *et al*., 2013; Thangavelu *et al*., 2015). Some biofuels are likely to contribute significantly to the future world mix of liquid transportation fuels and to establish targets for such biofuel should be considered only after careful evaluation of their sustainability (Mandil & Shihab-Eldin, 2010). Biofuel production and use should meet several essential criteria: biofuels should result in significant greenhouse gas savings compared to fossil fuels; rely on environmentally sound agricultural management systems for production of feedstock; preserve biodiversity and cultural heritage; be socially inclusive; integrate with food and other biomass use sectors and contribute positively to overall land-use

(Mandil & Shihab-Eldin, 2010). There is rising concern on environmental impacts caused by the expansion of biomass resources production and use as energy.

1.2 Statement of the Problem

The combination of improving energy security and providing support to rural economies through production of the bio-crops has been motivating biofuel developments in several countries (Gheewala *et al.*, 2013; IRENA, 2019). An additional factor is the growing need to reduce GHG emission to mitigate climate change. Global GHG emissions in 2017 were estimated at about 53.5 $GtCO_2$-equivalent, an increase of 0.7 $GtCO_2$-equivalent compared to that estimated in 2016 (UNEP, 2018). The CO_2 emissions from fossil fuels and industry dominate total GHG emissions (UNEP, 2018). The global energy-related CO_2 emissions were about 33.3 Gt in 2018 (IEA, 2018). In 2010, transport sector contributed 7.0 Gt CO_2-equivalent of direct GHG emissions which accounted to approximately 23% of total energy-related CO_2 emissions (IEA, 2012; JRC/PBI, 2013; Sims *et al*., 2014; UNEP, 2018). Among the main GHG emitting sectors, fossil energy use for transport is one of the major challenges in the future. As indicted earlier, many countries have supported their fossil fuel supplies and consumption by blending the fossil fuels with biofuels. The energy input and GHG emissions involved in biofuel production are sensitive to the feedstock type, conversion process, co-products and local conditions (IEA-ESTAP & IRENA, 2013). All these elements are sources of significant uncertainties in estimating biofuel performance in terms of energy efficiency and GHG emissions. In many processes, technological variants may lead to a significant increase in emission thus eliminating most of the benefits of biofuels. The promotion of biofuels is part of the overall policy to reduce GHG emissions (IEA-ESTAP & IRENA, 2013). Policy measures should promote technologies with best performance in GHG reductions (IEA-ESTAP & IRENA, 2013). Therefore, there is need to investigate the energy balances, GHG emissions and emissions of other environmental pollutants in the production of a biofuel so as to assess its energy and environmental performance when considered as fossil fuel substitute (O'Connell *et al*., 2019).

The determination of energy balances and environmental impacts in the life cycle of a biofuel is used to evaluate its sustainability and are good indicators of environmental performance evaluation of a biofuel production (Silalertruska & Gheewala, 2009; Rocha *et al*, 2014; Numjuncharoen *et al*., 2015; Khatiwada *et al*, 2016; Hanif *et al.*, 2017). Net Energy Balances determine the energy efficiency of the biofuel, while environmental impacts identify and determine environmental implications of the biofuel (Wang *et al*.; 2014; Wang *et al*., 2015; Gabisa *et al*., 2019). Life cycle cost analysis in production of a biofuel needs to be investigated so as to determine the viability of the particular fuel as a source of energy. Life cycle cost analysis aims to determine the direct production costs and environmental costs of the biofuel (Nguyen & Gheewala, 2008; Silalertruksa *et al*., 2012, Santoso, 2013). LCA studies open opportunities to identify the best strategies for mitigating environmental emissions at early stages of development (Parisi *et al.*, 2019).

Study conducted by German Technical Cooperation (GTZ) and the Government of Kenya (GOK) indicated Kenya as a prospective and potential producer of bioethanol from sugarcane and sweet sorghum (GTZ & GOK, 2008). The study indicated that if the two energy crops are grown and expanded in areas with suitable climate, 50-560 million litres of bioethanol could be produced from sugarcane yearly, and over 30 billion litres of bioethanol from sweet sorghum. Bioethanol is anticipated to contribute to sustainable development. Thus information on contribution of bioethanol to the energy security, economic development and environmental burden of a country is required to ensure sustainable bioethanol production. Study by Lora *et al*. (2011) indicates the commonly used sustainability indicators of biofuels include output energy/input energy relation (net energy analysis), economic analysis (cost of production) and environmental impacts evaluation using impact categories indicators. Energy efficiency and environmental performance of bioethanol production from sugarcane molasses and sweet sorghum stalk juice in Kenya and most African countries is currently not there. This study therefore focused on carrying out a Life Cycle Assessment (LCA) in the production of bioethanol from the sugarcane molasses and the sweet sorghum stalk juice. LCA is a well-developed scientific approach for evaluating the sustainability of products and/or services (Khatiwada, 2013). The Study evaluated emissions, environmental impacts, energy balances and costs involved in

production of bioethanol of each of the bioethanol systems. LCA analysis differs in definition of system boundaries, functional units, allocation methods, and selection of environmental impacts categories. Environmental impacts considered in this study were global warming (climate change), acidification, eutrophication, human toxicity, ecotoxicity and photochemical ozone formation so as to assess fully the environmental burden of bioethanol.

1.3 Justification of the Study

Bioethanol is an energy source derived from renewable biomass. This study evaluated environmental impacts, energy balances and costs involved in bioethanol production from the sugarcane molasses bioethanol and the sweet sorghum stalk juice bioethanol. The study therefore would provide information and data related to environmental, energy and cost performance in each of the bioethanol systems considered. These would assist in identification on areas where improvement can be done.

1.4 Objectives of the Study

1.4.1 Main Objective

The main objective of this study is to investigate the performance of bioethanol produced from the sugarcane molasses and the sweet sorghum stalk juice; in terms of environmental impacts, energy use, and cost from a life cycle perspective.

1.4.2 Specific Objectives

i. To quantify environmental emissions in the production of bioethanol from sugarcane molasses and sweet sorghum stalk juice in Kenya.
ii. To evaluate environmental impacts of the quantified emissions in the production of bioethanol from sugarcane molasses and sweet sorghum stalk juice in Kenya.
iii. To investigate energy balances in the production of bioethanol from sugarcane molasses and sweet sorghum stalk juice in Kenya.
iv. To determine production and environmental costs in the production of bioethanol from sugarcane molasses and sweet sorghum stalk juice in Kenya.

1.5 Research Questions

The following questions were asked in this study

i. What material and energy resources are involved in the production of bioethanol?
ii. What emissions are released to the environment in each stage and their contribution to the key environmental impacts involved in bioethanol production?
iii. What is the contribution of material and energy resources to energy performance in bioethanol production?
iv. What costs are involved in the bioethanol production?

1.6 Scope of the Study

The scope of study is “cradle to gate” covering stages in the life cycle of bioethanol production. These include cultivation and harvesting of the feedstocks, feedstocks transportation, cane or stalk milling, bioethanol conversion, co-generation and wastewater management. The production of farm inputs (fertilizers, herbicides, and pesticides) and industrial inputs (lime and sulphuric acid) are also considered in the study.

1.7 Significance of the Study

This study provided data/ information on cleaner energy production. The data/information provided includes environmental performance, energy efficiency and costs involved in bioethanol production from the sugarcane molasses bioethanol and the sweet sorghum stalk juice bioethanol. The quantification of environmental impacts, energy balances, and costs is desirable to help policy makers/bioenergy stakeholders to make meaningful decisions in regard to bioethanol production from the sugarcane and the sweet sorghum.

1.8 Limitation of the Study

The life cycle of bioethanol production from sweet sorghum stalk juice includes cultivation of sweet sorghum, harvesting of the stalk, milling of the stalk to obtain the juice and the conversion of the juice to bioethanol. There is no industrial plant in Kenya and within the neighboring countries converting sweet sorghum to bioethanol. Thus all data related to industrial processing for the sweet sorghum bioethanol was obtained from literature.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Modern forms of energy empower human beings in a number of ways which include; increasing productivity, providing illumination, fuelling transportation, powering industrial and agricultural processes, cooling and heating rooms, to name just some of them (Allesina *et al*., 2015). Adequate energy service not only dramatically increases human capabilities and opportunities; they are integral to poverty alleviation and environmentally sound social and economic development (Ahuja & Tatsutani, 2009). The continuous depletion of fossil fuel reserves which are limited, global concern on climate as well as threats to energy security have led to interest in the exploration, production and utilization of biofuels in household and transport sector. Biofuels production and use reduce dependence on fossil fuel and contribute to rural and sustainable development (Demirbas, 2008; Ben-Iwo *et al*., 2016). Energy security, environmental concerns, foreign exchange and socio-economic well-being of rural people are reasons that have led to promotion of biofuels (Demirbas, 2008). Use of productive cropland for bioenergy crops could lead to the competition between food versus fuel (Srinivasulu *et al*. 2019). Marginal and degraded lands where food crops may not be profitable offer opportunity to develop cellulosic bioenergy systems.

Liquid biofuels are made from biomass and have qualities that are similar to those of gasoline, diesel or other petroleum derived fuels. The two dominant liquid biofuels are bioethanol and biodiesel with 80% and 20% of the market respectively that together meet 30% of the global transport fuel demand (IEA-ETSAP & IRENA, 2013). Bioethanol is the most common biofuel, accounting for more than 90% of total biofuel usage (IEA, 2007). It can be produced from any feedstock that contains a high amount of sugar such as sugarcane, sweet sorghum and sugar beet (OFID/IIASA, 2009). Bioethanol can also be produced from materials that can be converted into sugar such as maize (corn), cassava, wheat, etc., by the fermentation of carbohydrates (OFID/IIASA, 2009). Bioethanol can also be produced from lignocelluloses materials such as agricultural and forest residues, short-rotation forestry (e.g. poplar, willow)

and perennial grasses (e.g. Miscanthus, switch grass) (IEA-ETSAP & IRENA, 2013). The technology to produce bioethanol from lignocelluloses feedstock is yet to become economically competitive.

Bioethanol has traditionally been used for the production of alcohol but is increasing being blended with gasoline in various proportions to produce gasohol (OFID/IIASA, 2009; Aguilar-Sanchez *et al*., 2018). Low level bioethanol blends such as E10 (10% bioethanol and 90% gasoline) can be used in conventional vehicles without engine modifications while high level blends such as E85 (85% bioethanol and 15% gasoline) can be used in specially motorized vehicles with engine modification such as flexible fuel vehicles (FFVs) (Balat *et al*, 2008; OFID/IIASA, 2009; Busic *et al*., 2018; Wiboyo *et al.*, 2019). Bioethanol blending increases octane levels and reduces carbon monoxide emission (Wiboyo *et al*., 2019). Bioethanol is also presently being used as a household fuel to replace liquid petroleum gas (LPG). Bioethanol gel burns in the same way as LPG i.e. almost same heat content and with non-sooty yellow flame.

Global bioethanol production has been increasing since the year 2000 of which 86% is utilized as fuel. In 2010, bioethanol contributed 82% (i.e. 86 billion litres) of the total liquid biofuels (i.e. 105 billion litres) used for transport in the world (REN21, 2011). This came mainly from sugarcane bioethanol produced in Brazil (31% of the global production) and corn bioethanol produced in the US (58% of global production) (RFA, 2011). In 2016, the global bioethanol production was about 100.2 billion litres (WBA, 2017). According to Renewable Fuels Association (RFA) industry statistics, fuel bioethanol production was estimated at about 108 and 110 billion litres in 2018 and 2019 respectively (RFA, 2020). In Kenya, the production of bioethanol has been from sugarcane molasses only. Initially in the 1980's, the bioethanol was intended to be used for production of gasohol fuel (blend of bioethanol and petrol), but the programme was abandoned as it was not viable due to production limitation. Presently, Kenyan manufacturers use bioethanol in the production of industrial alcohol. In 2016, bioethanol production in Kenya was 136,000 litres per day as cited by Knoema, a world data atlas.

A review study by Blottnitz and Curran (2007) of forty seven (47) published assessments compared bioethanol systems with majority of them focusing on net energy and GHGs emissions with differing assumptions and system boundaries. The study recommended that bioethanol should be made from sugar crops in tropical countries.

2.2 Status of Bioethanol Production in Selected Regions

2.2.1 Bioethanol Production in Brazil and United States

In 2008, about 15% of global corn production (mostly in the United States) and 18% of sugarcane (mostly in Brazil) was used for bioethanol production (Daynard & Daynard, 2011). In 2019, fuel bioethanol production in the United States was about 60 billion litres (54% of the total global production) while in Brazil it was about 33 billion litres (30% of total global production) (RFA, 2020). Fuel bioethanol production in the United States was mainly from corn while in Brazil it was mainly from sugarcane (RFA, 2020). Modern biofuel markets emerged in response to oil price hikes in the 1970s. Various countries responded with proposals for alternative fuel policies, but only Brazil and the United States created a biofuel production sector in this period, the former using sugarcane and the latter corn (HLPE, 2013). The broader strategic goal was to reduce levels of dependence on energy imports, and especially in the case of Brazil, improve the balance of payments of a time high oil import bill (HLPE, 2013).

In 1975, Brazil launched a programme to boost ethanol production and consumption known as PROÁLCOOL. The sugarcane sector responded well to the PROALCOOL program. The program addressed both supply and demand; with a mix of research and development support, supply or investment subsidies, mandatory installments of bioethanol pumps, taxation of gasoline and regulation policies. Bioethanol production in Brazil rose rapidly, from less than 1 billion litres/year in 1975 to around 12 billion litres/year in 1984 (HLPE, 2013). Demand was created by setting up of a 20% blending level for bioethanol in gasoline. Dedicated bioethanol fuelled car using 100% (hydrous) increased and by early 1980s up to 90% of new car sales were alcohol-only engines (Wilkinson & Herrera, 2010).

The PROALCOOL program in Brazil consisted of two phases:

- Phase 1 (1975-1979) targeted subsidized expansion of sugarcane distilleries and an increase of the blending of bioethanol and gasoline.
- Phase 2 starting in 1980 saw the introduction of dedicated bioethanol fuelled cars. The technology of these cars was developed at public research centres in the 1970s and then passed on to the private sector (Pelkmans *et al*., 2008). Bioethanol powered cars reached 94.4% of total automobile sales by 1986.

In USA, interest for alternatives to petroleum fuels peaked during the energy crisis of 1970's. Bioethanol production rose substantially in the 1980s in the wake of Energy Tax Act of 1978 which introduced a subsidy for blending bioethanol into gasoline, and the 1980 Energy Security Act, which offered insured loans for small bioethanol producers, price guarantees and federal purchase agreement, and established a tariff on foreign bioethanol. Following the 2003 Renewable Fuel Standards (RFS) legislation which called for a phasing out of the methyl tertiary butyl ether [MTBE] (a fuel additive), bioethanol was the only practical substitute for MTBE. The ban of MTBE created a 13.2 million litres market for bioethanol (Keeney, 2009). The 2005 Energy policy Act required 28.4 billion litres of bioethanol to be incorporated in transport fuels by 2012, putting in place at the same time a system for trading bioethanol credits. In 2007, RFS was expanded with the figure for corn bioethanol set at 56.8 billion litres by 2015, and a total biofuels target set at 136 billion litres in 2022 (HLPE, 2013). The new targets were accompanied by number of state and federal policy support measures: tax incentives, fuel quality regulations, federal or state car fleet requirements, credits for alternative fuel motors, state subsidies to producers, grants and loans programme and tax exemption (Schnepf & Yacobucci, 2013). Bioethanol production in USA short up from 6.4 million litres in 2001 to 52.6 billion litres in 2011 overtaking Brazil whose bioethanol production was 20.8 billion litres (HLPE, 2013).

2.2.2 Bioethanol Production in India

India imported 75 percent of its crude oil consumption in 2010 (Ahn & Graczyk, 2012). It was the third largest emitter of CO_2 after China and US in 2018, emitting

about 2.48 billion metric tons, a global share of 7.3% (Forbes, 2020). Vehicle fleet grew from 90 million in 2005 to 140 million in 2011. Petroleum consumption in transport sector is 51 percent against only 4 percent for agriculture (GAIN, 2012). In response to dependence on energy imports and to the concern over growing emissions, owing to a rapidly growing transport sector, India has embarked on promotions of clean fuel. In 2003, it decided on a 5 percent bioethanol blending programme, but by the end of the decade only a 2 percent blending had been achieved (GAIN, 2012). Its bioethanol comes principally from molasses and its target of 5 percent which was later increased to 10 percent has never been met. Nevertheless, a target of 20 percent for all biofuels was set for 2017 in the National Policy on Biofuels in 2009 (GAIN, 2012). The four objectives of the policy are:

i. Meet energy needs of its vast rural population, stimulating rural development and increasing employment opportunities.
ii. Address global concerns with emissions reductions through environmentally friendly biofuels.
iii. Derive biofuels from non-edible feedstock on degraded soils or wastelands unsuited to food and feed, thus avoiding a possible conflict between food and fuel.
iv. Optimum development of indigenous biomass and promotion of next generation biofuels.

Bioethanol has not advanced as planned as a transport fuel (GAIN 2012), but electricity from sugarcane biomass is an important factor in power generation.

2.2.3 Bioethanol Production in China

China accounts for 25 percent of the world's poor and food insecure despite recording a high economic growth (Sumner, 2012). As a result of the size of its economy and its high rate of economic growth, GHG emissions are increasing. Its car sales market, 18.5 million in 2011 is now the largest in the world and is expected to increase to 30 million a year by 2020 (Madsllen, 2012). China is also dependent on oil imports; they accounted for 55% of oil needs in 2010, and is estimated to increase by 75 percent by 2030 (CNPC, 2010). China launched its renewable energy policy in 2000 and set a

renewable energy target of 10% of total energy demand by 2010 increasing to 15% by 2020 (Shiyan *et al*., 2012).

For liquid biofuels, the target set for 2020 was 10 million litres of bioethanol and 2 billion litres of biodiesel (Qiu *et al*., 2012). According to Qui *et al.* (2012) such bioethanol targets represent 14 percent of total gasoline consumption but would use 20 percent of China's maize/corn production, a 6.6 percent of all its cereal production at 2009 figures. This had possible food security implications thus China revised its biofuel policy and in its program decided on use of non-cereal crops and the incorporation of marginal land (Qui *et al.,* 2012). Sweet sorghum, sweet potato and cassava became the preferred crops and bioethanol targets fixed at 4 billion litres in 2010 and 10 billion in 2020. In addition to domestic supplies, China imports from countries within the region especially Thailand, as well as producing grain bioethanol from corn and wheat (GAIN, 2012).

2. 2.4 Bioethanol Production in Africa

Some African Countries which include Malawi, Zimbabwe, Kenya, South Africa, Sudan, Tanzania and Swaziland have an established tradition of bioethanol production from sugarcane molasses (Deenanath *et al*., 2012, Sekoai & Yoro, 2016). From 2000 an increasing number of African countries had adopted biofuels/bio-energy policies, some with targets and mandates for transport fuel blending (UNU-WIDER, 2017). The motive of this is varied ranging from increasing energy self-sufficiency and foreign exchange savings to rural development objectives (Deenanath *et al*., 2012). Energy security on the African continent is not limited to finding substitutes to fossil fuel imports although this is an important motive in a number of energy dependent countries.

In Malawi, bioethanol production from sugarcane molasses was from Dwangwa Estate producing 15- 20 million litres annually and Nchalo Plant producing 12 million litres (Deenanath *et al*., 2012, Sekoai & Yoro, 2016). The bioethanol was blend with petrol to produce E10 gasohol (10% bioethanol with 90% petrol). In South Africa biofuels contribute 9-14% of the renewable energy (Sekoai & Yoro, 2016). The government of South Africa aimed to begin blending of bioethanol with petrol to reduce reliance on

imported fuel and they identified sorghum as one of the potential feedstock for bioethanol production (Sekoai & Yoro, 2016). Bioethanol production in Sub-Saharan Africa has been Stagnant (Deenanath *et al*., 2012). Food security, land availability and government policies are some of hurdles of achieving sustainability of the production of bioethanol Sub-Saharan Africa (Deenanath *et al*., 2012).

2.2.4.1 Bioethanol Production in Kenya

Starting early 1980's, Kenya produced bioethanol and blended it with petrol to produce gasohol. The record oil prices of 1970s and 1980s made the government to initiate the gasohol policy. The policy mandated a 10% bioethanol blend but due to production limitation, this was only achieved in the Nairobi market. Agro-Chemical and Food Company (ACFC) based in Muhoroni (Western Kenya) produced all of the bioethanol used in the programme from sugarcane molasses, thus it had to be transported to Nairobi. The gasohol programme became uneconomical (hence was abandoned 15 years later) due to a number of factors, including a drop in global oil prices, a surge in the price of bioethanol for alcoholic consumption in exports markets and a deterioration of bioethanol production. To bring gasohol to the same retail price as petrol, the Government had to reduce the customs tariff on gasohol. Even with this subsidy, the production of gasohol was still not viable. The gasohol programme ceased and the bioethanol is now used to produce industrial alcohol and alcohol beverage. There are three bioethanol plants, ACFC, Spectre International Limited and Mumias Sugar Company. Most of the bioethanol is used by the alcohol beverage markets in Kenya, Uganda and DRC, and some sold for other industrial purpose such as production of methylated alcohol. The bioethanol plants do not operate at full capacities and thus require almost all the molasses from the sugar processing companies in Kenya. This is not possible since almost half of the molasses produced is sold to farmers and small scale brewers in Uganda who offer higher purchase prices than the bioethanol plants (GTZ & GoK, 2008). The average yields of sugarcane declined from 66.4 t/ha in 2015 to 55.1 t/ha in 2018 and also there was a decrease in sugar production from about 637,000 tonnes to 491,000 tonnes in the same years, respectively (Mati & Thomas, 2019). The decline in productivity is due to low quality sugarcane varieties, poor agronomy practice and delay in harvesting the cane (KSB,

2009). The current sugar productivity is not at its optimum, as they need to introduce fast maturing types so as to meet the demand for the molasses. The annual domestic demand of sugar in Kenya is over 900,000 tonnes and therefore it is a net importer of sugar (Mati & Thomas, 2019).

Mumias Sugar Company produces bioethanol from its molasses. The integrated production of sugar, bioethanol and power by Mumias Sugar Company is a more efficient and sustainable model of production. Mumias Sugar Company plan to put up a large sugar and bioethanol factory near the Tana River that will use irrigation to increase yields. Mumias Sugar Company's goal is to produce a globally competitive sugar product while also producing bioethanol for domestic and export market. Spectre International plans to increase its production capacity from its current 65,000 litres per day to 230,000 litres per day (GTZ & GoK, 2008). With the limitations on available land and competition with food production, the planned bioethanol production cannot be supplied by sugarcane alone. Spectre International Limited plan to meet this increased capacity with sweet sorghum and other crops and have rolled out experimentation on this programme (GTZ & GoK, 2008). ACFC also plan to use sweet sorghum as an alternative to molasses.

The greatest potential benefits with sweet sorghum is its ability to thrive in drier and marginal agricultural areas (compared to sugarcane) and can compete economically with the cheaply available molasses due to its high-value grain production (Roman *et al.*, 2010). International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has a sweet sorghum program and their offices in Nairobi are willing to provide agronomy research and development assistance to the bioethanol producing companies. There are certain important concerns that need to be addressed for a project to make a feedstock as a source of bioethanol production. These include the market, productivity of the feedstock production, cost of the feedstock compared to other feedstock sources, potential production areas, production technologies, feedstock supply arrangements between feedstock producers and processing plants, incentives for industry players, and impact on the environment (Ranola *et al.*, 2009).

2.3 Sugarcane Production

The botanical classification of sugarcane is *Saccharum officinarum* and belongs to the family Gramineae. It is a perennial plant which can grow up to 4.25m. Sugarcane is a tropical crop requiring a hot climate but also grows well in subtropical climate (Hussain *et al*., 2018). It has a wider adaptability where temperature ranges from 20 and 35^{o}C, with a high humidity favouring rapid cane elongation during the main growth period. It requires a rainfall of between 1100 and 1500 mm, abundant in the months of vegetative growth followed by a dry period for ripening. Sugarcane grows well in deep well drained soils of medium fertility of sandy loamy soil textures with a pH range between 6 and 7 (DPP, 2012). The planting of sugarcane is by using setts which are planted at a 45 degree angle or laid horizontally in a furrow and covered lightly with soil until they sprout, and then sides of the furrow are turned inward (DPP, 2012).

Sugarcane propagation is by means of cuttings of immature canes called setts, seed, seed-cane or seed-pieces (Mutonyi, 2014). Sugarcane produce a huge quantity of biomass, thus require higher volumes of nutrient elements (Mutonyi, 2014). Phosphorus fertilizer is broadcasted and worked into the soil during primary cultivation. Nitrogen fertilizer is applied through broadcasting directly into the soil and as top dressing during the growth period. The cane should be harvested when it has reached maturity so as to realize maximum yields. Harvesting under-aged or over-aged cane with improper methods of harvesting leads to loss in cane yield, sugar recovery, poor juice quality and problems in milling due to extraneous matter (Mutonyi, 2014). Harvesting of the cane can either be manual harvesting using skilled laborers or mechanical harvesting which employs highly mechanized huge harvesters.

Sugarcane as a biofuel crop has expanded yielding anhydrous bioethanol and hydrated bioethanol by fermentation and distillation of sugarcane juice and molasses (Hartemink, 2008)). By-products are bagasse and vinnase (stillage). Bagasse, a by-product of both sugar and bioethanol production can be burned to generate electricity. It provides most of the fuel for steam and electricity generation for sugar milling in

Brazil and Australia. One hectare of sugarcane land with a yield of 82 t/ha produces about 7,000 litres of bioethanol (Sparks, 2008)

2.3.1 Bioethanol Processing from Sugarcane Molasses

Bioethanol can be produced directly from sugarcane juice or from molasses produced during the manufacture of sugar. Sugar manufacture starts with sugarcane milling to extract the juice using the roller mills or diffuser (Garcia *et al*, 2011). The juice is clarified, filtered and then concentrated to produce syrup. The syrup is then crystallized and sugar crystals are separated from the molasses by centrifugation. This process as depicted in Figure 2.1 may be repeated generally upto three times. Products of the first crystallization/centrifugation are termed “A” sugar and “A” molasses. Second stage products are termed “B” sugar and “B” molasses. Third stage products are “C” sugar and “C” or final molasses. The “C” products do not contain recoverable sucrose but still have 50 percent fermentable sugars (Garcia *et al*, 2011). Final molasses are fermented by yeast culture and the product obtained is distilled to produce hydrated bioethanol of 96 percent purity. An alternative that allows higher quantities of molasses to be fermented is starting fermentation using “B” molasses. In this case only two crystallizations are undertaken to obtain “A” and “B”.

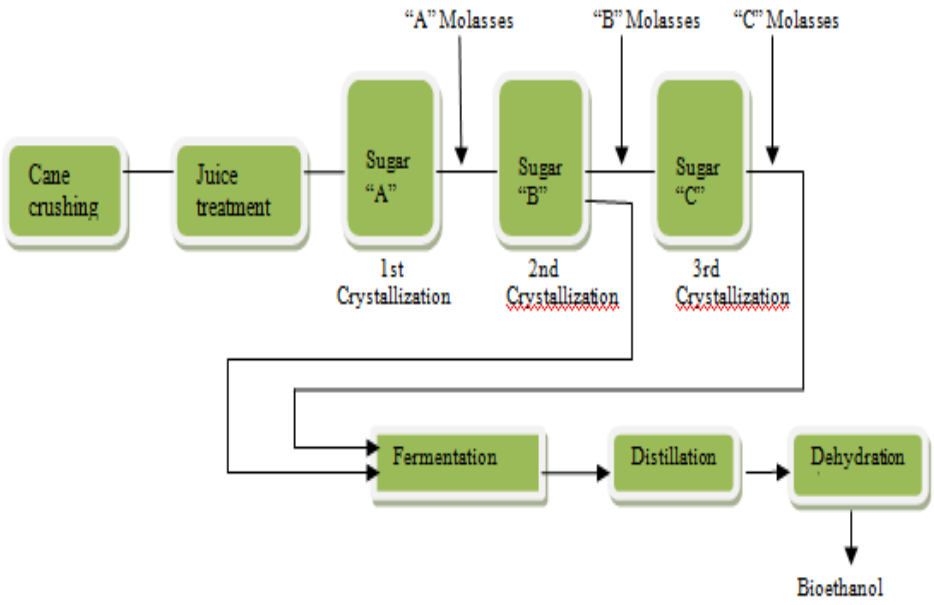

Figure 2.1: Industrial processes for production of bioethanol from sugarcane

Source: Garcia *et al*., 2007

2.4 Sweet Sorghum Production

Sweet Sorghum (sorghum bicolor (L) Moench) is rapidly-maturing, C_4 plant of the same family with maize, wheat, millet and rice. 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. It was introduced in Kenya mainly for its grain which is used as food but its juice from the stalk can be used for bioethanol production. Sweet sorghum can thus simultaneously produce energy, food and feed products (Janssen *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 (Whitfield *et al*., 2012).

Sweet sorghum produces a nutritionally valuable grain which can be ground into flour and used for baking into bread or other human food products. The grain can be extracted and used directly as an animal feed. The grain can also be used as feedstock

for biofuel production, with the starch component fermented to bioethanol. The juice from the sweet sorghum stalk can be extracted and used to produce a number of products. The juice has high concentration of glucose and fructose making it particularly suitable for fermentation (Fernandes *et al.*, 2014; Buruiană *et al.*, 2018) but unsatisfactory for crystal sugar production. The juice from sweet sorghum can 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.

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 (RIRDC, 2013).

Sweet sorghum compared to sugarcane has a higher tolerance to salt, drought and flooding (Almodares & Hadi, 2009; Davila-Gomez *et al*., 2011; Almodares *et al*., 2011; Rao *et al*., 2013; Tari *et al*., 2013; Fernandes *et al.*, 2014; Mathur *et al*., 2017). Even under these conditions, sweet sorghum produces greater amounts of biomass (Wu *et al*., 2010; Almodares *et al*., 2011, Ekefre *et al.*, 2017). Sweet sorghum requires less water than sugarcane and requires less fertilizer to produce significant biomass (Almodares & Hadi, 2009; Almodares & Hatamipour, 2011). Sweet sorghum produces a comparable amount of fermentable sugars to sugarcane (Wu *et al*., 2010, Jia *et al*., 2013). 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 (Fernandes *et al*., 2014; Mathur *et al*., 2017).

Sweet sorghum is believed to have originally developed in tropical regions (Srinivasa et al., 2010; Tari *et al*., 2013). It also grows in temperate climate (Bakhite *et al*., 2019). 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.

Although sweet sorghum is well adapted to temperate climates, growth is maximized at high temperature (Almodares & Hadi, 2009). Sweet sorghum is drought resistant and can be grown in marginal lands (Mathur *et al*., 2017) 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 when irrigated 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 (Wu *et al*., 2010) and has been reported to produce bioethanol yields of around 3100 L/ha (Smith & Burton, 1993; Almodares & Hadi, 2009). Nan and Ma (1989) achieved 2500-3200kg/ha from the stalk. Sweet sorghum can be harvested 2-3 times in a year and better agronomical stability than sugarcane (Aguilar-Sanchez *et al*., 2018)

2.4.1 Bioethanol Processing from Sweet Sorghum Stalk Juice

Sweet sorghum juice can be used for bioethanol production with average fermentation efficiencies from 85 to 90 percent (Almodares and Hadi, 2009; Prasad *et al*., 2007; Wang *et al*., 2009; Wu *et al*., 2010). Sweet sorghum stalks contain approximately 70 percent water and the solids are comprised primarily of structural carbohydrates (cellulose and hemicelluloses) and non-structural carbohydrates (sucrose, glucose and fructose). Presence of significant amounts of inverted sugars (glucose and fructose) in sweet sorghum juice makes it difficult to be used for crystallized sugar production in large-scale processes. Sweet sorghum juice is rich in fermentable sugars making it an excellent potential for yeast fermentation (Turhollow *et al*., 2010). Sweet sorghum juice is obtained by mechanical crushing using roller mills similar to ones employed by the sugarcane mills (RIRDC, 2013). Imbibition water is added during the final

stage of the crushing process to solubilize residual sugars resulting in over 95 percent recovery of fermentable sugars. Extraction process by pressing (use of a presser) results to lower yields compared to roller mills. Pressing is a batch process which is difficult to optimize for industrial production. The amount of sugars in the juice varies according to the cultivar, harvesting season, plant maturity and other agronomic factors (Ekefre *et al.*, 2017; Dar *et al.*, 2018). 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). The quality of juice is influenced by the growing conditions i.e. the stage of growth and the environment (Olweny *et al.*, 2013). 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. After extraction, sweet sorghum juice is fermented, distilled and dehydrated to produce anhydrous bioethanol as depicted in Figure 2.2.

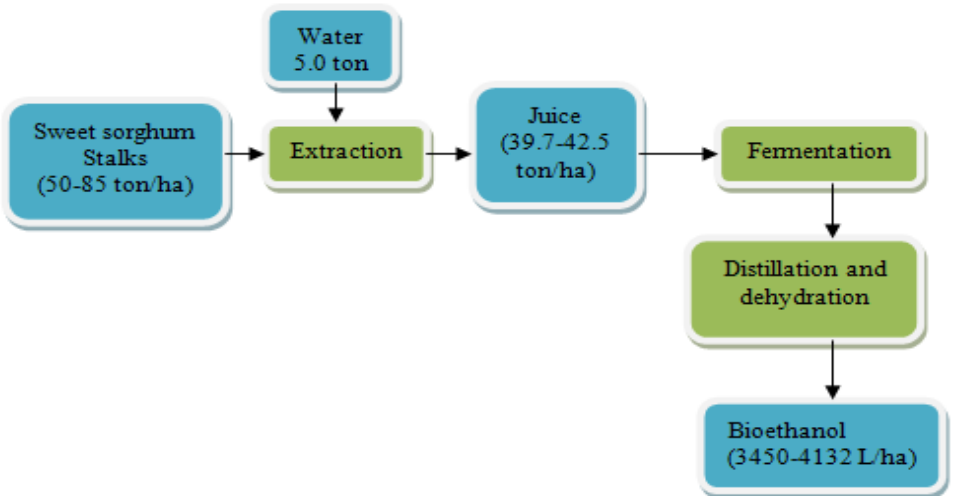

Figure 2.2: Flowchart for bioethanol production from sweet sorghum juice

Source: Almodares and Hadi (2009)

2.5 An Overview on Life Cycle Assessment

Policies and targets for biofuels have been set in several countries. The main drives for the setting of such policies are potential contributions to energy security, climate change mitigation and rural development (Mandil & Shihab-Eldin, 2010; Von Maltitz & Stafford, 2011). Life Cycle Assessment (LCA) methodology has increasing been used to assess the potential benefits and/or undesired side effects of biofuels (Jeswani *et al.,* 2020). The LCA methodology study evaluates the environmental flows related to a product or process during all life cycle stages. It is regulated by the International Organization for Standardization (ISO) i.e. ISO 14040 and ISO 14044 standards which provide the principles, framework requirements and guidelines for conducting an LCA study.

Regardless of the crops analyzed, most sources converge that the agricultural and transformation phases and an isolated number of variables within these two phases account for the vast majority of total impacts over the life cycle of bio-energy products. The distribution of impact share within these two phases depends on both the type of feedstock and impact indicator analyzed.

The agriculture phase contributes a significant share of GHG emissions and is by far the dominant contributor to acidification and eutrophication, largely due to emission of nitrous oxide (N_2O), other nitrogen oxides gases (NO_X) and sulphur oxides (SO_X) associated with the use of fertilizers. Co-products are another relevant issue in the agricultural phase. The treatment of co-products and the way impacts are allocated to them significantly affect the results of the analysis. The impacts of energy use are significant in the technology used in conversion phase. The quality and type of process energy used (e.g. heat and power from fossil fuels or bagasse) can significantly affect the overall results (Wang *et al.* 2007). LCA results are affected by life cycle inventories databases used for modeling upstream processes and life cycle impact assessment method indicators applied.

Studies by Dunn *et al*. (2011), Izursa *et al.* (2012) as cited from Venkata (2013), considered fossil fuel energy embodied in farm machinery in their LCA analysis and

found it to be low. The embodied energy is dispersed over the life time of the equipment and thus its effect is negligible. LCA researchers, Garcia *et al.* (2011), Silalertruksa and Gheewala (2009), and Seabra *et al.* (2011) indicated that the impacts of the embodied energy in farm and industrial machinery need be neglected.

2.6 Allocation Methods

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

Economic valuation considers the amount and market price of products and co-products and is based on the assumption that market prices are the driver of the production process. Disadvantage of this approach is that prices are not constant overtime. 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 might distort relative prices (Gnansounou *et al.*, 2009; Reijinders & Huijbrebts, 2009).

Allocation by mass and energy content account for physical properties. Mass content accounts for the relative masses of biofuels and co-products, and energy content account for the energy content value in biofuels and co-products. The advantage of this is that its heating values are constant, easily determined and comparable to allocation by substitution. A possible disadvantage of this allocation is that a given co-product may have high calorific content but a low market price.

In substitution allocation or “system expansion” the biofuel is considered the only product but emission or energy substituted by co-products are dedicated. This procedure is recommended by ISO 14040, 2006 and ISO 14044, 2006. Substitution

may be difficult to apply in many cases because one co-product can be utilized in more than one form and a choice has to be made about the type of substitution. Also data may not be available on life-cycle emissions and substituted product energy values. A study by Gnansounou and Dauriat (2005) assessed the influence of various allocation methods on the energy ratio of bioethanol fuel from wheat in a Swiss plant. The values of the energy ratio were 0.70 for without allocation, 1.08 for economic value, 1.54 for energy content, 1.21 for system expansion and 5.01 for mass content. Thus, the results obtained vary with the allocation method used.

2.7 Environmental Impacts

2.7.1 Global Warming/Climate Change

The Earth naturally absorbs and reflects incoming solar radiation and emits longer wavelength terrestrial radiations back into space. The absorbed solar radiation is balanced by the outgoing terrestrial radiation emitted to space (Harde, 2013). Gases in the atmosphere absorb a portion of this terrestrial radiation. The energy from this absorbed terrestrial radiation warm the Earth's surface and atmosphere, creating the "the natural greenhouse effect" (Manning, 2020). The greenhouse effect is primarily a function of the concentration of water vapour, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and other trace gases in the atmosphere that absorb the terrestrial radiation leaving the surface of the Earth (IPCC, 1996). Without the natural heat-trapping properties of these atmospheric gases, the average surface temperature of the Earth would be about 33^{o}C lower (IPCC, 2001).

There is scientific evidence that accelerated global warming is caused by increased levels of GHGs in the atmosphere (IPCC, 2001). Human activities have led to increases in the concentration of GHGs leading to a strengthening of the greenhouse effect which regulates Earth's temperature and has resulted to global climate change (IPCC, 2001). United Nations Framework Convention on Climate Change (UNFCCC) define climate change as a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods (IPCC, 2007).

Biomass use for energy generation is considered “carbon neutral” over its life cycle because combustion of biomass releases the same amount of CO_2 as captured by the plant during its growth (Hanaki & Portugal-Pereira, 2018; Martínez *et al*., 2020). Combustion of fossil fuels for energy generation releases CO_2 that has been locked up for millions of years. Bioenergy has an almost closed CO_2 cycle, but there are GHG emissions in its life cycle largely from the production stages: external fossil fuel inputs are required to produce and harvest the feedstocks, in processing and handling the biomass, in bio-energy plant operation and in transport of feedstocks and biofuels. Carbon is stored in three different pools: vegetation, litter and soil. When changing land utilization, these storage pools can change until a new equilibrium is reached.

Soil contains around 50 – 300 tC/ha compared with 2 – 20 tC/ha in pasture or crop biomass. Globally the soil carbon pool is estimated to hold 2500Gt of carbon, compared with 560Gt carbon in vegetation and 760Gt in the atmosphere (Lal, 2008). Because the soil carbon pool is so large, even relatively small increases or decreases in its size can be of global significance. The potential to sequester carbon in the soil is very site specific and highly dependent on former and current agronomic practices, climate and soil characteristics (Kane, 2015; Ogle *et al*., 2019; Rumpel & Chabbi, 2021). Soil carbon stock reflects the balance between the inputs from plant residues and other organic matter and losses due to decomposition, erosion and leaching. Carbon storage in soil is complicated by the fact that soil carbon depletion and build-up are relatively slow processes, so measuring changes is difficult (Heller *et al*., 2003). Experimental data by (Tolbert *et al*., 2002, Hansen *et al*., 2004) and modeling studies by (Grigal & Berguson, 1998) indicate that short rotation perennial bio-energy crops can increase soil carbon compared with intensive cropping. Increasing intensity of harvest from agricultural and forest systems and replacing pastures with short rotation energy crops may deplete soil carbon (Cowie *et al*., 2006). Application of fertilizer also has influence on soil carbon stocks of dedicated energy crops. The CO_2 released through combustions matches the carbon absorbed by the plants from the atmosphere through photosynthesis. In addition growing biomass may increase soil carbon stocks. Bioenergy has therefore significant potential for emission reductions by substituting fossil fuels.

Anthropogenic nitrous oxide (N_2O) emissions are caused by two processes; nitrogen fertilizer production and field application. N_2O is released from nitrogen-based fertilizers and is a major of GHG emissions in agriculture (Crutzen *et al*, 2008; Zah *et al*, 2007; IPCC, 2006). Direct N_2O emissions occur from nitrification and denitrification at the site, while indirect emissions are associated with the volatilization and leaching of nitrogen which is converted into N_2O following atmospheric deposition or in waterways. The significant of these emissions is indicated in the very high characterization factor of N_2O in terms of greenhouse gas equivalent emissions. According to the Intergovernmental Panel on Climate Change (IPCC) 1 kg of N_2O has the same effect of 298kg of CO_2 emissions over a time horizon of 100 years (Solomon *et al*., 2007). Thus even small changes in the nitrogen balance and rate of N_2O emissions can significantly affect the overall GHG balance results for biofuels. The use of fertilizers and related nitrogen balance and N_2O emissions depend on site specific aspects, thus it is difficult to identify representative average emission factors. The application of fertilizer to agricultural land has an effect on the nutrient balance of the soil. Emissions from fields vary depending on the soil type, climate, crop, tillage method, and fertilizer and manure application rates (Larson, 2005). The impacts of N_2O emissions are significant for annual biofuel crops since fertilization rates are larger for these than for perennial energy crops. Crops grown in high rainfall environments or under flood irrigation have the highest N_2O emissions, as denitrification the major process leading to N_2O production is favoured under moist soil conditions where oxygen availability is low (Wrage *et al*., 2005). LCA studies utilize default N_2O emission factors published by IPCC, which estimates emissions from several sources (IPCC, 2006). The most commonly applied method is which provides a global average emission factor of 1 percent of applied fertilizer. This is acknowledged at the international level as a common reference thus facilitating the comparability of results.

CH_4 is released in bio-energy process chain through combustion of fossil fuels, anaerobic decomposition of organic feedstocks and emissions from soil organic matter (Paolini *et al*., 2018). Cultivation of agricultural crops can reduce the oxidation of methane in aerobic soils and thereby increase the concentration of methane in the atmosphere (Wang *et al*., 2017; Ali *et al*., 2019)). The reduction in soil uptake

(oxidation) of methane is related both to the use of nitrogen fertilizer and cultivation type; therefore, reduction in methane uptake is equivalent to an emission of methane from cultivated soil. Such reduction is sensitive to a number of site-specific factors, such as soil temperature, soil moisture and the amount and kind of nitrogen fertilizer. CH_4 emissions related to fertilizer use can thus range from near zero to on the order of 100g CH_4/kg N (Delucchi & Lipman, 2003).

Global warming/climate change is expressed in unit of kg CO_2 equivalents. GHGs are expressed in the unit of CO_2 equivalents by using the global warming potentials (GWPs). The GWPs are a quantified measure of the globally averaged relative radiative forcing impacts of a particular GHG. IPCC (1996) defined GWP as the cumulative radiative forcing – both direct and indirect effects – integrated over a period of time from the emission of a unit mass of a gas relative to carbon dioxide (CO_2). Direct effects occur when the gas itself is a GHG. Indirect radiative forcing occurs when chemical transformations involving the original gas produce a gas or gases that are GHGs. GWPs are quantified for time horizons of 20, 100 and 500 years for a number of known GHGs such as CO_2, CH_4, N_2O, chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs) and several halogenated hydrocarbons etc. (Guinèe, 2002). GWPs are calculated as shown in Equation 2.1:

$$GWPi = \frac{\int_0^T ai.ci(t)dt}{\int_0^T aCO2.cCO2(t)dt} \quad \text{.....2.1}$$

Where

GWP_i = Global warming potential for gas i

a_i = thermal radiation absorption (instant radiative forcing) following an increase of one unit in the concentration of gas i

$c_i(t)$ = concentration of gas i remaining at time t after emission

aCO_2 = thermal radiation absorption following an increase of one unit in the concentration of CO_2

cCO_2 (t) = concentration of CO_2 remaining at time t after emission

T is the number of years for which the integration is carried out (e.g. 20 or 100 years)

The production of bioethanol contributes to emission of GHGs. The sources of GHG emissions in this study include production and use of fossil fuels, fertilizers, pesticides and herbicides. Other sources of GHG emissions include energy production as well as its use, and biomass burning.

2.7.2 Acidification

Acidification refers to processes that increase the acidity of water and soil systems by hydrogen ion concentration. It is caused by atmospheric deposition of acidifying substances generated largely from emissions of sulphur oxides (SO_x), nitrogen oxides (NO_x) and ammonia (NH_3) (Aksoyoglu *et al*., 2020).

Sulphur oxides (SO_X): SO_2 and SO_3 are the acidic anhydrides of sulphurous acid (H_2SO_3) and sulphuric acid (H_2SO_4) respectively (Aksoyoglu *et al*., 2020). These oxides upon absorption of water from the atmosphere they form these strong acids which both release two hydrogen ions when deposited as shown below.

$$SO_2 + H_2O \longrightarrow H_2SO_3 \longrightarrow 2H^+ + SO_3^{2-}$$

$$SO_3 + H_2O \longrightarrow H_2SO_4 \longrightarrow 2H^+ + SO_4^{2-} \quad \text{..... 2.2}$$

Nitrogen oxides (NO_X): NO and NO_2 are acidic anhydrides of nitrous acid (H_2NO_2) and nitric acid (H_2NO_3) respectively. In Troposphere, NO is oxidized to H_2NO_2 while NO_2 is oxidized to H_2NO_3. Further, NO is oxidized to NO_2 by reaction with ozone as indicated below:

$$NO + O_3 \longrightarrow NO_2 + O_2 \quad \text{..... 2.3}$$

NO_2 can further be oxidized to nitric acid

$$NO_2 + OH^- + M \longrightarrow HNO_3 + M \quad \text{.....2.4}$$

Where OH^- is the hydroxyl radical present in the atmosphere and M is an inactive body which can remove surplus energy.

Ammonia: This is itself a base, absorbing H^+ ions via the reaction,

$NH_3 + H^+ \longrightarrow NH_4^+$, but on complete mineralization through nitrite (NO_2-) to nitrate (NO_3-), releasing a proton,

$$NH_3 + 2O_2 \longrightarrow H^+ + NO_3^- + H_2O \quad \text{.....2.5}$$

These acidifying substances have high water solubility and thus their atmospheric residence time is limited to a few days. Therefore, acidification is a regional effect with its extent limited to the region around the point of emission.

Acidifying substances may fall to the soil or water with rain as wet deposition or in the form of particle or gases as dry deposition. Acidification is harmful to plants and aquatic life (Leduc *et al*., 2013). For example, mass deaths of fish can occur in acidified waters. In acid conditions, heavy metals which are hazardous become easily soluble and can be absorbed by living organisms (Guinèe, 2002). Acid deposition is corrosive and damages construction and building materials such as metals. Acidification is quantified by using acidification potentials (AP) for substances having the same effect as SO_2 in reflection to acidification (Hauschild & Wenzel, 1998). Acidification potentials are expressed as SO_2 equivalent (SO_2 eq), i.e. the potentials are expressed relative to the potential of SO_2. Acidifying substances in bioethanol production chain were expected to be emitted from biomass burning and from use of agrochemicals and fossil fuel.

2.7.3 Eutrophication

Eutrophication is enrichment of the aquatic and terrestrial ecosystems with macro-nutrients, nitrogen and phosphorus (O'Hare *et al*., 2018). Eutrophication is characterized by excessive plant and algal growth due to the increased availability of one or more of the limiting growth factors needed for photosynthesis such as sunlight, carbon dioxide and nutrient fertilizers (Shindler, 2006). In terrestrial systems, addition

of nutrients may change the species composition of vegetation by favouring those species which benefit from higher levels of nutrients to grow faster than more nutrient efficient plants. Terrestrial eutrophication is caused by deposition of airborne emissions of nitrogen compounds like nitrogen oxides (NO_x) from combustion processes and ammonia (NH_3) from agriculture.

In aquatic systems, addition of nutrients through surface run-off from an agriculture setting has the impact of fertilizing the plants and algae with a number of consequences for the ecosystem. Enrichment of the aquatic environment with nutrient salts lead to an increased production of plankton, algae and higher aquatic plants (Ngatia &Taylor, 2018). Species composition of the plant community changes to more nutrient-demanding species, algal blooms create shadowing and thus filtering the light penetrating the water mass changing life conditions of macrophytes which need the light for photosynthesis and oxygen depletion near the bottom of the water body where dead algae deposit and degrade. Human-pollution through the impacts of fertilizer use, untreated wastewater effluents, and detergents significantly increases nutrient loading into water bodies, accelerating eutrophication beyond natural levels and generating deleterious changes to the natural ecosystem (Wang *et al*., 2019).

In this study both wastewaters and use of nitrogen and phosphate fertilizers are the sources of pollutants leading to eutrophication. Wastewaters disposed into water bodies and nutrients washed also to nearby water bodies lead to eutrophication of such waters.

2.7.4 Human Toxicity

Human toxicity – in LCA context – covers the impacts on human health of toxic substances such as heavy metals present in the environment (Guinèe, 2002). Heavy metals include Copper (Cu), Lead (Pb), Mercury (Hg), Zinc (Zn), Nickel (Ni), Arsenic (As), Cobalt (Co), Cadmium (Cd), Vanadium (V), Antimony (Sb), Tin (Sn) etc. Different substances released to air, water and soil during the life cycle of biofuels have toxicological effects on humans. The toxic substances are transferred to humans through contact, inhalation and ingestion. Examples of impacts on human health include irritation and corrosive effects, allergic effects, organ damage and

carcinogenic effects. Human toxicity is expressed in kg 1, 4-dichlorobenzene equivalents (Guinèe, 2002). Thus, all pollutants in this impact category are converted to 1, 4-dichlorobenzene equivalents by making use of the human toxicity potentials (HTP). The HTP is an index that reflects the potential harm of a unit chemical released to the environment based on both the inherent toxicity of a compound and its potential dose (Krewitt *et al*, 2002). The use of herbicides and pesticides, biomass burning and use of fossil fuels during bioethanol production were expected to release heavy metals to the environment that cause human toxicity.

2.7.5 Ecotoxicity

Ecotoxicity is adverse effect of toxic substances on an ecosystem. The substances contributing to Ecotoxicity are numerous and include mainly heavy metals and organic substances. Presence of toxic substances in the environment such as heavy metals alters the composition of species of ecosystem, destabilizing it, thereby threatening their existence (Lim & Schoenung, 2011). Ecotoxicity is expressed in kg 1, 4-dichlorobenzene equivalents [1, 4-DCBeq] (Guinèe, 2002). Thus, all pollutants in this impact category are converted to 1, 4-dichlorobenzene equivalents by making use of the Ecotoxicity potentials (ETP). In this context, use of herbicides, pesticides and fossil fuels, biomass burning during bioethanol production expected to result to emission of toxic substances that contribute to Ecotoxicity.

2.7.6 Photochemical Ozone Formation

Ozone is formed in lower atmosphere (troposphere) photo-chemically when nitrogen oxides (NO_x), carbon monoxide (CO), methane (CH_4) and other volatile organic compounds (VOCs) react in the atmosphere in the presence of heat and sunlight forming a phenomenon known as smog. It is formed during summer weather. Smog is a known cause of health problems such as irritation to respiratory system and damage of vegetation (Baumann & Tillman, 2004).

Photochemical ozone formation is expressed in kg ethene equivalents. All pollutants involved in this impact are converted to kg equivalents using the characterization factors referred to as photochemical ozone creation potentials (POCP) [Guinèe, 2002].

POCP is presented as a relative value where the amount of ozone produced from a certain VOC is divided by the amount of ozone produced from an equally large emission of ethene. The unit of POCP is kg ethene equivalents per kg gas (kg C_2H_4/kg VOC). Ethene is chosen as a reference gas as it is one of the most potent ozone precursors of all VOC's. Biomass burning and fossil fuels use result in emissions of carbon monoxide (CO), nitrogen oxides (NO_x), methane (CH_4) and volatile organic compounds (VOC_S) which are the drivers of photochemical oxidant formation.

2.8 Overview on Life Cycle Assessment (LCA)

Life cycle assessment is a technique to assess environmental impacts associated with all stages of a products life, which is from raw material extraction, through materials processing, manufacturing, distribution and use. LCA is a tool used to assess environmental burdens of a product or service by identifying, quantifying and evaluating all resources consumed; all emissions and wastes released into the environment as shown in Figure 2.3 (Eshton, 2012).

An LCA study involves a thorough inventory of energy and materials that are required across the industry value chain of the product or service and calculate the corresponding emissions to the environment. LCA assess cumulative potential impacts of the products life cycle. The aim is to document and improve the overall environmental profile of the product. The results of an LCA study give the potential environmental impacts of a product system over its life cycle and help to identify opportunities for improvement (Guinee, 2002).

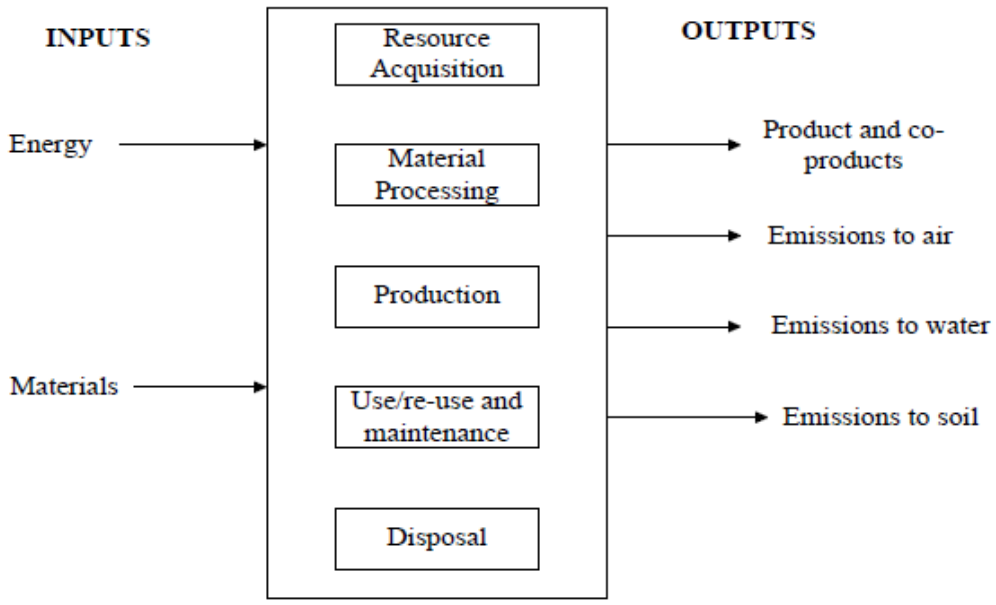

Figure 2.3: Contents of LCA

Source: ISO 14040/44 (2006)

There are different LCA variants namely; cradle-to-grave, cradle-to-gate, cradle-to-cradle, gate-to-gate and well-to-wheel. The cradle-to-grave is the full LCA from resource extraction to use phase and disposal phase. The cradle-to-gate is an assessment of a partial product life from resource extraction to factory gate before it reaches the customer. The cradle-to-cradle is a case of cradle-to-grave assessment where the end-of-life disposal step for the product is a recycling process. The gate-to-gate is a partial LCA looking only at only one value-added process in the entire production cycle. The well-to-wheel is an LCA used for transport fuels and vehicles

2.9 Reviews on LCA Studies for Sugarcane Molasses and Sweet Sorghum Stalk Juice-based Bioethanol Systems

LCA studies for molasses-based bioethanol have been undertaken in countries such as Mexico (Garcia *et al*, 2011), Thailand (Nguyen *et al.*, 2007; Silalertruksa and Gheewala, 2009), Nepal (Khatiwada & Silveira, 2009; Khatiwada & Silveira, 2011), Tanzania (Eshton, 2012; Eshton & Katima, 2012; Eshton & Katima, 2015), India (Soam *et al*., 2015) and Indonesia (Venkata, 2013; Khatiwada *et al*., 2016). There are

variations within these LCA studies with regards to the definition of system boundaries, functional units, farming practices, conversion technologies and allocation methods used for accounting for co-products, and therefore the results obtained vary.

Garcia *et al*. (2011) estimated the life cycle GHG emissions and energy balances of sugarcane bioethanol production in five possible scenarios in Mexico. In one of the five scenarios, final molasses (also referred to as "C" molasses) was used as the raw material for bioethanol production and bagasse fuel was the only source of energy. For this scenario, the study considered energy allocation and economic allocation methods to partition the GHG emissions between molasses and sugar, obtaining overall net GHG emissions of 1073 g CO_2 eq and 1257 g CO_2 eq per litre of bioethanol respectively.

Nguyen *et al*. (2007) studied the fossil energy savings and GHG mitigation potentials of bioethanol as a gasoline substitute in Thailand. In this study the overall GHG emission was found to be about 3313 g CO_2 eq per litre of bioethanol. The use of coal as a fuel and CH_4 emissions from the anaerobic pond contributed about 35 and 56% of the total GHG emissions respectively. Numjuncharoen *et al*. (2015) indicated that substituting biomass fuel for fossil fuel as primary fuel in steam production greatly effects to GHG emission reduction. The study by Numjuncharoen *et al*. (2015) further indicated that the utilization of biogas produced from wastewaters in steam generation insignificantly reduces the GHG emissions, if primary fuel in steam generation is biomass.

Khatiwada and Silveira (2011) analyzed GHG emissions from molasses-based bioethanol production and use in Nepal. The study found the overall net GHG emission to be 432.5 g CO_2 eq per litre of anhydrous bioethanol. The production and use of agrochemicals (fertilizers, herbicides and pesticides), and use of fossil diesel for transport of inputs and outputs were found to be the major contributors to GHG emissions.

Soam *et al.* (2015) investigated LCA of fuel bioethanol from sugarcane molasses in northern and western India. The study conducted a LCA for one ton fuel grade bioethanol in the northern region (NR) and western region (WR) of India. The study

used four different allocation approaches; WA (without any allocation), MA (mass allocation), EA (energy allocation) and MPA (market price allocation/economic allocation) to distribute emissions and energy consumption between product and co-products. The emissions obtained for NR and WR for the four different allocation approaches are shown in Table 2.1. The study clearly shows that the result obtained for the net GHG emissions depends on allocation method used.

Table 2.1: GHG emissions (kg CO_2 eq/ ton bioethanol)

Allocation	Northern region (NR)	Western region (WR)
WA	8188.4	7349.6
MA	513.5	519.1
EA	793.6	818.1
MPA	4327.9	4093.9

Source: Soam *et al.* (2015)

Silalertruksa and Gheewala (2009) determined the environmental performance of bioethanol production in Thailand. Eshton (2012) determined the environmental performance of bioethanol production and use in Tanzania. Table 2.2 indicates the impact categories analyzed and the results obtained in each study. The human toxicity results obtained by Eshton (2012) and Silalertruksa and Gheewala (2009) differed significantly because the latter did not account for emissions due to heavy metals and particulates from sugarcane burning.

Table 2.2: Environmental impacts per litre of bioethanol

Impact	Unit	Eshton (2012)	Silalertruksa & Gheewala (2009)
GHG emissions	g CO_2 eq	423	685.5
Acidification	g SO_2 eq	11.9	12.5
Eutrophication	g PO_4^{3-}	4.57	19.6
Human toxicity	g 1,4 DCB eq	105	19.1
Ecotoxicity	g 1,4 DCB eq	7.35	-
Photochemical ozone formation	g C_2H_4 eq	3.62	5.8

Adapted from Eshton (2012) and Silalertruksa & Gheewala (2009)

Gabisa *et al*. (2019) analyzed the environmental performance and energy balance of ethanol production based on sugarcane molasses in Ethiopia. This study aimed to identify environmental hotspots so as to devise improvement options. Pre-harvest cane trash burning and fertilizer application in agriculture stage were found to contribute the most pollutant emissions in all impact categories considered in this study. Sensitivity analysis indicated that the price of molasses influences energy ratio and GHG emissions and it shifts allocation of upstream emissions from sugar to molasses. Another LCA study of ethanol production from sugarcane molasses in Ethiopia by Demissie & Gheewala (2019) found that pre-harvest cane trash burning and application of fertilizer contributed the most to GHG emissions, POCP and land use impact categories. In this study, ethanol production stage contributed the most in acidification, ecotoxicity and eutrophication impact categories due to use of light fuel oil in power and steam generation for ethanol plant, and the discharge of vinasse into the river.

Wang *et al.* (2014) used life-cycle analysis method to evaluate energy efficiency and environmental performance of bioethanol production from sweet sorghum stem in China. In this study, NER and NEV were found to be 1.56 and 8.56 MJ per litre of bioethanol, respectively, the positive values of NER and NEV indicating the bioethanol production can produce net energy. Human toxicity, eutrophication and acidification were the most negative environmental impacts in that order. Steam generation contributed to human toxicity and acidification, while fertilizer loss from farmland contributed to eutrophication. The inventory allocation methods, vinasse reuse and feedstock yields affected the results obtained. In this study, it was found that the energy efficiency and environmental performance of bioethanol production from sweet sorghum stem could be enhanced by use of vinasse as fuel for steam generation, and also by controlling fertilizer loss through better cultivation practice.

Another LCA by Wang *et al.* (2015) in China to determine the environmental sustainability of bioethanol production from sweet sorghum stem on saline-alkaline land obtained positive NEV and NER values. Eutrophication and acidification were

the major environmental impacts, this due to agrochemical loss to surrounding water and atmospheric environment. In this study it is indicated that substituting fossil energy use with vinasse for steam generation significantly improves energy efficiency and decreases environmental impacts. Ding *et al.* (2017) also conducted a LCA on production of bioethanol from soluble sugar in sweet sorghum stalk in China. The results in this study indicated that farming was the largest contributor to environmental impacts due to high use of fertilizer and fossil fuels. In this study it is indicated that less usage of nitrogenous fertilizer, use of cleaner energy and applying energy saving technology in industry processes will go along in controlling environmental impacts in China.

Aguilar-Sachez *et al*., (2018) evaluated using LCA potential environmental impacts and energy efficiency of bioethanol production from sweet sorghum stalks cultivated in the state of Yucatan, Mexico. Cultivation of sweet sorghum was found to be responsible for the largest emissions due to production and use of agrochemicals. Cultivation of sweet sorghum and distillation of bioethanol were found to be the most energy intensive. The NER value was positive indicating production of the bioethanol return more energy than the fossil energy they consume. Bioethanol production from stalk juice coupled with cogeneration using bagasse for energy and heat was found to be a good option, both energetically and environmentally.

2.10 Life Cycle Cost Analysis of Bioethanol Production

Bioethanol is one of the most promising biofuels from renewable sources, and thus to make it competitive, its production cost should be lowered. The current world bioethanol research is geared towards its production in a socially, environmentally and economically sustainable way. Importantly there is need to identify areas in its production pathway where it is possible to reduce its production cost. Life cycle costing is a method of calculating the total cost of a product induced throughout its life cycle. Full-cost assessment is based on the total of internal costs paid during a product life cycle, and external costs which is not reflected in the market prices. The internal costs are the production costs, while the external costs are the environmental costs.

This study considered the production and environmental costs of bioethanol production from sugarcane molasses as well as from the sweet sorghum stalk juice.

2.10.1 Production Costs

Bioethanol production costs are determined from the installed capital costs, feedstock costs, and operation and maintenance costs, with the feedstock costs dominating the total production costs (IRENA, 2013). Total operating costs for bioethanol plants include costs of feedstock, chemicals, yeast, and transport of feedstock, energy, labour, maintenance, water, insurance and other operating costs (IRENA, 2013).

The production of bioethanol from sugarcane and sweet sorghum stalks creates large quantities of bagasse that can be burned to provide process heat and electricity. The excess electricity can be sold to the national grid. The use of high efficiency boilers to combust bagasse to produce steam to drive turbines and create electricity would increase capital costs. Study by Dias *et al*. (2010) report that for a plant producing 1000 m^3/day of anhydrous bioethanol, the capital costs would increase by about USD 40 to 60 million but it would yield electricity for sale to the grid by about 68 to 155kWh/ tonne of sugarcane. In Brazil, the value of the electricity exported by burning bagasse reduces the cost of bioethanol produced by about 8-10% on average (IRENA, 2013).

2.10.2 Environmental Costs

Environmental costs are indices used for calculating the price to the society of environmental pollution and are expressed in monetary terms per kilogram pollutant. They indicate the willingness to pay (WTP) for preventing pollution and other unwanted impacts. Environmental Priority Strategies (EPS) in product design is a model developed in Sweden at Chalmers University of Technology with participation from industry to calculate external environmental costs.

2.10.2.1 Environmental Priority Strategies (EPS) 2000

The EPS method was developed in 1990-1991 as a conceptual tool for LCA. EPS version 2000 (Steen, 1999:4; Steen, 1999:5) is an update of the 1996 version and the

1994 version. EPS system's rule and terminology comply with the ISO standards for LCA. The EPS system aim was to communicate an understanding of the magnitude of impacts in monetary terms for easy weighting against other items that can be considered for product development.

2.10.2.2 The EPS Default Method

EPS was developed following a top-down approach, starting from what the product designers would like to know in order to be able to decide which environmental concerns to follow in a choice between two concepts of a product. The methodology was then gradually developed as per existing knowledge from environmental sciences. Data input to the models was on use of abiotic resources emissions from processes involved in life cycle of products, risk assessment and valuation models for resulting environmental effects.

The application of EPS default method to an LCI assessment is by means of indexes. These indexes are ready made weighted factors that describe the impacts of resources and emissions. The inventory results of individual flows for an activity are multiplied by the corresponding weighting factors and then summed up to give one total value. The EPS default method evaluates impacts on the environment through its impact on one or several safeguard subjects. EPS method is based on five safeguards subjects and the willingness to pay (WTP) for protecting these subjects. The safeguard subjects include human health, biodiversity, abiotic resources, ecosystem production capacity, and cultural and recreational values. Each of these five subjects has a number of sub-categories called "unit effects" or impact category. Each impact category has a category indicator and a weighting factor.

The impacts of resources and emissions are valued in EPS on a relative scale in Environmental Load Units (ELU) according to the WTP to avoid negative effects (changes) on the safeguard subjects. Monetary measure is produced in the EPS default method where one ELU is assumed to equal to one EURO. To estimate the WTP for preserving lives, the Contingent Valuation Method (CVM) is used when applicable. Table 2.3 shows the monetary values for the key safeguards subjects considered in

EPS. The values were calculated on the basis of various European and US studies described by Steen (1999b).

Table 2.3: EPS safeguard subjects, related impact categories and weighting factors

Safeguard subject	Impact category	Category indicator	Indicator unit	Weighting factor (ELU/ indicator unit)
Human health	Life expectancy	Years of life lost(YOLL)	Person-year	8.5E+04
	Severe morbidity	Severe morbidity	Person-year	1.0E+05
	Morbidity	Morbidity	Person-year	1.0E+04
	Severe nuisance	Severe nuisance	Person-year	1.0E+04
	Nuisance	Nuisance	Person-year	1.0E+03
Ecosystem production capacity	Crop growth Capacity	Crop	kg	1.5E-01
	Wood growth capacity	Wood	kg	4.0E-02
	Fish and meat production capacity	Fish and meat	kg	1.0E+00
	Soil acidification	Base cat-ion Capacity of soils	Mole H+-equivalent	1.0E-02
	Production capacity of irrigation water	Irrigation water	kg	3.0E-02
	Production capacity of drinking water	Drinking water	kg	3.0E-03
Biodiversity	Species extinction	Normalized extinction of species (NEX)	---	1.1E+11

Source: Steen B. (1999:5)

2.10.2.3 Estimation of EPS Default Values

The possible effects of CO_2 emissions (impact categories) and their corresponding pathways, and the characterization factors for each of these pathways are shown in Table 2.4. In determination of the EPS default value of $CO_{2,,}$ the characterization factors are multiplied with weighting factors and the products added to obtain an index. For example, the pathway specific characterization factors for all impacts on Years of Lost Life (YOLL) are added to give 7.93E-07 YOLL/kgCO_2, which is multiplied with weighting factor for YOLL (8.50E+04 ELU/YOLL) to give the YOLL indicator contribution to the total index, 6.74E-02 ELU/kgCO_2. Then all contributions from the indicators affected by CO_2 are added to give 1.08E-01 ELU/kgCO_2.

Table 2.4: Characterization of CO_2 air emissions for the estimation of corresponding EPS index

Impact category (Indicator)	Pathway	Pathway specific characterization factor (Indicator/kg)	Indicator's contribution EPS default Impact index (ELU/kg)	EPS default impact index (ELU/kg)
Life Expectancy (YOLL)	Heat stress	7.43E-08		
	Starvation	6.80E-07		
	Flooding	5.70E-09		
	Malaria	3.30E-08		
	All pathways	7.93E-07	6.74E-02	
Severe morbidity	Starvation	3.15E-07		
	Malaria	3.80E-08		
	All pathways	3.53E-07	3.53E-02	
Morbidity	Starvation	3.15E-07		
	Malaria	3.40E-07		
	All pathways	6.55E-07	6.55E-03	
Crop Production Capacity (Crop)	Desertification	7.56E-04	1.13E-04	
Wood Production Capacity (Wood)	Global warming	-1.16E-03		
	CO_2 fertilization	-3.93E-02		
	All pathways	-4.05E-02	-8.09E-04	
Extinction of Species(NEX)	Climate change	1.26E-14	1.39E-03	
All	All			1.08E-01

Source: Steen B. (1999:5)

2.11 Research Gaps (Contribution of this study)

i. Sweet sorghum is a new and alternative energy crop which is under development in tropical and semi-arid regions for bioethanol production. Only limited LCA studies on production of bioethanol from sweet sorghum have been done globally. This is the first LCA done in Kenya.

ii. LCA studies have been undertaken for molasses-based bioethanol in countries such as Mexico (Garcia *et al*, 2011), Thailand (Nguyen *et al*, 2008), Nepal (Khatiwada & Silveira, 2009; Khatiwada & Silveira, 2011) and Tanzania (Eshton

& Katima, 2012). These studies have been conducted in different conditions and environment and thus cannot be replicated to Kenya.

iii. Limited studies on life cycle costing on bioethanol from different feedstocks have been done globally. No study has been done in Kenya.

iv. This study used LCA to evaluate net energy balances, environmental impacts and also carryout cost analysis in the production of bioethanol in Kenya. No such studies have been published in Kenya. Therefore this study will provide data on cleaner energy production as well as information on energy and environmental performance.

CHAPTER THREE

METHODS AND MATERIALS

3.1 Introduction

The study used Life Cycle Assessment (LCA) to evaluate environmental impacts for the sugarcane molasses and the sweet sorghum stalk juice bioethanol systems. Life cycle assessment or analysis, a method for determining the environmental impacts of a product during its life cycle was used in this study to assess environmental performance of bioethanol by identifying, quantifying and evaluating resources consumed, emissions and wastes released to the environment.

3.2 Research Design

The study selected sugarcane molasses and sweet sorghum stalk juice for bioethanol production. Sugarcane molasses is a by-product for sugar production and thus considered as a waste. The sweet sorghum stalk juice is obtained from non-edible part of the sweet sorghum plant. Thus, the two selected, sugarcane molasses and sorghum stalk juice do not compete with the food supply chain and hence their use in bioethanol production does not compromise food security. Appendix I shows the summary of activities involved in carrying out this research work.

3.3 Materials

This was a non-experimental study and no laboratory or field experiments were conducted. The research work was based on field visits. During this visits, data was collected and verified. The materials used included a computer, internet, paper publications, questionnaire and stationary.

3.4 Methods

This study used the LCA tool to evaluate the environmental impacts of the sugarcane molasses and the sweet sorghum stalk juice bioethanol systems. The LCA models for each of the bioethanol system were constructed in the Chain Management by Life

Cycle Assessment (CMLCA) software. The CMLCA software is available online at http://www.cmlca.eu/ . The methodology used to carry out the LCA is the one described by ISO 14040/ISO 14044 series (2006). In this methodology, LCA is divided into four phases namely; the Goal and Scope Definition, the Life Cycle Inventory Analysis (LCI), the Life Cycle Impact Assessment (LCIA) and Interpretation of Results as shown in Figure 3.1.

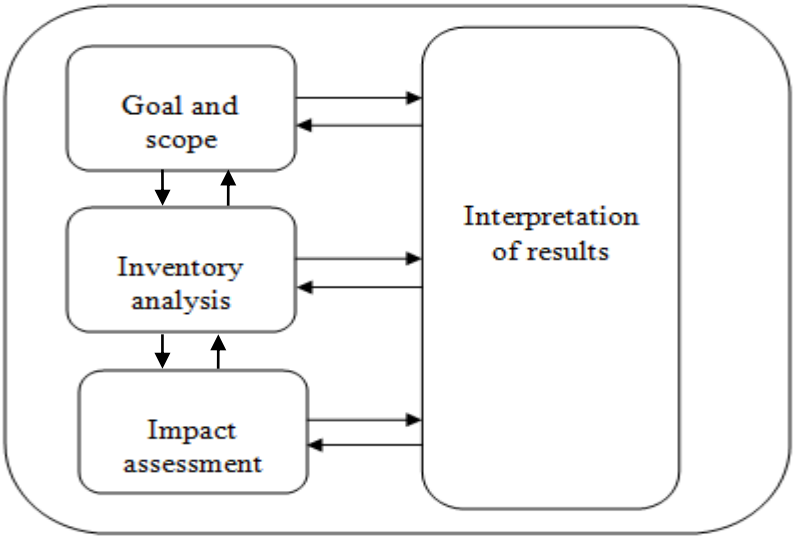

Figure 3.1: Phases of an LCA

Source: ISO 14040 (2006)

3.4.1 Goal and Scope definition

At this phase, the goal and scope definitions were defined, the intended application of the results and intended users of the study were specified. The goal definition states the main objective of the study. The scope definition describes the range of areas of the intended LCA study. The functional unit of the bioethanol systems was defined and this provided the reference to which the inputs, outputs and emissions were related.

3.4.2 Life Cycle Inventory (LCI) Analysis

The LCI analysis phase involved first identifying the system boundary which defined the unit processes of each of the bioethanol systems studied. Data was then collected and calculations done to quantify the inputs and outputs for each of the bioethanol systems. The inventory analysis was performed in CMLCA software. The data collected were related to the defined functional unit. The inventory results obtained was a list containing the quantities of pollutants released to the environment.

3.4.3 Life Cycle Impact Assessment (LCIA)

The LCIA phase aimed to evaluate environmental impacts of the inventory results. The potential environmental impact categories were selected and defined. The characterization method for each impact category was also selected. The characterization method comprised the characterization model, category indicator and characterization factors. The inventory results are then associated with environmental impact categories and categories indicators (Guinee, 2002; ISO 14040/44, 2006). The characterization factors were used to convert the inventory results to a common unit of an impact category. The characterization method used to calculate the environmental impacts of the bioethanol systems studied is the CML-IA (Van Oers, 2010). The LCIA was performed in CMLCA software. The environmental impact categories assessed include global warming/climate change, acidification, eutrophication, human toxicity, ecotoxicity and photochemical ozone formation.

3.4.3.1 Global Warming/Climate Change

The characterization model presented in equation 3.1 developed by the Intergovernmental Panel on Climate Change (IPCC) was used to evaluate this impact. The characterization factors used are the global warming potential (GWP) for a 100-year time horizon (GWP_{100}) for each GHG emission to the air presented in Table 3.1. The reference substance of this impact category is the carbon dioxide (CO_2) and indicator result presented in kg $CO_{2\ eq}$.

$$\text{Climate change} = \sum_i GWP_{100i} \times m_i \quad \text{3.1}$$

Where;

GWP_{100i} is the global warming potential of substance i integrated over 100 years (kg CO_2 eq/kg emission).

m_i is the quantity of substance i in kg.

Table 3.1: Characterization factors for Global Warming

Substance	Global Warming Potential (kgCO_2eq/kg emission)
Carbon dioxide (air)	1
Methane (air)	25
Nitrous oxide (air)	298

Source: IPCC (2007)

3.4.3.2 Acidification

The characterization model used to assess this impact is the RAINS 10 model developed by IIASA presented in equation 3.2 (Guinee, 2002). The characterization factors used are the acidification potentials presented in Table 3.2 for each acidifying emission to air measured in kg SO_2 eq/kg emission and the unit of indicator result is kg SO_2 eq.

$$\text{Acidification} = \sum_i AP_i \times m_i \quad \text{.....} \quad 3.2$$

Where;

AP_i is the acidification potential for substance i

m_i is the emission to air of substance to the air.

Table 3.2: Characterization factors for Acidification

Substance	Acidification Potential($kgSO_2eq/kg$ emission)
Ammonia(air)	1.88E+00
Hydrogen chloride(air)	8.80E-01
Hydrogen fluoride(air)	1.60E+00
Nitrogen oxides (air)	7.00E-01
Sulphur oxide (air)	1.00E+00

Source: van Oers (2010)

3.4.3.3 Eutrophication

The characterization model used is a stoichiometric procedure which identifies the equivalence between N and P for both terrestrial and aquatic systems shown in equation 3.3. The characterization factors used are the eutrophication emission to air, water and soil measured in kg PO_4 equivalents/kg emission presented in Table 3.3. The indicator result is presented in kg PO_4 eq.

$$\text{Eutrophication} = \sum_i EP_i \times m_i \quad \text{..... 3.3}$$

Where;

EP_i is characterization factor of substance i.

m_i is the emission of substance i to air, water or soil.

Table 3.3: Characterization factors for Eutrophication

Substance	Eutrophication Potential($kgPO_4$/kg emission)
Phosphate (fresh water)	1.00E+00
Ammonia (air)	3.50E-01
Ammonium ion (fresh water)	3.30E-01
Nitrogen oxide (air)	1.30E-01
Nitrogen (air)	4.20E-01
Chemical oxygen demand, COD (fresh water)	2.20E-02
Nitrous oxide (air)	2.70E-01
Phosphorus (fresh water)	3.06E+00
Nitrate (air)	1.00E-01
Phosphorus (air)	9.70E-01

Source: van Oers (2010)

3.4.3.4 Human Toxicity

The characterization model used to assess this impact is the USES 2.0 model developed at RIVM shown in equation 3.4 (Guinèe, 2002). The characterization factors used are the human-toxicity potential (HTP) for each emission of a toxic substance to air, water and soil measured in kg 1, 4-dichlorobenzene equivalent/kg emission presented in Table 3.4. The indicator result is presented in kg 1, 4-dichlorobenzene eq (kg I, 4- DCBeq).

$$\text{Human toxicity} = \sum_i \sum_{ecom,i} HTP_{ecom,i} \times m_{ecom,i} \quad \text{.....3.4}$$

Where;

$HTP_{ecom,i}$ is the human toxicity potential for substance *i* emitted to emission compartment ecom (air, fresh water, sea water, agricultural soil or industrial soil).

$m_{ecom,i}$ is the emission of substance i to medium ecom.

Table 3.4: Characterization factors for Human Toxicity

Substance	Human toxicity potential (kg 1,4-DCB/kg emission)
Ammonia (air)	1.00E-01
Particulates (air)	8.20E-01
Hydrogen chloride (air)	5.00E-01
Cadmium (air)	1.50E+05
Arsenic (air)	3.50E+05
Chromium (air)	7.00E+00
Cobalt (air)	1.70E+04
Copper (air)	4.30E+03
Hydrogen fluoride (air)	2.90E+03
Lead (air)	4.70E+02
Mercury (air)	2.60E+02
Nitrogen oxides (air)	1.20E+00
Nickel (air)	3.50E+05
Zinc (air)	9.60E+01
Mercury (fresh water)	1.00E+02
Zinc, ion (fresh water)	2.10E-01
Cadmium (fresh water)	1.10E+01
Copper, ion (fresh water)	4.50E+01
Nickel, ion (fresh water)	4.30E+01
Toluene (air)	3.30E-01
Phenol (fresh water)	4.90E-02
Toluene (fresh water)	3.00E-01
Benzene (air)	1.90E+03
Benzene (fresh water)	1.80E+03
Selenium (air)	4.80E+04
2,3,7,8-tetrachlorobenzo-p-	8.60E+08
Chromium V (air)	3.40+06
Formaldehyde (air)	8.30E-01
Cadmium (agri. soil)	2.00E+04
Lead (agri. soil)	3.30E+03
Zinc (agri. soil)	6.40E+01
Arsenic (agri. soil)	3.20E+04
Atrazine (agri. soil)	2.10E+01
Glyphosate (agri. soil)	1.50E-02
Diuron (agri. soil)	1.30E+03

Source: van Oers (2010)

3.4.3.5 Ecotoxicity

The characterization model used to assess ecotoxicity is the USES 2.0 Model shown in equation 3.5 (Guinee, 2002). The characterization factors used are the ecotoxicity potential for each emission of a toxic substance to air, water and soil measured in kg I, 4 – DCB eq/kg emission presented in Table 3.5. The indicator result is presented in kg 1, 4 – DCB eq.

$$\text{Ecotoxicity} = \sum_i \sum_{ecom,i} ETP_{ecom,i} \times m_{ecom,} \quad \text{.....3.5}$$

Where;

$ETP_{ecom,i}$ is the ecotoxicity potential for substance *i* emitted to compartment such as air, fresh water, sea water, agricultural soil or industrial soil.

$m_{ecom,I}$ is the emission substance *i* to medium ecom.

Table 3.5: Characterization factors for Ecotoxicity

Substance	Ecotoxicity Potential (1,4-DCB eq/kg emission)
Lead (fresh water)	9.30E+02
Cadmium (air)	8.10E+01
Arsenic(air)	1.60E+03
Chromium (air)	3.00E+03
Cobalt (air)	1.10E+02
Copper (air)	7.00E+02
Hydrogen fluoride (air)	2.90E-03
Lead (air)	1.60E+01
Mercury (air)	2.80E+04
Nickel (air)	1.20E+03
Zinc (air)	1.20E+03
Zinc, ion (fresh water)	2.50E-21
Copper, ion (fresh water)	4.10E-21
Nickel, ion (fresh water)	1.00E-18
Toluene (air)	1.60E-05
Arsenic, ion(fresh water)	7.60E-04
Cadmium, ion (fresh water)	1.40E-20
Phenol (fresh water)	2.50E-06
Toluene (fresh water)	1.40E-05
Chromium, ion (fresh water)	2.30E-19
Benzene (air)	1.60E-05
Benzene (fresh water)	1.40E-05
Selenium (air)	5.30E+01
Vanadium (air)	6.70E+02
Chromium (air)	3.00E+03
Formaldehyde (air)	9.40E-01
Cadmium (agri. soil)	1.70E+02
Lead (agri. soil)	3.30E+01
Zinc (agri. soil)	2.50E+01
Arsenic (agri. soil)	3.30E+03
Atrazine (agri. soil)	6.60E+00
Glyphosate (agri. soil)	9.60E-02
Diuron (agri. soil)	2.30E+03

Source: van Oers (2010)

3.4.3.6 Photochemical Ozone Formation

The characterization model used to assess this impact was UNECE Trajectory Model shown in equation 3.6 (Guinee, 2002). The characterization factors used are photochemical ozone creation potential (POCP) for each of VOC or CO to the air and measured in kg ethene equivalents/kg emission presented in Table 3.6. The indicator result is presented in kg ethene eq.

$$\text{Ozone formation} = \sum_i POCP_i \times m_i \quad \text{.....3.6}$$

Where;

$POCP_i$ is the photochemical ozone creation potential for substance *i*

m_i is the quantity of substance i emitted in kg.

Table 3.6: Characterization factors for Photo-oxidant formation

Substance	POCP(kg ethene/kg emission)
NMVOC, non-methane volatile organic compounds (air)	7.00E-03
Methane (air)	6.00E-03
Carbon monoxide (air)	2.70E-02
Sulphur dioxide (air)	4.80E-02
Toluene (air)	6.37E-01
Ethane (air)	1.23E-01
Heptane (air)	4.94E-01
Pentane (air)	3.95E-01
Propane (air)	1.76E-01
Hexane (air)	4.82E-01
Benzene (air)	2.18E-01
Acetone (air)	9.40E-02
Acetaldehyde (air)	6.40E-01
Formaldehyde (air)	5.20E-01

Source: van Oers (2010)

3.5 Assumptions for the Bioethanol Systems

The assumptions made for each biofuel system are as listed below

Assumptions for the sugarcane molasses bioethanol system

i) 5 year cycle period (plant crop and three ratoon crops)
ii) The average turn around distance (factory-farm-factory) is 44 km
iii) All stillage from bioethanol fermentation is concentrated and combusted in boilers.
iv) Only 270 kg/ton cane of bagasse is combusted in boilers.

Assumptions for the sweet sorghum stalk juice bioethanol system

i) 1 year cycle period (plant crop and one ratoon crop)
ii) The average turn around distance (factory-farm-factory) is 30 km
iii) All the bagasse is combusted in boilers

3.6 Data Collection

Life cycle of bioethanol production include cultivation, processing, transportation and bioethanol conversion. Data on farming (land preparation, planting, crop management, harvesting), milling and bioethanol conversion was collected during field visits. The questionnaire depicted in Appendix II indicates the data collected in each of the stages of the life cycle of the bioethanol production. In addition, some of the data was obtained from scholarly published papers. The data for sugarcane molasses-based bioethanol production was collected from Mumias Sugar Company, Nzoia Sugar Company and Spectre International. These three companies are located in western part of Kenya. Data for sweet sorghum farming was collected from Kenya Agriculture and Livestock Research Organization (KALRO) from field trials carried out in various part of western Kenya. Since there is no industrial plant converting sweet sorghum stalk juice to bioethanol in Kenya and within the neighboring countries, data for bioethanol conversion from sweet sorghum stalk juice was obtained from literature. Table 3.7 shows the company, visit dates and the persons interviewed. Data gathered during field visits include amount of product and co-products, amount of fertilizer, amount of

industrial chemicals, process energy source, amount and use of co-products and wastes, and diesel, thermal and electricity consumption. Secondary data which includes lower heating values of main product and co-product, emission and energy factors for fertilizers, chemicals and electricity was obtained from scientifically recognized literature.

Table 3.7: Field visits

	Section	Person interviewed
Mumias Sugar Company Ltd	Training	Training Manager
	Agronomy	Agronomist
	Processing Plant	Production Manager
	Harvesting	Harvesting Manager
	Bioethanol conversion	Production Manager –
	Cogeneration plant	Engineer
	Field	Field Officer
	Procurement	Procurement Officer
Nzoia Sugar Company	Nucleus Estate	Manager
Spectre International	Processing	Chemical Engineer
Kenya Agriculture & Livestock Research Organization	Agronomy	Agronomist/ Researcher

3.7 Calculation of Emissions

3.7.1 Emissions due to Fertilizer Addition

Nitrogen fertilizer additions to soil result in nitrous oxide (N_2O) emissions. According to IPCC (2006), N_2O is naturally produced in the soils through the process of nitrification and denitrification. N_2O is directly and indirectly emitted from the soil due to nitrogen fertilizer (IPCC, 2006). Equations 3.7, 3.8, 3.9, 3.10, 3.11 and 3.12 were used to calculate the direct and indirect soil N_2O emissions (IPCC, 2006).

(i) Direct emissions (N_2O directly from N inputs)

$$N_2O\text{-}N_{Ninputs} = (F_{SN} + F_{ON} + F_{CR} + F_{SOM}) * EF_1 \quad \text{.....3.7}$$

Where:

EF_1 = Emission factor N_2O emission from N inputs, kg N_2O-N/kg N inputs = 0.01

F_{SN} = Synthetic fertilizer applied (kg N)

F_{ON} = Organic N applied as fertilizer e.g. manure (kg N)

F_{CR} = N in crop residues (kg N)

F_{SOM} = N mineralization associated with the loss of soil organic matter resulting from change of land use or management of mineral soils (kg N)

$$N_2O_{DIRECT} = N_2O\text{-}N_{Ninputs} \times {}^{44}/_{28} \quad \text{.....3.8}$$

(ii) Indirect emissions (N_2O from atmospheric deposition of N volatilized from managed soils)

$$N_2O\text{-}N_{(ATD)} = [(F_{SN} * FRAC_{GASF}) + (F_{ON} * FRAC_{GASM})] * EF_2 \text{.....3.9}$$

Where:

EF_2 = Emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces (kg N_2O-N/kg NH_3-N +NO_X-N volatilized) = 0.01

$FRAC_{GASF}$ = Fraction of synthetic fertilizer N that volatilized as NH_3 and NO_X, kg *N* volatilized/kg N applied = 0.10

$FRAC_{GASM}$ = Fraction of applied organic N fertilizer (F_{ON}) that volatilizes as NH_3 and NO_X, kg N volatilized/kg N applied or deposited = 0.20

$$N_2O_{(ATD)} = N_2O\text{-}N_{(ATD)} \times {}^{44}/_{28} \quad \text{.....3.10}$$

(iii) Indirect emissions (N_2O from N leaching/runoff from managed soils)

$$N_2O\text{-}N_{(L)} = (F_{SN} + F_{ON} + F_{CR}) * FRAC_{LEACH} * EF_3 \quad \text{.....3.11}$$

Where:

EF_3 = Emission factor for N_2O emissions from N leaching and runoff, kg N_2O-N/kg N leached and runoff = 0.0075

$FRAC_{LEACH}$ = Fraction to all N added to/ mineralized in managed soils where leaching/runoff occurs, kg N/kg N additions = 0.30

$$N_2O\ (L) = N_2O\text{-}N_{(L)} \times {}^{44}/_{28} \quad \text{.....3.12}$$

Ammonia (NH_3) and nitrogen oxides (NO_X) are also emitted to air like nitrous oxide (N_2O) while nitrogen is emitted to surface waters through leaching. Ammonia emitted is 8-10% of the nitrogen applied, nitrogen oxides are 21% of nitrous oxide emitted and amount of nitrogen leaching is 30% of nitrogen applied (IPCC, 2006). The phosphorus content of synthetic fertilizers and manure is emitted to the soils which have an impact on freshwater eutrophication. The fraction of phosphorus emission that reaches freshwater is approximately 0.05 of the phosphorus from synthetic fertilizers and manure (Agri-footprint 2.0, 2015).

3.7.2 Emissions due to Production of Farm Inputs

Farm inputs considered in this study include fertilizers, herbicides, pesticides and insecticides. The production of each of these chemicals has emissions associated with it. Production of seed cane is another cultivation activity which also has emissions associated with it. Equation 3.13 was used to calculate emissions for the production of these inputs;

$$Ep = M_S * EF_s \text{..} \quad \text{.....3.13}$$

Where:

Ep = Emissions due to production of farm inputs

M_S = Amount of substance/chemical used (kg/ha/yr)

EF_s = Emission factor or coefficient (kgCO_{2eq}/kg) (as indicated in Table 3.7)

Another cultivation activity is human labour which is required in land preparation, planting, crop management and harvesting. Equation 3.14 was used to calculate emissions due human labour;

$$El = N_{md} \times EF_{md} \quad \text{.....3.14}$$

Where;

El = Emissions due to human labour

N_{md} = Number of man-days per ha (man-days/ha) [one man-day is equivalent to a 8 hrs]

EF_{md} = Emission factor/coefficient (kg CO_{2eq}/man-day) (as shown in Table 3.8).

Table 3.8: Emission factors in Cultivation phase

Particulars	Value	Units
Nitrogen (N) production[a]	3.97	$kgCO_{2eq}/kg$
Phosphorus (P_2O_5) production[a]	1.3	$kgCO_{2eq}/kg$
Potash (K_2O) production[a]	0.71	$kgCO_{2eq}/kg$
Herbicide production[a]	25	$kgCO_{2eq}/kg$
Sugarcane seeds production[a]	0.0016	$kgCO_{2eq}/kg$
Insecticide production[b]	29	$kgCO_{2eq}/kg$
Human labour[a]	5.59	$kgCO_{2eq}$/man-day

[a] Emission coefficients cited from Khatiwada *et al*. (2016)
[b] Emission coefficients cited from Macedo *et al*. (2008)

3.7.3 Emissions due to Inputs in Milling and Bioethanol Production

Inputs in milling include among them sulphur, lime, juice flocculants, imbibition water, steam and electricity; and for bioethanol production they are sulphuric acid, urea, yeast, sodium hydroxide, antifoam agent, steam and electricity. Bagasse is combusted in boilers to produce steam for process heating and power generation. Equation 3.15 was used to calculate the emissions in milling and bioethanol production phases. Emission factors for material (or chemicals) used in milling and bioethanol production are presented in Table 3.9.

$$Emissions = A_{mb} * EF_{mb} * Y_c \quad \text{.....3.15}$$

Where:

A_{mb} = Amount of material (kg/tc)

EF_{mb} = Emission factor (kg CO_{2eq}/kg)

Y_c = Yield = 65 ton for sugarcane or Yc= 55.88 ton for sweet sorghum

Table 3. 9: Emission factors for inputs in cane milling and bioethanol production

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

[a] Emission coefficients cited from Khatiwada et al (2016)

3.7.4 Emissions from Burning of Fossil Fuels

Fossil fuels such as diesel on combustion emit substances which include carbon dioxide (CO_2), carbon monoxide (CO), Methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), sulphur oxide (SO_2), non-methane volatile organic compounds (NMVOC) and particulate matter (IPCC 1996; IPCC 2006). Heavy metals such as zinc (Zn), cadmium (Cd), nickel (Ni), copper (Cu), selenium (Se) and chromium (Cr), inorganic compounds such as ammonia, organic compounds such as benzene, waste heat etc are other pollutants associated with combustion of diesel and their emissions are obtained from the Ecoinvent database (Ecoinvent v2, 2010). Emissions from diesel combustion were calculated using Equation 3.16 (IPCC 1996, IPCC 2006);

$$Emissions = F_c * EF_G \quad \text{.....3.16}$$

Where;

F_c = amount of fuel combusted (TJ)

EF_G = emission factor of a gas (kg gas/TJ), default values of some gases are provided by IPCC 1996, IPCC 2006 as depicted in Table 3.10.

Table 3. 10: 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: Adapted from IPPC (1996), IPCC (2006)

3.7.5 Emissions from Burning Bagasse in Boilers

Bagasse is burned in boilers to produce steam for power generation for plant operations. Burning of bagasse in boilers is a source of carbon dioxide (CO_2), carbon monoxide (CO), Methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), sulphur oxide (SO_2), particulates, heavy metals such as zinc (Zn), cadmium (Cd), arsenic(As), copper (Cu), lead (Pb) and chromium (Cr), inorganic compounds such as ammonia and phosphorus, organic compounds such as benzene and toluene (Eshton, 2012). Emissions due to burning of bagasse in boilers were determined by using Equation 3.17. Emission factors for these substances are depicted in Table 3.11.

$$Emissions = B_b * EF_S \quad \text{.....3.17}$$

Where:

B_b = quantity of bagasse combusted per ha (kg/ha)

EF_S = emission of a substance in kg per kg bagasse (kg/kg bagasse)

Table 3.11: Emissions 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 v2 (2010)

3.8 Calculation of Energy Consumption

The lifecycle energy balance was used to measure bioethanol energy efficiency. The study considered the energy flows of the entire chain of bioethanol production and the energy consumption were estimated, including feedstock production, bioethanol conversion, and transportation. To calculate the lifecycle energy balance, fossil fuel inputs and renewable energy inputs were determined for all processes in the bioethanol production chain.

3.8.1 Energy Input in Cultivation Phase

For energy requirement during cultivation phase, the study considered various substances used in land preparation, planting and crop management. The study estimated energy input in production of chemicals (fertilizer, herbicides, pesticides and insecticides), production of cane seeds and the usage of diesel in tillage and transportation. Equation 3.18 was used to calculate the energy requirement of these activities. The energy coefficients for inputs in cultivation phase are shown in Table 3.12.

$$Energy = M_S * EF_C \quad \text{.....3.18}$$

Where;

Energy = energy input (MJ/ha)

M_S = amount of substance/chemical (kg/ha/yr)

EF_C = Energy coefficient (MJ/ha)

Human labour input is another activity in cultivation phase. 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 the year 2014 was 17.2% while that of renewable was 82.8%, obtained from International Energy Agency energy statistics (IEA, 2014)

Table 3.12: Energy coefficients for inputs in cultivation phase

Particulars	Value	Units
Nitrogen (N) production[a]	56.3	MJ/kg
Phosphorus (P_2O_5) production[a]	7.5	MJ/kg
Potash (K_2O) production[a]	7	MJ/kg
Herbicide production[a]	355.6	MJ/kg
Sugarcane seeds production[a]	0.02	MJ/kg
Insecticide production[b]	358	MJ/kg
Human labour[c]	7356.8	MJ/ha
Diesel use (land tillage)[d]	43.33	MJ/kg
Diesel (transportation)[d]	43.33	MJ/kg

[a] Energy coefficients cited from Khatiwada *et al*.(2016)
[b] Energy coefficients cited from Macedo *et al*.(2008)
[c] Calculated energy coefficient
[d] Energy coefficients cited from IPCC (1996)

3.8.2 Energy Input/Output in Industrial Phase

Industrial phase in bioethanol production involves milling, bioethanol conversion, power cogeneration from bagasse and treatment of wastewater in waste stabilization ponds. Chemicals, steam and electricity are the major inputs in milling and bioethanol conversion. Bagasse provides energy (steam and electricity) for milling and bioethanol production processes. Equation 3.19 was used to calculate the energy input/output for milling and bioethanol conversion processes. The energy coefficients for milling and bioethanol conversion processes are depicted in Table 3.13.

$$Energy = A_p * EF_p * Y_C \quad \text{.....3.19}$$

Where:

A_p = Amount of material/chemical (kg/tc)

EF_p = Energy coefficient (MJ/kg)

Y_C = Cane yield (tc/ha) = 65

Table 3.13: Energy coefficients for inputs in milling and bioethanol conversion

Substance	Energy coefficient (MJ/kg)
Lime production[a]	0.1
Bagasse combustion[b]	19.25
Sulphuric acid production[a]	0.11
Urea[a]	2.39
Yeast[a]	17.56

[a] Energy coefficients cited from Khatiwada *et al*.(2016)

Energy coefficients cited from Ramjeawon (2009)

3.10 Allocation Methodology

In the LCA methodology, allocations are proportionally made to share the accountability for life cycle resource (or energy) 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 cane industry. Bagasse is consumed internally as it is combusted in boilers 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). Therefore, only allocation of sugar and molasses was performed.

The study used economic allocation to partition the resource (energy) consumption and environmental burdens between sugar and molasses. This methodology used the market prices of co-products as parameters to partition the resource consumption and environmental burdens. Molasses is a low value product compared to sugar, thus this allocation methodology would encourage its use for bioethanol production (Khatiwada *et al*., 2016). Most importantly, economic allocation helps identify the most economically viable option on the use of co-products and also inform decision makers about the economic implications of devised policy (Nguyen & Gheewala, 2008; Khatiwada & Silveira, 2011).

In 2013/2014, the average market price of sugar was about US $ 988.2/tonne of sugar while for molasses was about US $ 57.4/tonne of molasses (KSB, 2014). This study adopted the findings of Gopal and Kammen (2009) on sugar and molasses prices in Brazil, India and Indonesia where there are molasses based bioethanol systems. In these countries, the price of sugar was found to be 5.5 times higher than that of molasses. Thus the price of molasses in Kenya in 2013/2014 was taken to be US $ 180/tonne. Equation 3.20 adapted from Khatiwada & Silveira (2011) is used to calculate the allocation ratio. The calculated partitioning ratios of sugar and molasses are presented in Table 3.14

$$Allocation\ ratio = \frac{Yield\ of\ sugar * Price\ of\ sugar}{Yield\ of\ molasses * Price\ of\ molasses} \quad \text{.....3.20}$$

Table 3.14: 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

The study used 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 these percentages. 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 is equivalent 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 is equivalent to a mass allocation of 60.3% for bioethanol and 39.7% for stillage.

3.11 Determination of Energy Balances

Energy balances deal with the saving of non-renewable fossil fuels compared to bioethanol in the entire production chain. Net energy value (NEV), net renewable energy value (NREV) and net energy yield ratio (NER) was used to evaluate the energy balance of bioethanol. The net energy value (NEV) of bioethanol was calculated as depicted in Equation 3.21:

$$NEV = E_F - E_T \quad \text{.....3.21}$$

Where E_F is the energy content of bioethanol and E_T is the total energy inputs.

The net renewable energy value (NREV) was calculated as shown in Equation 3.22:

$$NREV = E_F - NE_T \quad \text{.....3.22}$$

Where E_F the energy content of bioethanol and NE_T is the fossil fuel input

The net energy yield ratio (NER) was calculated as depicted in Equation 3.23:

$$\text{Net energy yield ratio (NER)} = \frac{\text{Energy content in bioethanol}}{\text{fossil energy input}} \quad \text{.....3.23}$$

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 indicate that low amount of fossil fuels are required to produce a particular amount of bioethanol as per the functional unit. Negative value of NEV indicate that the total energy consumption (both fossil and renewables) to produce the bioethanol is higher than its final energy content. The implication of this is that the bioethanol production is not a viable process and vice versa.

3.12 Determination of Life Cycle Costing

3.12.1 Production costs

The production costs considered expenses at each stage in the life cycle of each of the bioethanol system studied. The costs were that of direct farm inputs which included diesel fuel, human labour agrochemicals. Production costs also included chemicals used in the milling and bioethanol conversion processes. The agriculture machines are hired at given rates for each of the conventional methods in land preparation. The quantities per hectare and the unit prices for inputs or operations for sugarcane molasses-based bioethanol and sweet sorghum stalk juice-based bioethanol are

depicted in Appendix V and Appendix VI, respectively. The calculation methodology of machinery hire costing for land preparation is demonstrated in Appendix VII.

3.12.2 External Environmental Costs

The external environmental costs of production of bioethanol considered in this study were estimated based on EPS version 2000 model. The EPS model is simple, flexible and applicable globally. The model provides external environmental costs for air, water and soil pollutants as well as resource consumption. This study considered environmental costs for air pollutants, mainly the GHG's. The adaptation of the model to Kenya is based on the hypothesis that the willingness to pay (WTP) is proportional to the per capital income (GDP expressed in terms of purchasing power parity). The WTP for Kenya is expressed by Equation 3.24 adapted from Nguyen & Gheewala (2008).

$$WTP_{Kenya} = WTP_{Sweden} * \frac{\text{PERCAP}-\text{GDP(PPP)Kenya}}{\text{PERCAP}-\text{GDP(PPP)Sweden}} \quad \ldots\ldots\ldots\ldots 3.24$$

Where *PERCAP-GDP (PPP)* $_{Kenya}$ = USD 1,800 and *PERCAP-GDP (PPP)* $_{Sweden}$ = USD 40,300 [CIA, 2014].

The ratio $\frac{\text{WTP Kenya}}{\text{WTPSweden}}$ also called "income elasticity of WTP" is thus derived as 0.045. The original external environmental costs for pollutants and resource consumption from EPS model are expressed in EURO/kg. Equation 3.25 was used to convert the external environmental costs from EURO/kg to Kshs equivalent/kg.

Kshs equivalent/kg

= EURO/kg * Av.exchange rate * income elasticity of WTP.....3.25

External environmental costs per unit of pollutants and fossil fuel use are shown in Table 3.15, in both EURO/kg emission and Kshs/kg emission. An average exchange rate of 1 Euro to Kshs 116 was used for this study, based on that of Central Bank of Kenya, 2014.

Table 3.15: Environmental costs per unit of pollutants and fossil fuel use

Environmental categories	Units	Euro per unit of pollutant	Kshs per unit of pollutant
Fossil fuel			
Diesel oil use	MJ	5.06E-01	2.64E+00
Emissions			
CO_2[air]	kg CO_2	1.08E-01	5.64E-01
NO_x[air]	kg NO_x	2.13E+00	1.11E+01
SO_2[air]	kg SO_2	3.27E+00	1.71E+01
NH_3[air]	kg NH_3	1.96E+00	1.02E+01
VOC [air]	kg VOC	2.14E+00	1.12E+01
CO [air]	kg CO	3.31E-01	1.73E+00
CH_4[air]	kg CH_4	2.72E+00	1.42E+01
N_2O [air]	kg N_2O	3.83E+01	2.00E+02
PM [air]	kg PM	3.60E+01	1.88E+02

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the findings of LCA of bioethanol production from sugarcane molasses and from sweet sorghum stalk juice. The results are presented following the guidelines recommended by ISO 140040/44 (2006).

4.2 Goal and Scope of the Study

The goal of this study is to evaluate energy balances and the potential environmental impacts of bioethanol production from sugarcane molasses and sweet sorghum stalk juice in Kenya. The functional unit was defined as one litre (1 L) of anhydrous bioethanol produced.

4.3 Life Cycle Inventory Analysis

This section presents the system boundary, field and literature data collected as well as the list of environmental emissions observed for each of the bioethanol system studied.

4.3.1 System Boundary for Sugarcane Molasses Bioethanol

The system boundary for the sugarcane molasses bioethanol system is presented in Figure 4.1. The processes modelled are sugarcane farming, transportation of the cane, sugarcane milling, conversion of molasses to bioethanol, power cogeneration, production of agrochemicals and industrial chemicals.

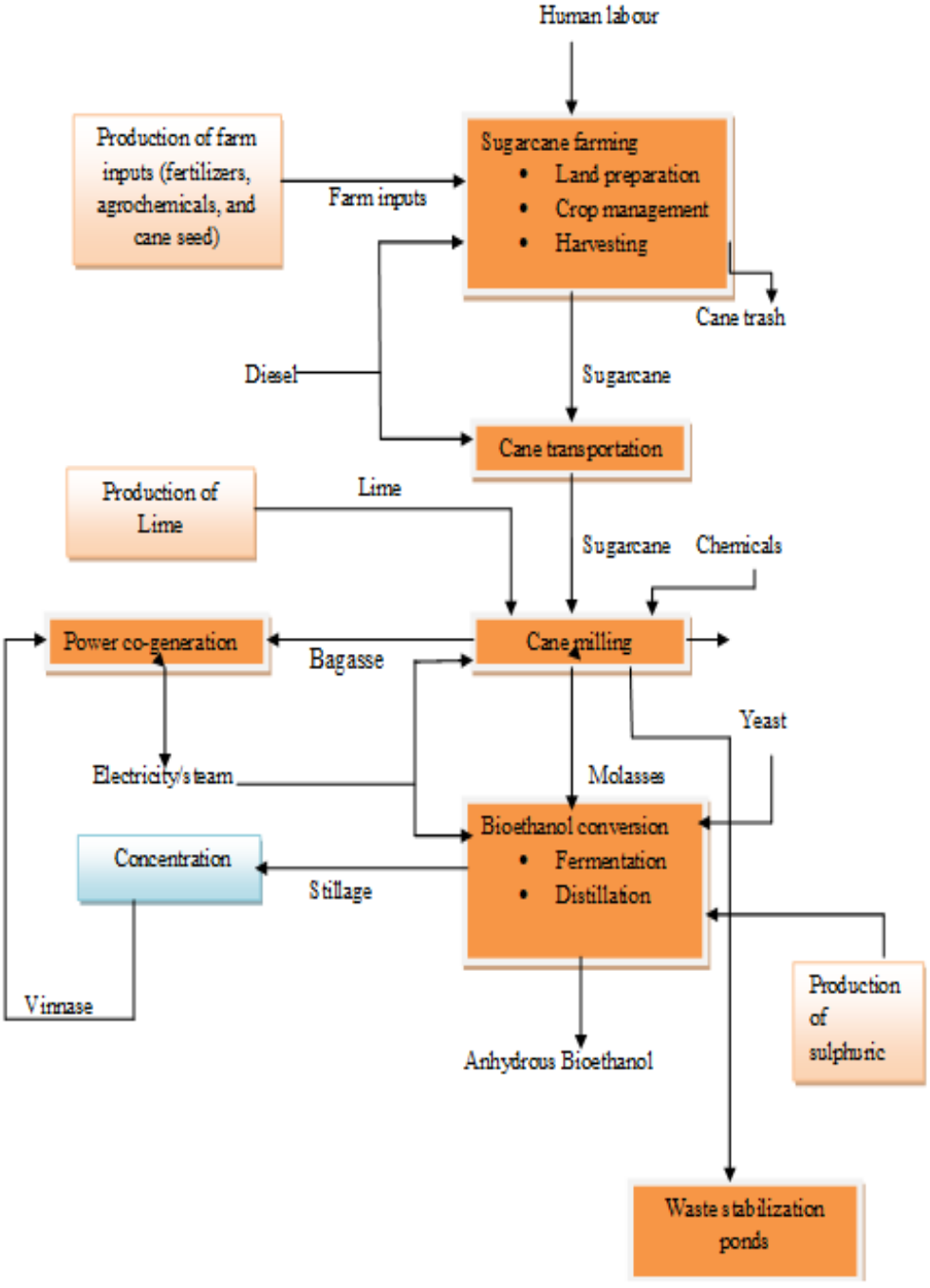

Figure 4.1: System boundary for sugarcane molasses based bioethanol

4.3.1.1 Sugarcane Farming and Harvesting

Lifecycle of molasses based bioethanol was found to start from land preparation prior to sugarcane planting. Land preparation was carried out using agricultural machineries through conventional methods and was found to consume 64.6 L/ha of diesel. The conventional methods include ploughing, harrowing and furrowing. Human labour (12 man-days/ha) was also required in land preparation. Duration of land preparation was 30 days. Before sugarcane planting, 30 tonnes of sugarcane seeds are first treated with 172 mls of a pesticide (Confidor) and 2 L of a fungicide (Follicur) diluted in about 600 litres of water. This amount of seed cane is planted in 5 ha and translates to 6 tonnes seed cane/ha. During planting, 250 kg of NPK Blend 1 fertilizer is applied per hectare. The NPK content of the Blend 1 fertilizer for planting is 12:30:7. All planting activities were undertaken manually requiring human labour of 12 man-days/ha. In ratoon management, 250 kg of NPK Blend 2 fertilizer is applied per hectare. The NPK content of the Blend 2 fertilizer for crop management is 26:0:20. About 3.9 L/ha of 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 harvesting is done 18 months after field planting and then once a year for three ratoons (5 year cycle period). The yield for each of the ratoons depends on ratoon management. For this study, sugarcane yield was taken to be 65 t/ha. During harvesting cane stalks are cut removing the leaves and tops termed as cane trash. The cane trash is lined in the fields along with root stumps to be used as organic fertilizer. Human labour for harvesting was 40 man-days/ha. Sugarcane is 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 tractor was found to be 1.6 km/L and that of the trucks to be 2 km/L. The turn round distance (factory-farm-factory) was found to be 44 km. Taking an average value of fuel economy of 1.8 km/L, the fuel used for sugarcane transportation per ha is 60.5 L. The data collected from the field for sugarcane farming are presented in Table 4.1

Table 4.1: Data for sugarcane farming

Item	Units	Amount
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	64.6
Diesel use for transportation	L/ha	60.5

4.3.1.2 Sugarcane Milling

Sugarcane milling involves a series of process stages which include cane preparation, juice extraction through a diffuser, clarification, boiling, seeding and centrifuging to obtain crystal sugar. During milling process, electricity, steam and chemicals are the major inputs. Sugar is the main product which is packed and transported for distribution. Molasses, filter cake, bagasse are the by-products. The filter cake is recycled back to the diffuser while the molasses is converted to bioethanol in distillery plant. The bagasse is combusted in boilers to produce process energy (steam and electricity) which is used in the plant with the excess electricity being sold to the national grid. Mumias Sugar Company make additional revenue from its bagasse-based co-generation plant. The company generates 34 MW of electricity, 8 MW for its internal use and the remaining sold to Kenya Power Company based on a long-term power purchasing agreement. Thus the co-generation plant enable Mumias Sugar Company to be energy self-sufficient and also it contributes to mitigating environmental pollution as it replaces the fossil-based energy pollution while satisfying the energy demand of the country. The wastewater from the milling process is taken to the oxidation ponds for treatment. Chemicals used during production of sugar include sulphur, flocculants and lime. Sulphur bleaches the sugar as well as forming sulphuric acid which together with the flocculants and lime assist in

clarification. From the data collected from the field, it was found that one tonne of sugarcane yields about 10% sugar, 37% bagasse, 3% molasses and 4% filter cake. Data for sugarcane milling are presented in Table 4.2.

Table 4.2: Data for inputs/outputs at sugarcane milling

Item	Units	Amount
Lime, $Ca(OH)_2$	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

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

4.3.1.3 Bioethanol Conversion

In the Distillery Plant, molasses is first pre-treated to dilute it and then hydrolyzed with 4% (w/w) sulphuric acid to make it fermentable. The conversion of molasses to bioethanol consists of two main steps. First, molasses is fermented with yeast (in presence of nutrients like urea) yielding dilute bioethanol at a concentration of about 9.5% in water. Second, the fermented mash is passed through distillation to yield concentrated bioethanol at 95% (w/w) in water. Vinnase, the by-product of bioethanol conversion, is dewatered up to 40-50% and mixed with bagasse in the ratio of 95:5 and is combusted in specially designed boilers. The wastewater for this phase is treated in waste stabilization ponds. Mumias Sugar Company generates 1500 m^3/day of wastewater. The inputs and outputs during the conversion of molasses to bioethanol are presented in Table 4.3.

Table 4.3: Data for inputs and outputs during bioethanol conversion

Item	Units	Amount
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[b]

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

4.3.2 System Boundary for Sweet Sorghum Stalk Juice-based Bioethanol

The System boundary for the sweet sorghum stalk juice bioethanol is presented in Figure 4.2. The processes modelled include sweet sorghum farming, transportation of the stalk, milling of the sweet sorghum stalk, conversion of stalk juice to bioethanol, power cogeneration, production of agrochemicals and industrial chemicals.

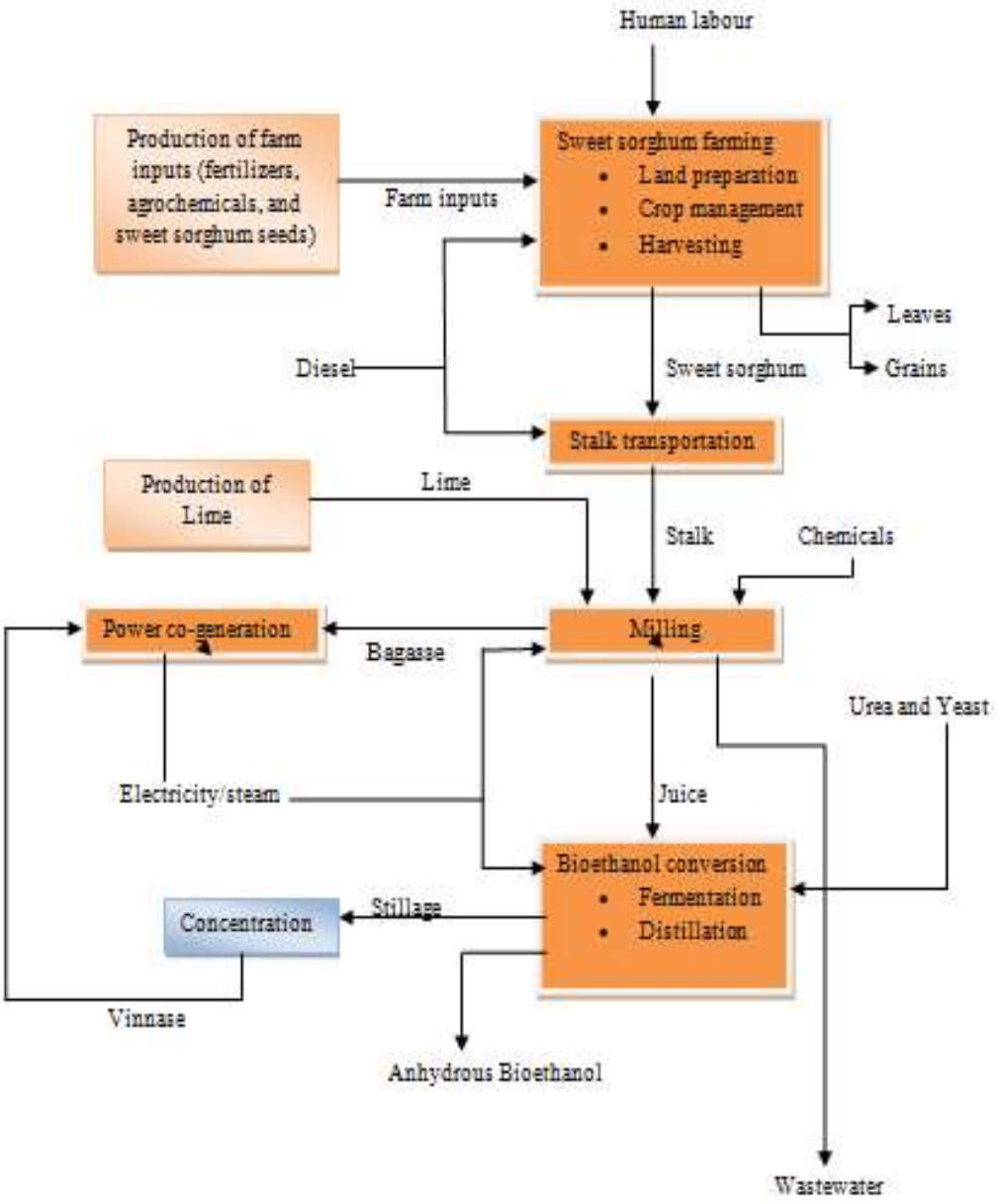

Figure 4.2: System boundary for sweet sorghum stalk juice based bioethanol

4.3.2.1 Sweet Sorghum Farming and Harvesting

Sweet sorghum farming/cultivation 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 6.4 kg of sweet sorghum seeds are used. Planting require a human labour of 24 man-days/ha. During planting, 120 kg of NPK Mavuno fertilizer is applied per hectare. Mavuno fertilizer NPK ratio 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, 120 kg of Mavuno top dress fertilizer (120 kg/ha) is applied per hectare. The NPK content of this fertilizer is 26:0:0 which translates to 31.2 kg/ha N fertilizer. During crop management, weeding is done manually by human labour for 15 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. It was assumed in this study that sweet sorghum leaves are left to rot in the farm and used as organic fertilizer. The study adopts a stalk yield of 55.88 ton/ ha/yr for the seed crop and ratoon crop reported by Rural Industries Research & Development Corporation, RIRDC (2013). Sweet sorghum harvesting requires a human labour of 48 man-days/ha. The study assumes further that 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 4.4.

Table 4.4: Data for sweet sorghum farming

Item	Units	Amount
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

[a] RIRDC(2013)

4.3.2.2 Sweet Sorghum Stalk Milling

Sweet sorghum stalk milling involves passing the stalks through a series of three roller mills to extract the juice. In milling process inputs include electricity, steam, chemicals, and the sweet sorghum stalks. The chemicals used include phosphoric acid, a flocculant and lime which assist in clarification of the juice. Outputs include juice, mud, bagasse and wastewater. The bagasse is combusted in boilers to generate the steam and electricity to be used in the plant. Excess electricity is sold to the national grid. The same model of bagasse-based co-generation plant similar to that of Mumias Sugar Company is assumed accruing the same benefits. This study assumes all the bagasse produced is combusted in boilers to produce steam. The wastewater is treated in waste stabilization ponds. Table 4.5 depicts the data for sweet sorghum milling.

Table 4.5: Data for sweet sorghum milling

Item	Units	Amount [a]
Lime	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)

4.3.2.3 Bioethanol Conversion

In the conversion of bioethanol from the sweet sorghum stalk juice, 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. Then, the fermented mash is passed through distillation to yield concentrated bioethanol of 95% (w/w) in water. Stillage which is the product that remains after fermentation is dewatered and then combusted together with bagasse in specially designed boilers. The inputs and outputs during the conversion of juice to bioethanol are presented in Table 4.6.

Table 4.6: Data in bioethanol conversion for sweet sorghum

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

[a] RIRDC (2013)

4.4 Inventory Results

4.4.1 Results for Sugarcane Molasses Bioethanol

The study performed an inventory analysis to evaluate life cycle emissions in the production of bioethanol from the sugarcane molasses. Emissions are from processes such as sugarcane farming, sugarcane milling, bioethanol conversion, power cogeneration and wastewater treatment. Emissions from cultivation of sugarcane are shown in Appendix III (C-1). It was found the key emissions to air per 1 ha of sugarcane field were 70 kg of CO_2, 0.6 kg of NH_3, 0.2 kg of NO_x, 0.15 kg of CO, 0.1 kg of SO_2, 0.1 kg of N_2O and 0.1 kg of particulates. Emissions to surface waters per 1 ha of sugarcane field were found to be 1.7 kg of Total-N and 0.04 kg of Total-P while the major emission to agricultural soils was 1.5 kg of Zn. Emissions to agricultural soils due to use of herbicides and pesticides were atrazine (3.33E-01 kg/ha), aldrin (1.26E-01 kg/ha) and glyphosate (1.13E-02 kg/ha).

Emissions from the use of diesel in farm machinery and transportation are shown in Appendix III (C-2). The use of diesel in farm machinery and transportation per 1 ha of sugarcane field released are 400 kg of CO_2, 2.66 kg of CO, 3.4 kg of NO_x, 1.87 kg of SO_2 and 2.01 kg of particulates. Emissions from combustion of bagasse in boilers are presented in Appendix III (C-4). Combustion of bagasse in boilers was found to release 10.5 kg NO_x, 1.5 kg of CH_4 and 1.36 kg of particulates per 1 ha of sugarcane field. The study found the major emissions released from bioethanol conversion as 132 kg/ha of CO_2 and 1020 MJ/ha of heat. About 100 substances were found to be emitted as depicted in Appendix III (C-7). The overall life cycle emissions in the production of bioethanol from molasses from 1 ha of sugarcane field were found to be 138 kg of CO_2, 9.0E-02 kg of NO_x, 1.0E-2 kg of SO_2, 4.2E-02 kg NH_3, 9.7E-03 kg of N_2O and 18.1 MJ of waste heat.

4.4.2 Results for Sweet Sorghum Stalk Juice Bioethanol

Emissions from sweet sorghum cultivation are shown in Appendix IV (D-1). The emissions released to air from cultivation of 1 ha of sweet sorghum field include 790 kg of CO_2, 1.14 kg of N_2O, 5.32 kg of NH_3 and 1.26 kg of NO_x. The emissions

released to water from cultivation of 1 ha of sweet sorghum field were 1.26 kg of Total-P and 1.60 kg of Total-N. Emissions to agricultural soils from cultivation of 1 ha of sweet sorghum field were 3.26 kg of Cu, 3.0 kg of Ni, 1.66 kg of Cr and 1.86 kg of aldrin. Appendix IV (D-2) shows the emissions from use of diesel in land preparation before planting and in transportation of farm outputs per 1 ha of sweet sorghum field. Use of diesel in land preparation and transportation of farm outputs released 252 kg of CO_2, 2.10 kg of NO_x, 1.18 kg of SO_2 and 1.26 kg of particulates.

Emissions from combustion of bagasse from 1 ha of sweet sorghum field in boilers are presented in Appendix IV (D-4). Emissions released due to combustion of bagasse in boilers were found to be 10.2 kg of NO_x, 1.3 kg of CH_4, 0.1 kg of N_2O and 1.3 kg of particulates. The emissions due to bioethanol conversion from sweet sorghum stalk juice from 1 ha of sweet sorghum field are shown in Appendix IV (D-5). The major emissions released due to bioethanol conversion include 1.64E+04 kg of CO_2, 7.71 kg of NO_x, 3.52 kg of particulates and 3.43 E+04 MJ of waste heat. The study found about 91 Pollutants were released in the overall life cycle production of bioethanol from sweet sorghum stalk juice from 1 ha of sweet sorghum field as depicted in Appendix IV (C-6). The overall life cycle emissions to air in the production of bioethanol from sweet sorghum stalk juice from 1 ha of field were 1.75E+03 kg of CO_2, 5.66 kg NO_x, 2.74 kg of particulates, and 7.13 kg of Total-N, 7.4 kg of Cr and 2.33E + 04 MJ of waste heat.

4.5 LCIA of Sugarcane Molasses Bioethanol

4.5.1 Global Warming/GHG Emissions

Greenhouse gas (GHG) emissions results of sugarcane molasses-based bioethanol production are presented in Table 4.7. The estimated net GHG emissions are 270.88 g CO_{2eq}/L bioethanol for the complete lifecycle chain. Sugarcane production phase is the major contributor to GHG emissions emitting about 78% of the total. The rest, 22% of the GHG emissions are emitted at the industrial phase. In sugarcane production phase, these emissions are due to production and application of chemical fertilizers, use of diesel in tillage and transport of farm outputs, production of herbicides, production of

pesticides and human labour. Industrial phase include sugarcane milling, power co-generation, bioethanol conversion and wastewater treatment**.**

Table 4.7: GHG emissions from sugarcane molasses-based bioethanol

Process	**Emissions (g CO_{2eq}/L bioethanol)**
Sugarcane production	**212.5**
Fertilizers	
Nitrogen fertilizer production	31.60
Phosphorus fertilizer production	2.19
Potash fertilizer production	4.26
Herbicide production	10.93
Insecticide/Pesticide production	1.41
Sugarcane seeds production	1.08
N_2O emissions (direct & indirect)	67.89
Human labour	47.62
Diesel (tillage)	23.38
Diesel (transportation)	22.14
Cane milling	**0.51**
Lime production	0.51
Co-generation	**49.19**
Bagasse combustion	49.19
Bioethanol conversion	**8.22**
Sulphuric acid production	0.77
Urea	7.40
Yeast	0.05
Wastewater treatment	**0.46**
Effluent treatment	0.46
Total emissions	**270.88**

Production of agrochemicals (fertilizers, herbicides, pesticides) contributes about 19% of the total GHG emissions with production of nitrogen fertilizer being the major contributor (14%). Addition of nitrogen fertilizers to soil results to soil emissions of N_2O which contributes 25% of the total GHG emissions. Diesel use in land tillage and farm outputs transportation contributes about 17% of the total GHG emissions. Diesel is a fossil fuel and on combustion emits greenhouse gases. Sugarcane milling and wastewater treatment contribute insignificant GHG emissions i.e. 0.19% and 0.17%

respectively of the total GHG emissions. In case of sugarcane milling, bagasse combustion in boilers is the energy source, a renewable energy resource. In this study, it was assumed that biomass based CO_2 is not included in the total GHG emissions. The emissions associated with human labour contribute about 18% of the total GHG emissions.

LCA of sugarcane molasses based bioethanol have been done in countries such as Thailand (Nguyen *et al.*, 2008, Silalertruksa & Gheewala, 2009), Nepal (Khatiwada & Silveira, 2009; Khatiwada & Silveira, 2011), Mexico (Garcia *et al*., 2011); Brazil (Macedo *et al*., 2008; Seabra *et al*., 2011), Tanzania (Eshton, 2012), Indonesia (Khatiwada *et al*., 2016), India (Soam et al., 2015), Ethiopia (Demissie & Gheewala, 2019; Gabisa *et al*., 2019). These authors reported the following GHG emissions per litre of bioethanol: Tanzania (423.0 g CO_{2eq}), Indonesia (616.5 g CO_{2eq}), India (696 g CO_{2eq}). Mexico (1250 g CO_{2eq}) and Nepal (432.5 g CO_{2eq}). In Thailand, Nguyen *et al*. (2008) and Silalertruska & Gheewala (2009) reported GHG emissions of about 3313 and 685 g CO_{2eq} per litre of bioethanol, 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. In Brazil, Macedo *et al*., (2008) and Seabra *et al*., (2011) reported GHG emissions of about 436 and 450 g CO_{2eq} per litre of bioethanol. All these previous results were higher than that obtained in this study (270.88 g CO_{2eq}). These results vary due to differences in farming practices, system boundaries, energy sources, allocation methodologies, conversion technologies, geographical regions and impact assessment model used. 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 use of coal as source energy in Thailand in the study by Silalertruksa & Gheewala (2009) contributed significant GHG emissions and it is observed to give similar results as study by Khatiwada *et al*. (2016) in Indonesia. In the studies by Eshton (2012) in Tanzania and Khatiwada & Silveira (2009) in Nepal, their results were similar and their difference to this study in GHG emissions is attributed to greenhouse gases emitted during irrigation. In the current study, sugarcane production was completely rainfed. In addition, cane burning in Tanzania and the production of biogas from wastewater in Nepal result in GHG emissions. The results of study by Nguyen *et al.* (2008) in Thailand are significantly

higher as the study assumed the stillage generated from fermentation of molasses is treated in the waste stabilization ponds resulting in CH_4 emissions. The result reported by Demissie & Gheewala (2019) was largely higher than that obtained in this study, but cultivation stage was the largest contributor as was observed in this study. 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. It should be noted that combustion of bioethanol was not in the scope of this study. The high GHG emissions reported by Garcia *et al*. (2011) were due to sugarcane burning to facilitate manual harvesting and the emissions due to land use change (LUC). Emissions due to LUC were the major contributors to the total GHG emissions in Mexico since the expansion of the bioethanol occurs on land of large carbon stock, the tropical rain forests. Macedo *et al*., (2008) and Seabra *et al*., (2011) reported slightly higher GHG emissions than that of this study and this can be attributed to sugarcane burning prior to harvesting. Soam *et al*., (2015) also reported a higher value of GHG emissions than that obtained in this study. This is due to use of electricity from the grid generated from fossil fuels, and also the use of fossil fuel for irrigation. In this study, there was 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.

4.5.2 Acidification Potential

In this study, acidification potential (AP) of the sugarcane molasses bioethanol was estimated at 0.313 g SO_{2eq} per litre of bioethanol produced. The acidification was due to atmospheric emissions of ammonia (NH_3), nitrogen oxides (NO_x) and sulphur dioxide (SO_2). As depicted in Figure 4.1, NH_3 is the major acidifying pollutant with a contribution of about 52%, followed by NO_x (40%) and SO_2 (8%) of total AP. Sugarcane farming and bioethanol conversion are the major sources of the acidifying

pollutants contributing to AP. The major source of NH_3 and SO_2 is sugarcane farming which accounts for about 94% of total NH_3 emissions and 58% of the total SO_2 emissions. NH_3 emissions are 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 due to the use of urea in bioethanol conversion which accounts for about 83% of total NO_x emissions.

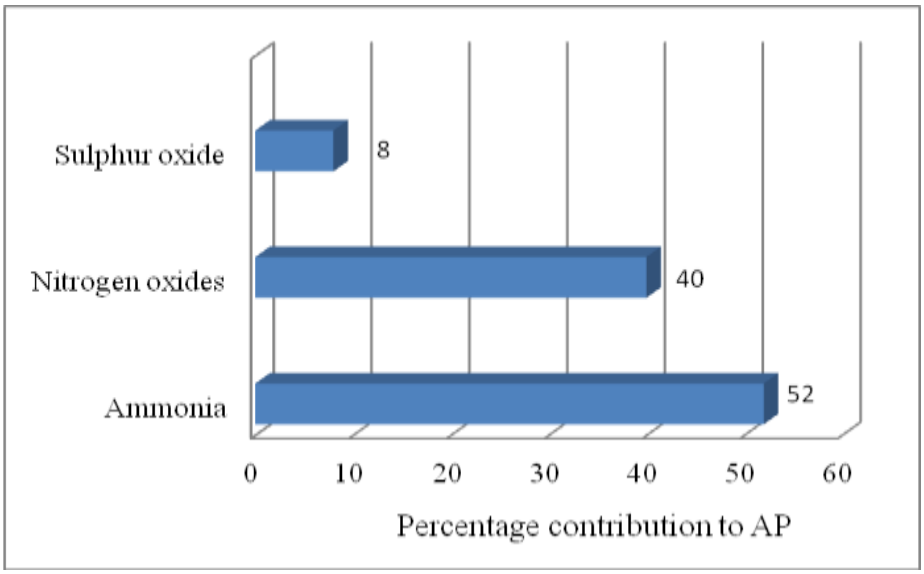

Figure 4.3: Acidification potential of sugarcane molasses bioethanol.

The AP obtained in this study was compared with results reported by Eshton (2012) in Tanzania, Silalertruksa and Gheewala (2009) in Thailand, and Demissie & Gheewala (2019) and Gabisa *et al.* (2019) in Ethiopia. Eshton (2012), Silalertruksa and Gheewala (2009), Demissie & Gheewala (2019) and Gabisa *et al.* (2019) reported AP of 11.9, 12.5, 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 previous studies. The higher value of AP reported by Silalertruksa and Gheewala (2009) is due to SO_2 emissions attributed to coal burning as well as NO_x emissions from sugarcane burning prior harvesting. Eshton (2012) also reported a higher AP value attributed to NO_x emissions from sugarcane burning before harvesting. The high AP value reported by Demissie & Gheewala (2019) was 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 is 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. In this study, there was no use of coal as a source of fuel, and also there was no sugarcane burning before harvesting. Thus this explains why a low AP value was obtained in this study.

4.5.3 Eutrophication Potential

Eutrophication is due to nutrient enrichment in both aquatic and terrestrial ecosystems. The obtained eutrophication potential (EP) of the sugarcane molasses-based bioethanol was about 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 contribute to eutrophication impact. Figure 4.2 depicts 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. Majority of NOx emissions in bioethanol conversion result from use of urea fertilizer to propagate yeast organisms for ethanol fermentation.

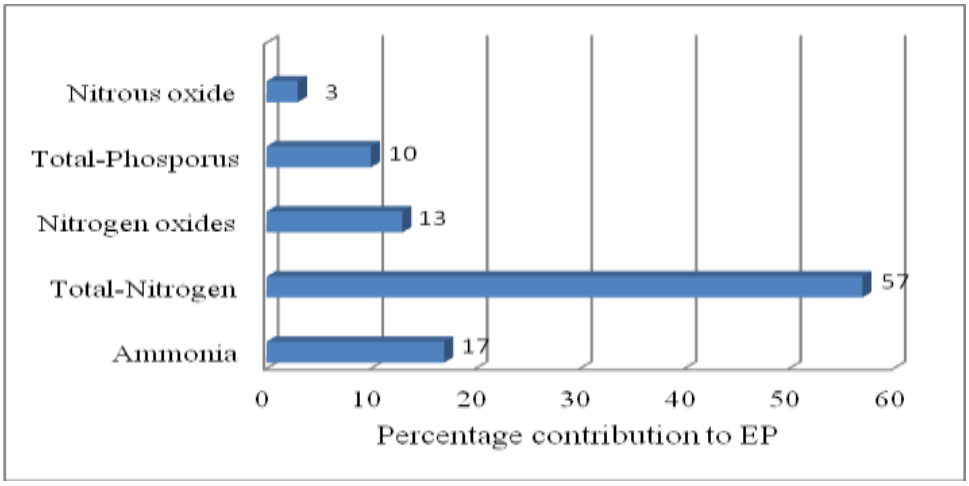

Figure 4.4: Eutrophication potential of sugarcane molasses bioethanol

The eutrophication impact obtained in this study (0.18 g PO_4^{3-} eq) was much lower compared to that reported by Eshton (2012) and that of Silalertruksa and Gheewala

(2009). The reported EP by Eshton (2012) and that of Silalertruksa and Gheewala (2009) were 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) were due to use of larger quantities of nitrogen and phosphate based fertilizers than that used in this study. Fertilizer application in Eshton (2012), Silalertruksa and Gheewala (2009) and this study were 260, 256 and 86 kg/ha respectively. In the study by Silalertruksa and Gheewala (2009), spent wash from bioethanol fermentation is treated in waste stabilization ponds which results in COD emissions, a source of eutrophication impact. Thus study by Silalertruksa and Gheewala (2009) reported a much higher EP value than Eshton (2012). In Demissie & Gheewala (2019) the use of light fuel oil and discharge of vinasse in the bioethanol plant was the largest contributor (92.3%) in eutrophication impact.

4.5.4 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. In this study, 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 4.3 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.

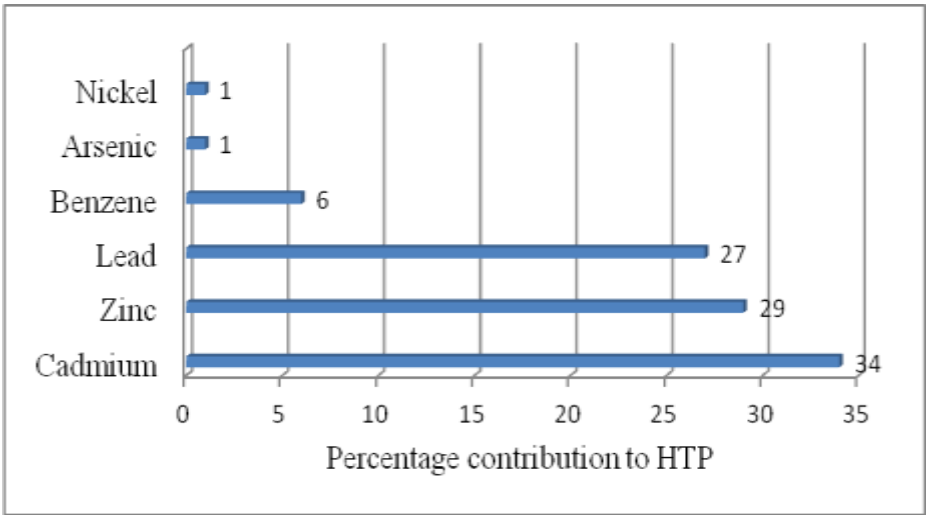

Figure 4.5: Human toxicity potential of sugarcane molasses bioethanol

The HTP result obtained in this study was compared with those reported by Eshton (2012), Silalertruksa and Gheewala (2009) and Gabisa *et al*. (2019). The HTP results reported by Eshton (2012), Silalertruksa and Gheewala (2009) and Gabisa *et al*. (2019) were 105, 19.11 and 93.07 g 1, 4-DCB eq per litre of bioethanol, respectively. The HTP obtained in this study was much lower than that obtained by Eshton (2012) since in this study there was no sugarcane burning before harvesting which result in emissions of heavy metals and particulates which contribute significantly to human toxicity. Silalertruksa and Gheewala (2009), in addition to not accounting emissions of heavy metals and particulates from sugarcane burning before harvesting, they did not account for emissions of the same from the use of fertilizers. Thus the reported HTP by Silalertruksa and Gheewala (2009) was significantly much lower than that obtained in this study. The HTP result 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.

4.5.5 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 depicted in Figure 4.4, ecotoxicity was found to be due to emissions of heavy metals and Atrazine. Zinc emissions were

found to contribute about 93% to the total ET. The emissions causing ecotoxicity were due to use of fertilizers, herbicides and pesticides.

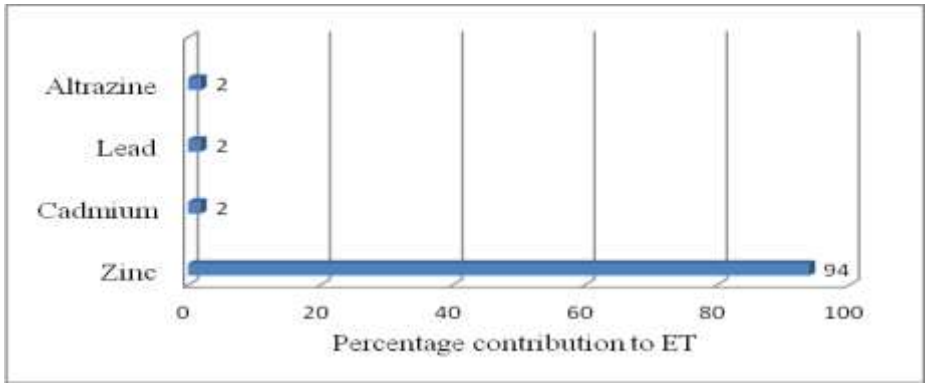

Figure 4.6: Ecotoxicity potential of sugarcane molasses bioethanol

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).

4.5.6 Photochemical Ozone Formation

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 4.5, this impact is due to the following emissions; carbon monoxide (CO), sulphur dioxide (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.

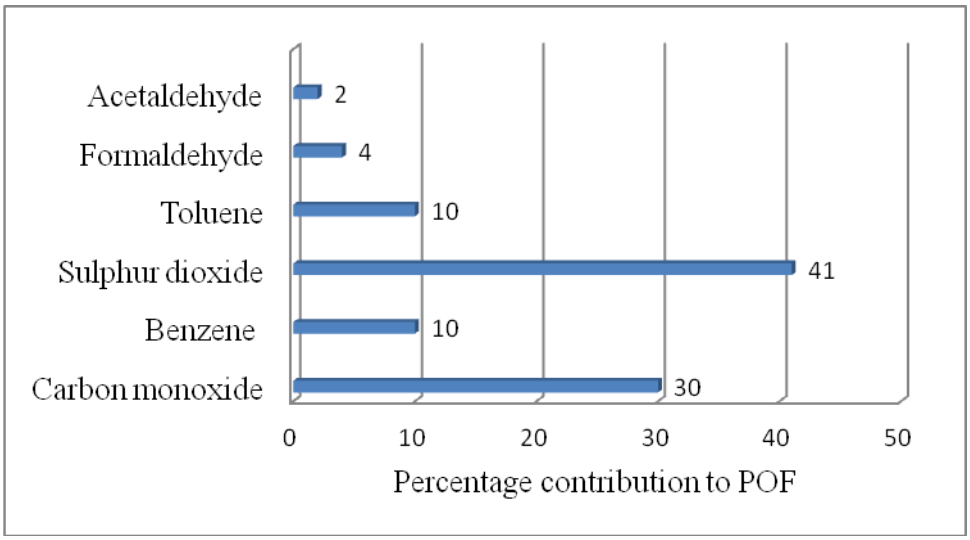

Figure 4.7: Photochemical ozone formation of sugarcane molasses bioethanol

4.6 LCIA of Sweet Sorghum Stalk Juice Bioethanol

4.6.1 Global Warming/GHG Emissions

The GHG emissions of the overall lifecycle of the sweet sorghum stalk juice-based bioethanol production are presented in Table 4.8. The net GHG emissions are estimated at 424.19 g CO_{2eq} per litre of bioethanol. The life cycle of sweet sorghum stalk juice based bioethanol can generally be divided into two phases i.e. sweet sorghum production phase and industrial phase. In sweet sorghum production phase, GHG emissions emanated from production of farm inputs (fertilizers, herbicides, pesticides and seeds), nitrogen fertilizer application, human labour and use of fossil diesel. The sub-processes considered in industrial phase included stalk milling, power co-generation and bioethanol conversion. Sweet sorghum production phase contributed 61% of the total emissions and the industrial phase contributed the rest.

Table 4.8: GHG emissions for sweet sorghum stalk juice-based bioethanol

Process	Emissions (g CO_{2eq}/L bioethanol)
Sweet sorghum production	**260.6308**
Fertilizers	
Nitrogen production	31.1783
Phosphorus production	7.3810
Potash production	1.5489
Herbicides production	10.9079
Seeds production	0.0018
N_2O emissions (direct & indirect)	75.8460
Human labour	88.4083
Diesel for tillage	24.0155
Diesel for transportation	21.3431
Stalk milling	**0.4102**
Lime production	0.4102
Co-generation	**142.6013**
Bagasse combustion	142.6013
Bioethanol conversion	**20.5497**
Urea	20.5308
Yeast	0.0189
Total emissions	**424.1920**

Production of farm inputs contributed about 20% of the total GHG emissions in sweet sorghum production phase while nitrogen fertilizers application, human labour and use of fossil diesel contributed 29, 34 and 17% respectively. The production and application of nitrogen fertilizers accounted for 41% of the total GHG emissions in sweet sorghum production phase and was noted to be the major contributor of the same in this phase. Bagasse combustion in boilers to generate steam and electricity (power co-generation) contributed 87% of the total GHG emissions in the industrial phase, bioethanol conversion 12.5% and stalk milling a partly 0.5%.

The GHG emissions obtained in this study was compared with that reported by Wang *et al*. (2014), Wang *et al*. (2015), Ding *et al*.(2017), Aguilar-Sachez *et al*. (2018) and Cai *et al*. (2013) who reported GHG emissions of about 699, 769, 532, 665 and 544

gCO_2eq per litre of bioethanol, respectively. These results are higher than that obtained in this study. The higher values reported by Wang *et al*. (2014) and Wang *et al*.(2015) than that obtained in this study is due to use of coal (a fossil fuel) in steam and electricity generation and the use of electricity from the national grid generated from fossil energy. In the study by Ding *et al*. (2017), the higher GHG emissions are due to use of higher amounts of nitrogen fertilizer (283 kg/ha) and fossil fuels. In Aguilar-Sachez *et al*. (2018) and Cai *et al*. (2013), the use of higher amounts of fertilizer results in higher GHG emissions. The use of bagasse as a source of fuel in this study results in lower GHG emissions. It should be noted in all studies, fertilizer production and use contribute significantly to GHG emissions.

4.6.2 Acidification Potential

The life cycle acidification potential of the sweet sorghum stalk juice bioethanol system was estimated to be about 2.05 g SO_2 eq per litre of bioethanol. As depicted in Figure 4.6, NH_3, NO_x and SO_2 are the emissions causing the acidification impact in the sweet sorghum stalk juice bioethanol system contributing 51, 43 and 5% respectively to the total acidification. These emissions come from sweet sorghum farming and bioethanol conversion mainly due to use of agrochemicals and fossil diesel. Sweet sorghum farming was found to contribute 95% NH_3, 10% NO_x and 70% SO_2. Bioethanol conversion contributed 4% NH_3, 90% NO_x and 30% SO_2.

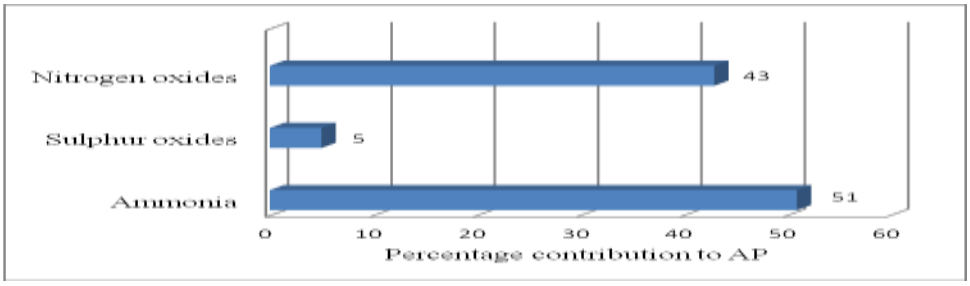

Figure 4.8: Acidification potential of sweet sorghum stalk juice bioethanol

This study made a comparison of AP obtained in this study to that reported by Wang *et al*. (2014), Wang *et al*. (2015), Ding *et al*. (2017) and Aguilar-Sachez *et al*. (2018) who reported AP of about 21.6, 12.43, 2.12 and 1.67 g SO_2eq per lire of bioethanol, respectively. The higher AP value reported by Wang *et al*. (2014) was due to steam

generation from coal, a fossil fuel. The higher value reported by Wang *et al*. (2015) was due to use of large amounts of N fertilizer (160 kg) compared to that used in this study (43.2 kg). The AP values reported by Ding *et al*. (2017) and Aguilar-Sachez *et al*. (2018) are comparable to that obtained in this study.

4.6.2 Eutrophication Potential

The calculated life cycle eutrophication of the sweet sorghum stalk juice bioethanol system is 1.46 g PO_4^{3-} eq per litre of bioethanol. The emissions causing eutrophication include Total-N, Total-P, NO_x, N_2O and NH_3, contributing 46, 26, 11, 3 and 13% respectively to the total eutrophication as depicted in Figure 4.7. It was observed that sweet sorghum production contribute 100% both Total-N and Total-P, which is due to use of fertilizers in this phase. NH_3, NO_x and N_2O were observed to be from sweet sorghum production (use of fertilizer) and bioethanol conversion (use of urea as a nutrient).

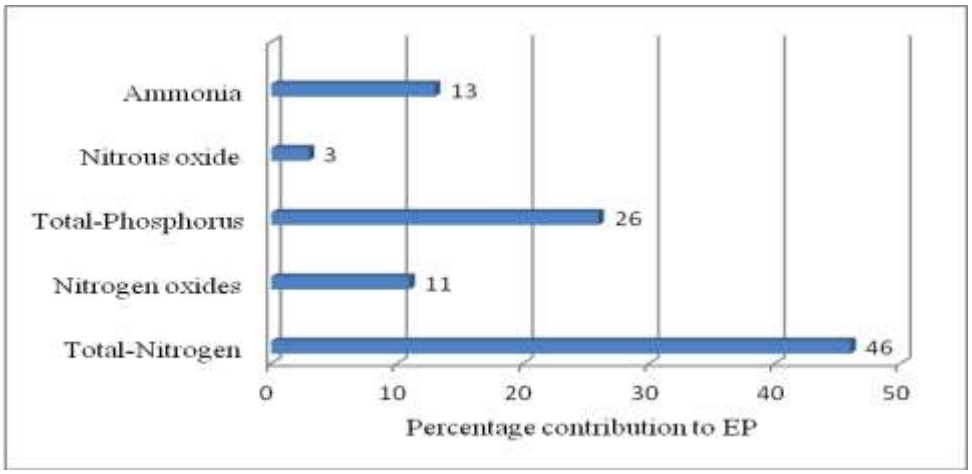

Figure 4.9: Eutrophication potential of sweet sorghum stalk juice bioethanol

The EP result obtained in this study was compared with that reported by Wang *et al*. (2014), Wang *et al*. (2015) and Aguilar-Sachez *et al*. (2018) who reported EP of about 4.3, 4.0 and 1.39 g PO_4^{3-}eq per litre of bioethanol, respectively. The slightly higher EP values than of this study in Wang *et al*. (2014) and Wang *et al*. (2015) is due use of large amount of chemical fertilizers. The EP reported by Aguilar-Sachez *et al*. (2018) is comparable to that obtained in this study.

4.6.3 Human Toxicity Potential

Results of human toxicity of Sweet sorghum stalk juice bioethanol system in this study are presented in Figure 4.8. The estimated human toxicity potential (HTP) was found to be 53 g 1, 4 DCB eq per litre of bioethanol. In this study the emissions found to cause human toxicity include NO_x, benzene, heavy metals, hydrogen fluoride, particulates and dioxins. NO_x, benzene and heavy metals emissions contributed 29, 38 and 30% respectively to the total HTP while hydrogen fluoride, particulates and dioxins contributed 1% each. The heavy metals include Ni, Cu, Cr (VI), Cd, As, Pb and Zn.

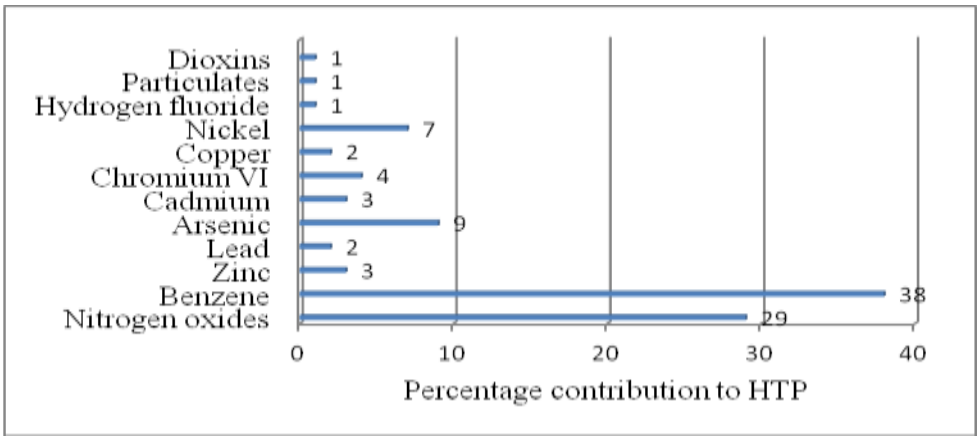

Figure 4.10: Human toxicity potential of SS stalk juice bioethanol

The result of HTP obtained in this study was compared with that reported by Wang *et al*. (2014), Wang *et al*. (2015), Ding *et al*. (2017) and Aguilar-Sachez *et al*. (2018) who reported HTP of about 180, 56.5, 18.6 and 185 g 1,4 DCBeq per litre of bioethanol. The higher HTP value reported by Wang *et al*. (2014) than of this study is due to use coal (a fossil fuel) for steam generation and agrochemicals production. In this study, there was no use of coal for steam generation. The HTP value of this study and that of Wang *et al*. (2015) are similar, this could be attributed to the latter of using only small amounts of coal. The lower HTP reported by Ding *et al*. (2017) could be attributed to low amounts of pesticide (0.27 kg/ha) used. The higher HTP value reported by Aguilar-Sachez *et al*. (2018) is due to use of larger amounts of pesticides (70 kg/ha), herbicides (6.8 kg/ha) and fertilizers (200kg/ha).

4.6.4 Ecotoxicity Potential

The ecotoxicity potential (ETP) of sweet sorghum stalk juice-based bioethanol was found to be 1.52 g 1, 4 DCB eq per litre of bioethanol. As depicted in Figure 4.9, ETP of sweet sorghum stalk juice based bioethanol is due to emissions of heavy metals. The heavy metals include Zn, Cr and Hg contributing 78, 11and 8%, respectively to the total ecotoxicity and Cu, As and Pb which contribute 1% each.

The ETP obtained in this study was compared with that reported by Wang *et al*. (2014), Wang *et al*. (2015) and Aguilar-Sachez *et al*. (2018) who reported ETP of about 7.2, 2.22 and 3.65 g 1, 4 DCBeq per litre of bioethanol. The higher ETP values reported by Wang *et al*. (2014) and Wang *et al*. (2014) than that of this study is due to Hg emissions from fossil energy combustion, and emissions of the same to soil from herbicides and pesticides. The ETP value reported in Wang *et al*. (2014) higher than that Wang *et al*. (2015) due to a large amount of coal used in the former. The higher ETP value reported by Aguilar-Sachez *et al*. (2018) is due to use of larger amounts of herbicides and pesticides.

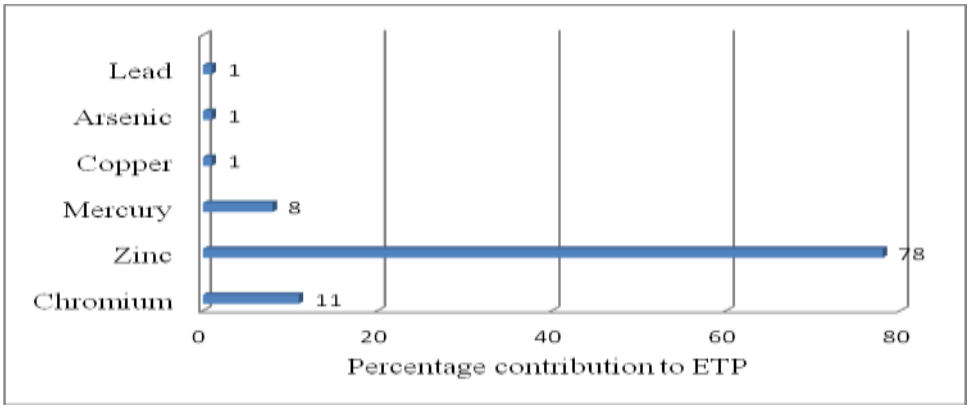

Figure 4.11: Ecotoxicity potential of sweet sorghum stalk juice bioethanol

4.6.5 Photochemical Ozone Formation

The calculated photochemical ozone creation potential (POCP) of the sweet sorghum stalk juice based bioethanol is 1.55E-02 g ethene eq per litre of bioethanol. As depicted in Figure 4.10, the emissions influencing this impact include CO, SO_2, benzene, toluene, formaldehyde, acetaldehyde and non-methane volatile organic

compounds (NMVOCs) contributing 28, 33, 15, 14, 5, 3 and 1% respectively, to the total POCP. The two major emissions, CO and SO_2 contributing to POF are due to use fossil diesel in cultivation of sweet sorghum and transportation of farm outputs.

Previous studies on sweet sorghum stalk juice bioethanol system by Wang *et al*. (2014), Wang *et al*. (2015), Ding *et al*. (2017) and Aguilar-Sachez *et al*. (2018) reported POCP values of about 0.56, 0.146, 0.23 and 0.09 g ethene eq per litre of bioethanol, respectively. Wang *et al*. (2014) and Wang *et al*. (2015) reported higher POCP values than that of this study due to emissions of SO_2 from fossil fuel combustion. Higher amounts of coal was used in Wang *et al*. (2014) than in Wang *et al*. (2015), hence the former reporting a higher POCP value than the latter. The slightly higher POCP value reported by Aguilar-Sachez *et al*. (2018) is due to use of larger amounts of pesticides (70 kg/ha). The higher POCP value reported by Ding *et al*. (2017) is due to high use of diesel in transportation and high use of fertilizers.

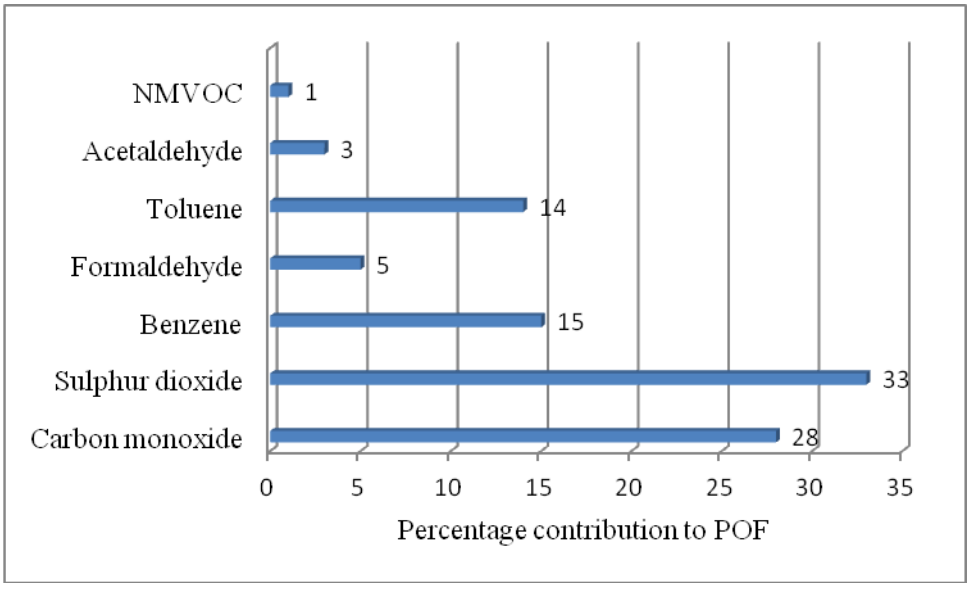

Figure 4.12: Photochemical ozone formation of sweet sorghum stalk juice bioethanol

4.7 Energy Balances Results

4.7.1 Energy Balances of Sugarcane Molasses-Based Bioethanol

Lifecycle energy balance results of bioethanol production from molasses are presented in Table 4.9. This Table shows the energy inputs (fossil and renewable) in cane cultivation, cane transportation, cane milling and bioethanol conversion. Production of chemicals inputs in farming, transportation, milling and bioethanol conversion consume fossil energy while steam and electricity generation consume renewable energy. The total energy consumption is estimated at 17.32 MJ per litre of bioethanol produced. The renewable energy contributes about 92% of the total energy consumption with most of the operations run with use of fuel bagasse combusted in boilers to generate steam and electricity.

The net energy value (NEV) for sugarcane molasses-based bioethanol has a positive value of 3.88 MJ/L bioethanol. This indicates that the total energy (fossil and renewable) required to make molasses based bioethanol is less than its energy content. The net renewable energy value (NREV) has a high positive value of 19.75 MJ/L bioethanol, indicating that the amount of fossil fuels used in the production cycle of the bioethanol is quite low, about 8.4% of total energy consumption. The net energy ratio (NER) obtained has a positive 14.62. This again indicates that a low amount of fossil energy is used to produce a renewable energy. The positive values of NEV and NREV indicate that the production of the molasses based bioethanol requires less non-renewable energy. As indicated in Figure 4.11, cane milling leads in energy consumption at 49% of the total energy consumed, followed by bioethanol conversion at 39%. In milling there are a number of processes involved in sugar production requiring large amount of steam and electricity. High energy consumption is also observed in bioethanol conversion, this is due to energy used in molasses fermentation, distillation and dehydration of bioethanol.

Table 4.9: Energy consumption and balances of sugarcane molasses bioethanol

Process	Fossil inputs (MJ/L bioethanol)	Renewable energy inputs (MJ/L bioethanol)
Cane cultivation		
Fertilizer		
Nitrogen production	0.4481	
Phosphorus production	0.0126	
Potash production	0.0420	
Herbicide production	0.1554	
pesticide production	0.0174	
Sugarcane seeds production	0.0135	
Human labour	0.1419	0.683
Diesel (tillage)	0.3138	
Cane transportation		
Diesel (transportation)	0.2939	
Cane milling		
Lime production	0.0007	
Electricity		0.280
Steam		8.234
Bioethanol conversion		
Sulphuric acid	0.0004	
Urea	0.0096	
Yeast	0.0018	
Electricity		1.584
Steam		5.085
Total energy	1.4511	15.866
Total input energy	17.32	
Energy content of bioethanol	21.2	
Net energy value (NEV)	3.88	
Net renewable energy value (NREV)	19.75	
Net energy ratio (NER)	14.62	

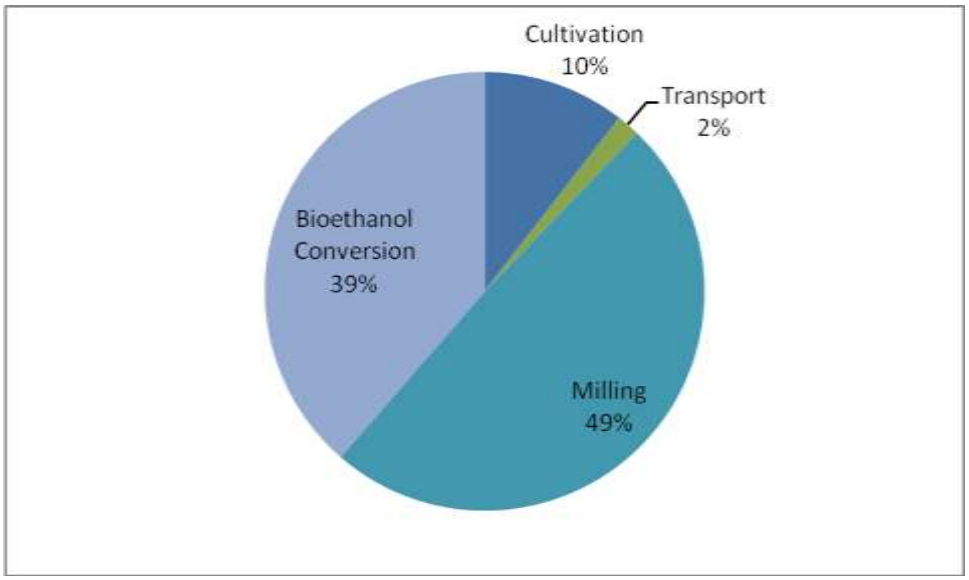

Figure 4.13: Energy consumption for sugarcane molasses based bioethanol in Kenya

Energy balances of sugarcane molasses based bioethanol have been done in countries such as Thailand (Nguyen *et al.*, 2008), Nepal (Khatiwada & Silveira, 2009), Tanzania (Eshton, 2012), Indonesia (Khatiwada *et al*., 2016), Mexico (Garcia *et al*. 2011), Ethiopia (Gabisa *et al*. 2019) and India (Soam *et al*. 015). Their energy balances are depicted in Table 4.10. It should be noted the NEV obtained are positive for Kenya Tanzania and Ethiopia, and negative for Nepal, Thailand and Indonesia. Thus for Kenya, Tanzania and Ethiopia, the total energy (fossil and renewable) required to produce one litre of bioethanol is less than the energy content of the bioethanol, while for Nepal, Thailand and Indonesia it is vice versa. The NER obtained in this study indicates that less amounts of fossil fuels is required to produce one litre of bioethanol in Kenya than in Tanzania, Nepal, Indonesia, Ethiopia, Mexico, India and Thailand in that order. The reported total energy consumption per one litre of bioethanol for various countries including that of this study is shown in Table 4.11. It is observed that the total energy consumption obtained in this study is less than of Tanzania, Thailand, Indonesia and Nepal in that order. Fossil energy use in this study is less than that reported in Tanzania, Nepal, Indonesia, Ethiopia and Thailand in that order. In

Tanzania, Nepal and India, higher fossil energy use attributed to diesel use in irrigation. In Thailand and Indonesia, higher fossil energy use are attributed to use of coal in steam production. In Mexico, the higher fossil energy consumption due to fuel oil use in the industrial phase. In Ethiopia there is less net renewable energy input resulting to low total energy input a moderately lower value of NER. To note, the source of energy in these countries is primarily from renewables, contributing 87-96% of the total energy consumption except Thailand.

Table 4.10: Energy Balances of Molasses Bioethanol Systems per litre of bioethanol

Country	NEV (MJ)	NREV (MJ)	NER	Researcher
Kenya	3.88	19.75	14.64	Current study
Thailand	-5.65	5.97	1.39	Nguyen *et al.* (2008)
Nepal	-13.05	18.36	7.47	Khatiwada & Silveira (2009)
Tanzania	0.995	19.13	10.2	Eshton (2012)
Indonesia	-6.98	17.72	6.09	Khatiwada *et al.* (2016)
Ethiopia	10.22	17	5.32	Gabisa *et al*. (2019)
Mexico	-	-	4.4	Garcia *et al*. (2011)
India	-	-	4.23	Soam *et al*. (2015)

Table 4.11: Energy Consumption of Molasses Bioethanol Systems per litre of bioethanol

Country	Fossil energy (MJ)	Renewable energy (MJ)	Total energy (MJ)
Kenya [a]	1,45	15.87	17.32
Nepal [b]	2.84	31.42	34.26
Indonesia [c]	3.48	24.69	28.18
Tanzania [d]	2.08	18.13	20.21
Thailand [e]	15.23	11.62	26.85
Ethiopia [f]	3.95	6.83	10.78

[a] Current study
[b] Khatiwada & Silveira (2009)
[c] Khatiwada *et al.*(2016)
[d] Eshton, 2012
[e] Nguyen *et al.*(2008)
[f] Gabisa et al.(2019)

4.7.2 Energy Balances of Sweet Sorghum Stalk Juice-Based Bioethanol

The energy consumption and energy balances for the production of bioethanol from sweet sorghum stalk juice are presented in Table 4.12. 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 about 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 less than its energy content. 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. The high positive value of NER (13.6) indicates low amount of fossil energy is required to produce a renewable energy. The positive values of NER and NREV indicate the production of the sweet sorghum stalk juice bioethanol require less non-renewable energy, hence less GHG emissions. As depicted in Figure 4.12, 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%. In bioethanol conversion, juice fermentation, distillation and dehydration of 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 less 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 4.12: Energy consumption and balances of sweet sorghum stalk juice bioethanol

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	

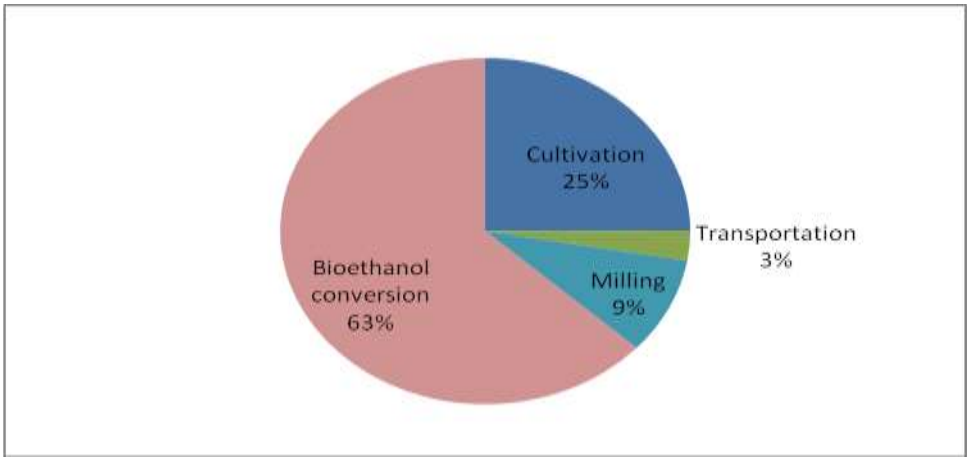

Figure 4.14: Energy consumption for sweet sorghum stalk juice based bioethanol in Kenya

The energy balances obtained of the sweet sorghum stalk juice bioethanol system of this study was compared with that calculated from results reported by Wang *et al*. (2014), Wang *et al*. (2015) and Ding *et al.* (2017) in China, Cai *et al*. (2013) in the United States and Aguilar-Sanchez *et al*. (2018) in Mexico. .In the calculation of energy balances, the bioethanol energy content (21.2 MJ/L) was used. The energy balances results are shown in Table 4.13. The very low NER and NREV values of the sweet sorghum stalk juice bioethanol system reported by Wang *et al*. (2014) is due to use of coal (a fossil fuel) to produce steam as well as in agrochemicals production processes. The lower NER value for the sweet sorghum bioethanol stalk juice system reported by Wang *et al*. (2015) is due to use of electricity generated using fossil energy. The high NREV values reported by Wang *et al*. (2015), Cai *et al*. (2013) and in this study is due to use of bagasse and vinasse as a fuel to produce steam and generate electricity, reducing the fossil fuel consumption. The low NER value reported by Ding *et al.* (2017) is due to extra power from fossil fuels supplied to the bioethanol plant. The very low value reported by Aguilar-Sanchez *et al*. (2018) can be attributed to a lower assumed bioethanol yield (33.84 L of bioethanol per ton of sweet sorghum stalk against 79.9 in this study). No fossil fuel is used to produce steam and generate electricity in this study; hence the higher calculated values of NER and NREV.

Table 4.13: Energy Balances of Sweet Sorghum Bioethanol Systems

NREV	NER	Researcher
19.68	13.6	Current Study
6.3	1.42	Wang *et al*.(2014)
15.14	3.5	Wang *et al*.(2015)
17.2	5.2	Cai *et al*. (2013)
-	3.33	Ding *et al*.(2017)
-	1.9	Aguilar-Sachez *et al*. (2018)

4.8 Sensitivity Analysis for Sugarcane Molasses-based Bioethanol

Sensitivity analysis was performed to evaluate the effect of changes in bioethanol yield and price of molasses on GHG emissions (environmental performance) and NER (energy efficiency). Molasses is the feedstock in bioethanol conversion process and the price of molasses is critical in determining the GHG emissions and NER under the economic allocation method. GHG emissions are a major environmental impact of great concern globally while NER is an indicator of the amount of fossil energy required to produce the renewable energy. The variation of GHG emissions with bioethanol yield and price of molasses was calculated and is presented in Figure 4.13. The value of GHG emission is sensitive to changes in bioethanol yield and price of molasses. Increasing bioethanol yield was found to result in a decrease in GHG emissions. An increase in bioethanol yield would have an effect of decreasing GHG emissions per the functional unit. For example, increasing bioethanol yield by 10%, the net GHG emissions was found to decrease from 270.88 gCO_{2eq} to 245.8 gCO_{2eq} (or 9.3% decrease) per litre of bioethanol. Prices of molasses and sugar dictate of how emissions are allocated to the same. Increasing price of molasses results in increase of GHG emissions. Increase in demand for bioethanol may lead to increases in the prices of molasses. An Increase in the price of molasses would have an effect of allocating more emissions to molasses. Increasing the price of molasses by 10%, the net GHG emissions were found to increase from 270.87 gCO_{2eq} to 293.7 gCO_{2eq} (or 8.4% increase) per litre of bioethanol. Therefore if the price of molasses increases, the emissions saving are likely to be reduced. Thus this sensitivity analysis is an indicator

to government policy makers and investors that there is need to identify the most suitable economic options on the commercial use for molasses.

Figure 4.14 shows the variation of NER with changes in bioethanol yield and price of molasses. Bioethanol yield and price of molasses were also found to be sensitive parameters to NER. Increasing bioethanol yield results in increase of NER. Increasing bioethanol yields would have an effect of allocating fewer resources per the functional unit, resulting in higher NER. For example, an increase to 10% of bioethanol yield result in increase of NER from 14.62 to 16.06 (or 9.6% increase). Increase in price of molasses results in decrease of NER. An increase in prices of molasses would lead to a higher allocation of resources to molasses and this will have a consequence of reducing the NER. An increase to 10% of price molasses results in decrease of NER from 14.62 to 13.17 (or 9.9% decrease). An increase in price of molasses would lead to higher allocation of resources to molasses thereby decreasing the NER. An increase in demand for bioethanol may lead to increases in price of molasses, which in turn reduces the GHG emissions saving. Improvement on agricultural practices will increase sugar cane yield and this will increase bioethanol yield. This will have an effect of increasing the GHG saving as well as reducing the fossil energy usage per functional unit.

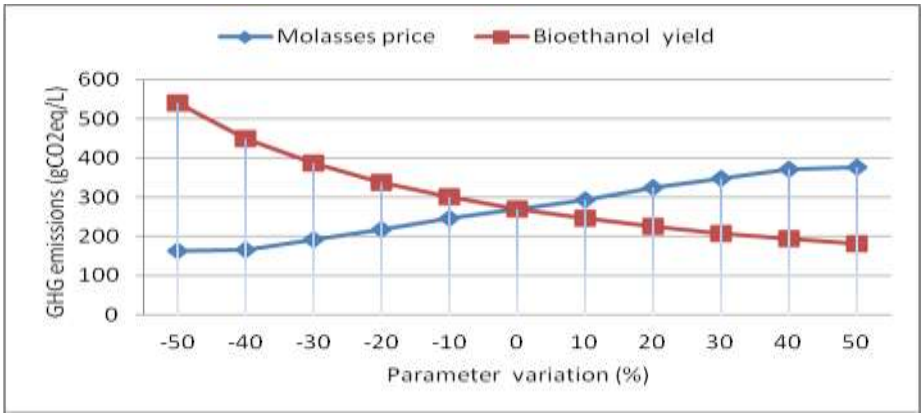

Figure 4.15: Sensitivity analysis of GHG emissions for sugarcane molasses bioethanol

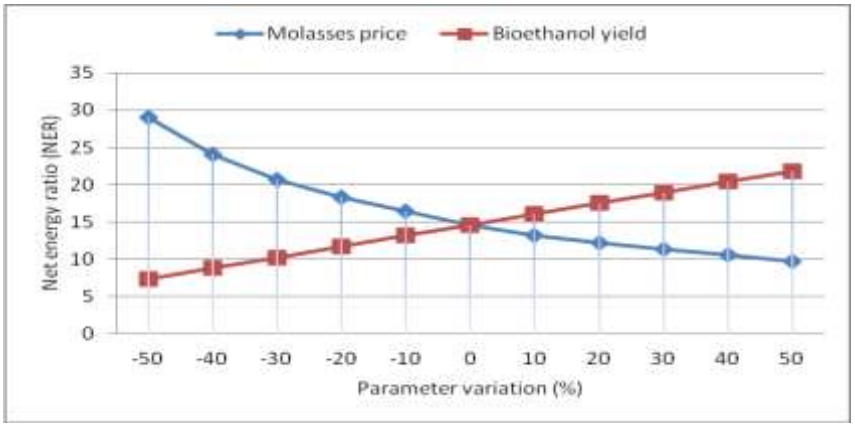

Figure 4.16: Sensitivity analysis of NER for sugarcane molasses bioethanol

4.9 Sensitivity Analysis for Sweet Sorghum Stalk Juice-based Bioethanol

Sensitivity analysis was performed to evaluate the effect of changes on sweet sorghum stalk (stem) yield, stalk juice yield and bioethanol yield on GHG emissions and NEV. In the cultivation of sweet sorghum, stalk yield, stalk juice yield and bioethanol yield are uncertain parameters. The stalk yield, stalk juice yield and bioethanol yield depend on cultivar, climate, location and production practices (Bellmer *et al*., 2010). The variation of GHG emissions with increases in stalk yield, juice yield and bioethanol yield is depicted in Figure 4.15. Stalk yield was found to be a sensitive parameter to GHG emissions but juice yield and bioethanol yield were not. Stalk yield increases due to use of more fertilizer which would result to an increase in GHG emissions per the functional unit. For example, an 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. Stalk yield increased by improvement of agricultural practices mainly through use of agrochemicals like fertilizers. The production and use of fertilizers are the key emitters of GHG emissions. Thus, high use of fertilizers to increase stalk yield will lead to increase in GHG emissions. The variation of NEV with increase in stalk yield, stalk juice yield and bioethanol yield are presented in Figure 4.16. Bioethanol yield was found to be sensitive to NEV but stalk yield and juice yield were not. Increasing bioethanol yield would have an effect of allocating more resources per the functional unit, hence resulting in decrease in NEV. For example, an 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. Bioethanol yield can be increased by improvement of agricultural practices through increased use of agrochemicals like fertilizers. Production of fertilizer use fossil energy. High use of fertilizers means more consumption of fossil energy, resulting in decrease of NEV.

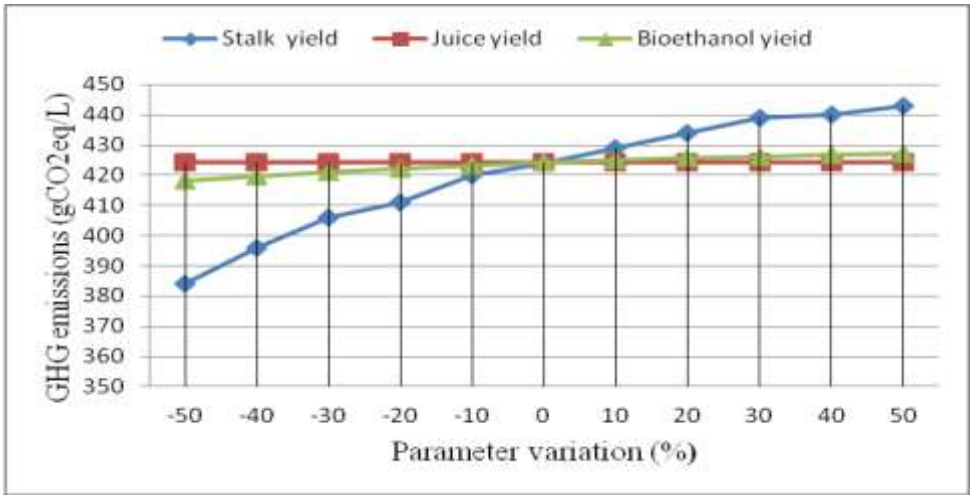

Figure 4.17: Sensitivity analysis of GHG emissions for sweet sorghum stalk juice bioethanol

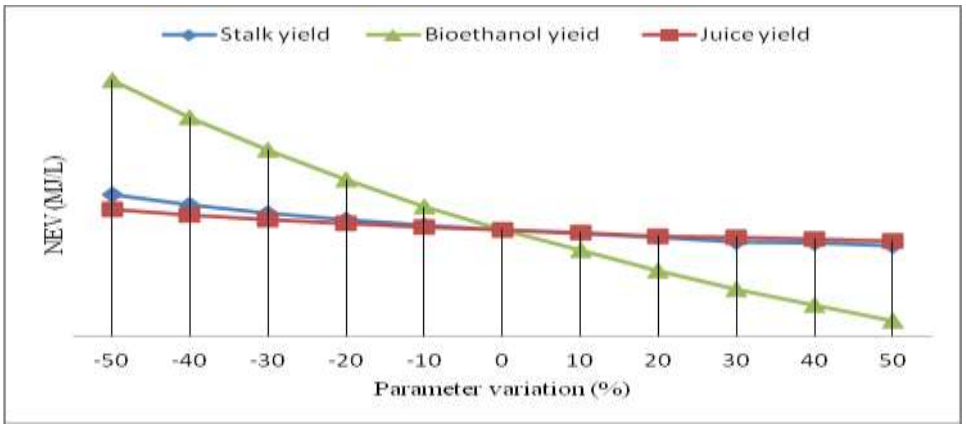

Figure 4.18: Sensitivity analysis of NEV for sweet sorghum stalk juice bioethanol

4.10 Life Cycle Cost Analysis

Life cycle cost analysis is an economical method of determining costs for a product's life cycle from raw material acquisition, installation, operation, maintenances, to final disposal (Nguyen *et al*, 2008; Luo *et al*, 2009, Farook, *et al.*, 2020). The costs arising

from bioethanol production from sugarcane molasses as well as sweet sorghum stalk juice were considered in this study.

4.10.1 Production Costs

The production costs in all processes were calculated based on material and energy inputs. Steady-state cost model was assumed in this life cycle cost analysis. Appendix E and Appendix F indicate how the production costs of sugarcane molasses-based bioethanol and that of sweet sorghum stalk juice-based bioethanol were calculated.

4.10.2 Environmental Costs

Environmental burdens resulting from fossil fuel consumption and emissions of air pollutants i.e. CO_2, CH_4, N_2O, CO, NO_x, SO_2, VOC, NH_3 and particulates (PM) were accounted for to determine the environmental costs. Table 4.14 presents the life cycle fossil energy use and emissions summary for the sugarcane molasses-based bioethanol and sweet sorghum stalk juice-based bioethanol.

Table 4.14: Life cycle fossil energy use and emissions summary

Environmental categories	Units/ha	Sugarcane molasses-based bioethanol	Sweet sorghum stalk juice-based bioethanol
Fossil fuel			
Diesel oil use	MJ	2.96E+02	2.71E+03
Emissions			
CO_2[air]	kg	1.38E+02	1.73E+03
NO_x[air]	kg	8.78E-02	5.66E+00
SO_2[air]	kg	1.23E-02	4.81E-01
NH_3[air]	kg	4.18E-02	2.50E+00
VOC [air]	kg	2.49E-03	9.98E-02
CO [air]	kg	1.60E-02	7.08E-01
CH_4[air]	kg	6.19E-04	3.26E-02
N_2O [air]	kg	9.65E-03	6.42E-01
PM [air]	kg	4.20E-02	2.74E+00

The environmental burdens listed were assessed and the environmental costs of emissions and fossil oil use estimated from the inventory results depicted in Table 4.14 and the cost per unit of air pollutants and fossil oil use shown in Table 3.15. The results obtained, the WTP per litre of bioethanol for each feedstock, are shown in Table 4.15.

Table 4.15: WTP for impacts for emissions and fossil oil use

Environmental categories	Cost item (Kshs per litre bioethanol)	
	Sugarcane molasses-based bioethanol	Sweet sorghum stalk juice-based bioethanol
Fossil fuel		
Diesel oil use	1.60E+00	1.60E+00
Emissions		
CO_2[air]	1.60E-01	2.21E-01
NO_x[air]	2.03E-03	1.41E-02
SO_2[air]	4.31E-04	1.84E-03
NH_3[air]	8.77E-04	5.74E-03
VOC [air]	5.71E-05	2.50E-04
CO [air]	5.67E-05	2.75E-04
CH_4[air]	1.80E-05	1.04E-04
N_2O [air]	3.96E-03	2.88E-02
PM [air]	1.62E-02	1.16E-01
Total	1.79E+00	1.99E+00

The cost analysis of bioethanol from the sugarcane molasses based-bioethanol and the sweet sorghum stalk juice based-bioethanol are shown in Table 4.16 and Table 4.17 respectively. The cost (production cost and environmental cost) of sugarcane molasses bioethanol system was found to be less than that of the sweet sorghum stalk juice bioethanol system. Cultivation stage was found to have the largest cost component in each of the bioethanol systems. In production of the sugarcane molasses based-bioethanol, cultivation cost was found to account for 88.4% of the total cost, while that of sweet sorghum stalk juice based-bioethanol accounts for 77.8% of the total cost. For the sugarcane molasses bioethanol system, agrochemical costs were found to be the highest contributing 33.8% of the total cultivation cost. For the sweet sorghum stalk juice bioethanol system, transportation cost of sweet sorghum stalks from the farm to the milling plant were found to be the highest contributing 30.2% of the total

cultivation cost. External environmental costs were found to contribute about 11.7% of the total cost in the sugarcane molasses based-bioethanol system while that of the sweet sorghum stalk juice based-bioethanol contributed 9.1%. Fossil oil use was found to contribute more than 80% of the total environmental cost in each of the bioethanol systems. Therefore reduction in fossil energy use in both bioethanol systems will greatly have impact on the production cost of bioethanol. This information is important to energy policy makers on biofuels.

Table 4.16: Cost analysis of the sugarcane molasses-based bioethanol

Process/raw material	Kshs/litre	Total	%
Cultivation		1.29E+01	84.3
Land preparation	1.89E+00		
Fertilizer	3.25E+00		
Herbicides/Pesticides	1.11E+00		
Human labour	1.13E+00		
Harvesting	1.87E+00		
Cane transportation	3.66E+00		
Milling		2.15E-01	1.4
Sulphur	4.81E-02		
Lime	1.53E-01		
Juice flocculant	1.42E-02		
Bioethanol conversion		3.94E-01	2.6
Sulphuric acid	1.47E-01		
Urea	2.12E-01		
Yeast	3.53E-02		
Environmental		1.78E+00	11.7
Fossil oil use	1.60E+00		
Air emissions	1.83E-01		
Total		1.53E+01	100

Table 4.17: Cost analysis of the sweet sorghum stalk juice-based bioethanol

Process/raw material	Kshs/litre	Total	%
Cultivation		1.69E+01	77.8
Land preparation	3.06E+00		
Fertilizer	2.18E+00		
Herbicides	9.90E-01		
Seeds	9.89E-01		
Human labour	1.99E+00		
Harvesting	2.60E+00		
Stalk transportation	5.10E+00		
Milling		1.24E-01	0.6
Lime	1.23E-01		
Juice flocculant	5.84E-04		
Bioethanol conversion		2.72E+00	12.5
Sodium hydroxide	7.00E-02		
Urea	4.81E-02		
Yeast	2.60E+00		
Environmental		1.99E+00	9.1
Fossil oil use	1.60E+00		
Air emissions	3.88E-01		
Total		2.17E+01	100

4.11 Interpretation of Results

The results obtained for the sugarcane molasses bioethanol system and those of the sweet sorghum stalk juice bioethanol system are the same as that of other studies (Nguyen *et al*., 2007; Khatiwada & Silveira, 2009; Silalertruksa & Gheewala, 2009; Eshton, 2012; Soam *et al*., 2015; Khatiwada *et al*., 2016; Gabisa *et al*., 2019; Demissie & Gheewala, 2019; Wang *et al*., 2014; Wang *et al*., 2015; Cai *et al*., 2013; Ding *et al*., 2017; Aguilar-Sachez *et al*., 2018. The findings in this study are that the production of the biocrops (sugarcane and sweet sorghum) is the stage which contributes greatly to the environmental impacts considered. This is due to emissions associated with the use of agrochemicals (fertilizers, herbicides and pesticides) and fossil fuels (diesel and

gasoline) during farming of the biocrops. GHG emissions in both bioethanol systems are highly influenced by use of nitrogen fertilizers through N_2O emissions and use of fossil fuels through CO_2 emissions. Nitrogen fertilizer use can be reduced by applying filter cake, cane trash, bagasse or any other biomass residues as organic fertilizers on the farm. The use of fossil diesel can be replaced by biodiesel which reduces CO_2 emissions as has been indicated in other studies. Energy balances of the sugarcane molasses bioethanol system and the sweet sorghum stalk juice bioethanol system indicate low fossil energy use. The cost of production of bioethanol from the sweet sorghum stalk juice and the sugarcane molasses bioethanol system is influenced by use of agrochemicals and fossil fuels. Therefore reduction in use of agrochemicals and fossil fuels will not only reduce environmental impacts but will also reduce production and environmental costs of bioethanol.

The production of bioethanol from sugarcane molasses and sweet sorghum stalk juice in Kenya is promising. Efficient utilization of all byproducts (cane trash, bagasse, filter cake and vinasse) will improve the sustainability of bioethanol production from these two feedstocks. Reducing nitrogen fertilizer use and introducing cleaner energy in industry processes will go along in controlling the environmental impacts and cost of bioethanol production.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter gives the summary of the research findings and the main conclusions drawn from the results. Further, the researcher offer recommendations for further studies.

5.2 Conclusion

The sugarcane molasses based bioethanol and sweet sorghum stalk juice based bioethanol were found to have net GHG emissions of 270.87 gCO_{2eq} and 424.19 gCO_{2eq} per litre of bioethanol, respectively. In both bioethanol systems, cultivation (farming) contributed the highest share of the total GHG emissions with the production and use of nitrogen fertilizer being the main contributor. This study reported low net GHG emissions for the sugarcane molasses bioethanol system, the reasons being that for the molasses bioethanol system there was no cane burning prior harvesting, no use of coal as source of energy and no pumped irrigation of sugarcane fields. The fossil energy use in the molasses bioethanol system was also found to be low. This is again due to there being no pumped irrigation of sugarcane fields or use of coal as a source of energy. In this study, low values of acidification potential (AP) and photochemical ozone creation potential (POCP) were obtained for the sugarcane molasses based bioethanol and the sweet sorghum stalk juice bioethanol systems. This was mainly due to there being no use of coal as an energy source and no biomass burning before cane (or stalk) harvesting. Lower values of human toxicity potential for both bioethanol systems were obtained, the explanation being there no biomass burning which would have resulted in emissions of heavy metals and particulates which contribute significantly to human toxicity.

This study found that in the production of bioethanol from the sugarcane molasses and the sweet sorghum stalk juice, 85% or more of the total energy consumption was renewable energy. The calculated values for NREV were 19.75 and 19.68 MJ per litre

of bioethanol for the sugarcane molasses and the sweet sorghum stalk juice bioethanol systems respectively; while the calculated values for NER were 14.62 and 13.6 per litre of bioethanol for the same bioethanol systems. The high positive values of NREV and NER in sugarcane molasses based bioethanol and in sweet sorghum stalk juice based bioethanol indicated that there was less non-renewable energy input in production of bioethanol in each case which results in less GHG emissions.

The study found cultivation stage to have the largest cost component of the total cost for both the sugarcane molasses bioethanol and the sweet sorghum stalk juice bioethanol. In each case, cultivation cost was more than 75% of the total cost. The environmental cost in each of the bioethanol system was found to be more than 9% of the total cost, which is substantial. Further, the study found that more than 80% of the total external environmental costs in both bioethanol systems were due to fossil oil fuel use.

5.3 Recommendations

The study recommends the following:-

- Maximum use of by-products should be encouraged. This include use of cane (or stalk) tops and leaves, bagasse and stillage as supplement fertilizer as well as boiler fuel. This will significantly reduce use of fossil fuels and chemical fertilizers which results in significant reduction mainly of air emissions, hence reducing environmental impacts, production and environmental costs.
- Production of biogas from wastewaters. Biogas is renewable source of energy; hence its production and use in bioethanol production may reduce the use of fossil fuels, hence reduce GHG emissions and improve NREV.
- The use of fossil fuels should be reduced by limiting fuel use to bagasse as this will improve energy ratios.
- The government should regulate the sale of molasses and give incentives to investors who engage in bioethanol production from molasses. This will go a long in promoting production of bioethanol from molasses.

- Future research on how sweet sorghum stalks crushing to express stalk juice can be integrated in sugarcane factories.

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APPENDICES

Appendix I: Research Activities

Literature review	• Study bioethanol production processes • Identifying inputs, outputs and emissions in each stage of the bioethanol processes • Study key environmental impacts • Study life cycle assessment [ISO standards for LCA i.e. ISO 14040(2006), ISO 14044 (2006)] • Study previous LCA studies done on bioethanol production
Data collection	• Data collection from field visits through interviews • Data collection from literature
Data analysis	• Calculation of energy inputs in each stage of sugarcane molasses based bioethanol and sweet sorghum stalk juice based bioethanol • Calculation of energy balances of sugarcane molasses based bioethanol and sweet sorghum stalk juice based bioethanol • Calculation of emissions in each stage of sugarcane molasses based bioethanol and sweet sorghum stalk juice based bioethanol • Study user manual (tutorial) for CMLCA software. • Building life cycle models in CMLCA software • Entering data i.e. Inputs, outputs and emissions of each process in the life cycle models • Performing inventory analysis, impact assessment and contribution analysis for sugarcane molasses based bioethanol and sweet sorghum stalk juice based bioethanol • Calculation of internal costs (production costs) and internal costs (environmental costs) of sugarcane molasses based bioethanol and sweet sorghum stalk juice based bioethanol
Research findings	• Presentations of progress reports • Report writing • Attending conferences and seminars • Publications • Presentation of final thesis

Appendix II: Questionnaire for Field Visits

B-1: Land Preparation

	Information and data
Land preparation methods/activities	
Agricultural machines used	
Quantity of fuel used per Ha	
Human labour per Ha	
Duration of land preparation	

B-2: Planting

	Information and data
Methods of planting	
Agricultural machines used	
Quantity of fuel used per Ha	
Human labour per Ha	
Type of fertilizer applied	
Quantity of fertilizer applied per Ha	
Fertilizer application method	

B-3: Crop Management

	Information and data
Type and quantity of fertilizer applied per Ha per year	
Type and quantity of herbicide applied per Ha per year	
Type and quantity of insecticide applied per Ha per year	
Type and quantity of pesticide applied per Ha per year	
Human labour per Ha	

	Information and data
Pre-harvest activities	
Harvesting methods	
Amount of fossil fuel used per Ha	
Quantity of post-harvest per Ha	
Post-harvest activities	
Human labour per Ha	

B-5: Transportation

	Information and data
Transportation methods	
Transportation distance (km)	
Amount of fossil fuel used	

B-6: Milling

	Information and data
Amount of feed	
Water consumption	
Quantity of sugar per tonne of feed	
Quantity of molasses/juice per tonne of feed	
Quantity of bagasse per tonne of feed	
Electricity consumption from the grid (kWh)	
Electricity consumption from co-generation (kWh)	
Type and quantity of chemicals used	
Quantity of wastewater produced	

B-7: Bioethanol Conversion

	Information and data
Quantity of molasses used	
Water consumption	
Quantity of yeast	
Electricity consumption (kWh)	

Steam consumption
Quantity of vinnase
Type and quantity of chemicals used
Quantity of bioethanol produced

B-8: Power Co-generation

Information and data
Quantity of bagasse used
Quantity of steam produced
Quantity of electricity produced(kWh)

Appendix III: Emissions in Sugarcane Molasses Bioethanol System

C-1: Emissions from sugarcane farming

Substance	Emission (kg/ha)
Carbon dioxide[air]	7.01E+01
Ammonia[air]	5.67E-01
Carbon monoxide[air]	1.49E-01
Nitrogen[fresh water]	1.70E+00
Methane[air]	2.08E-03
Nitrous oxide[air]	1.12E-01
Nitrogen oxides[air]	2.09E-01
Sulphur dioxide[air]	1.02E-01
NMVOC[air]	2.93E-02
Particulates[air]	1.10E-01
Glyphosate[Agr. soil]	1.15E-02
Aldrin[Agr. soil]	1.26E-01
Altrazine[Agr. soil]	3.33E-02
Phosphorus [Fresh water]	4.13E-02
Cadmium[Agr. soil]	5.62E-03
Copper[Agr. soil]	1.90E-01
Zinc[Agr. soil]	1.50E+00
Lead[Agr. soil]	2.69E-02
Nickel[Agr. soil]	1.61E-01
Chromium[Agr. soil]	2.67E-01
Mercury[Agr. soil]	6.37E-04

C-2: Emissions from use of diesel for cultivation and transport of farm outputs

Substance	Tillage Emissions (kg/ha)	Transportation Emissions (kg/ha)	Total Emissions (kg/ha)
Carbon monoxide[air]	5.60E-02	2.60E+00	2.66E+00
Carbon dioxide[air]	2.07E+02	1.93E+02	4.00E+02
Methane[air]	2.80E-02	1.01E-02	3.81E-02
Nitrous oxide[air]	1.68E-03	1.01E-02	1.18E-02
Nitrogen oxides[air]	2.80E-01	3.12E+00	3.40E+00
Sulphur oxide[air]	9.70E-01	9.01E-01	1.87E+00
NMVOC, non–methane volatile organics[air]	1.40E-02	5.20E-01	5.34E-01
Particulates[air]	1.04E+00	9.67E-01	2.01E+00

C-3: Heavy metal emissions from use of fertilizers

Substance	N-Fertilizer Emissions (kg/ha)	P-Fertilizer Emissions (kg/ha)	K-Fertilizer Emissions (kg/ha)	Total Emissions (kg/ha)
Cadmium [Agr. Soil]	4.26E-04	5.93E-04	5.35E-06	1.02E-03
Copper [Agr. Soil]	1.85E-03	1.36E-03	2.57E-04	3.46E-03
Zinc [Agr. Soil]	1.44E-02	1.26E-02	3.32E-04	2.73E-02
Lead [Agr. Soil]	3.90E-03	1.01E-03	4.28E-05	4.95E-03
Nickel [Agr. Soil]	1.48E-03	1.32E-03	1.34E-04	2.94E-03
Chromium [Agr. Soil]	5.53E-03	8.15E-03	3.10E-04	1.40E-02
Mercury [Agr. Soil]	7.10E-06	4.50E-06	0.00E+00	1.16E-05

C-4: Emissions from bagasse combustion in boilers

Substance	Emission (kg/ha)
Ammonia[air]	5.27E-02
Carbon monoxide[air]	9.56E-01
Methane[air]	1.35E+00
Nitrous oxide[air]	1.35E-01
Nitrogen oxides[air]	1.05E+01
Sulphur dioxide[air]	1.02E-01
Particulates[air]	1.36E+00
Arsenic[air]	3.02E-05
Benzene[air]	4.77E-03

Cadmium[air]	2.11E-05
Lead[air]	7.51E-04
Toluene[air]	9.02E-03
Zinc[air]	9.02E-03
Copper[air]	6.63E-04
Phosphorus[air]	9.02E-03
Chromium V[air]	1.20E-06

C-5: Emissions from bioethanol conversion

Name	Unit	Emissions/ha
Carbon dioxide[air]	kg	1.32E+02
Ammonia[air]	kg	1.44E-03
Carbon monoxide[air]	kg	5.18E-03
Methane[air]	kg	3.23E-04
Nitrous oxide[air]	kg	1.90E-03
Nitrogen oxides[air]	kg	7.26E-02
Sulphur dioxide[air]	kg	2.06E-03
NMVOC, non-methane volatile organic compounds[air]	kg	4.51E-04
Particulates[air]	kg	3.32E-02
Arsenic[air]	kg	8.24E-07
Benzene[air]	kg	6.71E-04
Chromium[air]	kg	3.26E-06
Heat, waste[air]	MJ	1.02E+03
Lead[air]	kg	2.06E-05
Mercury[air]	kg	2.47E-07
Nickel[air]	kg	4.94E-06
Toluene[air]	kg	2.22E-04
Zinc[air]	kg	2.47E-04
Calcium[air]	kg	4.83E-03
Copper[air]	kg	1.81E-05
Manganese[air]	kg	1.41E-04
Fluorine[air]	kg	4.12E-05
Magnesium[air]	kg	2.98E-04
Benzene ethyl[air]	kg	2.22E-05
Potassium[air]	kg	1.93E-02
Sodium[air]	kg	1.07E-03
Chlorine[air]	kg	1.48E-04
Acetaldehyde[air]	kg	5.02E-05

Phenol[air]	kg	5.97E-09
Phosphorus[air]	kg	2.47E-04
Benzene hexachloro[air]	kg	5.34E-12
Benzene(a) pyrene[air]	kg	3.69E-07
Bromine[air]	kg	4.94E-05
2,3,7,8 - tetrachlorodibenzo - p- dioxins[air]	kg	2.30E-11
Formaldehyde[air]	kg	9.61E-05
Xylene[air]	kg	8.87E-05
PAH, Polycyclic aromatic hydrocarbons[air]	kg	8.12E-06

C-6: Emissions from wastewater treatment

Substance	Unit	Emissions/ha
Ammonia[air]	kg	2.73E-03
Carbon monoxide[air]	kg	1.70E-03
Nitrogen[fresh water]	kg	4.78E-03
Methane[air]	kg	4.88E-03
Nitrous oxide[air]	kg	1.45E-03
Nitrogen oxides[air]	kg	6.92E-03
Sulphur dioxide[air]	kg	8.63E-03
NMVOC, non-methane volatile organic compounds[air]	kg	2.22E-06
Cadmium[Agr. soil]	kg	3.81E-08
Copper[Agr. soil]	kg	7.65E-05
Zinc[Agr. soil]	kg	2.09E-05
Lead[Agr. soil]	kg	2.12E-06
Nickel[Agr. soil]	kg	7.17E-07
Chromium[Agr. soil]	kg	1.66E-06
Mercury[Agr. soil]	kg	3.81E-08
Arsenic[air]	kg	2.47E-10
Cadmium[air]	kg	5.36E-12
Chromium[air]	kg	3.12E-13
Heat, waste[air]	MJ	1.23E+00
Lead[air]	kg	2.00E-10
Mercury[air]	kg	3.29E-11
Nickel[air]	kg	7.85E-12
Zinc[air]	kg	8.63E-10
Calcium[air]	kg	5.80E-05
Copper[air]	kg	1.43E-10
Phosphorus[air]	kg	1.52E-06
Ammonium, ion[fresh water]	kg	1.07E-01

Arsenic, ion[fresh water]	kg	8.24E-07
BOD5, Biochemical oxygen demand[fresh water]	kg	9.65E-02
Cadmium, ion[fresh water]	kg	1.39E-07
Calcium, ion[fresh water]	kg	4.78E-01
Chloride[fresh water]	kg	3.95E-01
Chromium VI[fresh water]	kg	6.63E-05
COD, Chemical oxygen demand[fresh water]	kg	2.97E-01
Copper, ion[fresh water]	kg	2.52E-05
DOC, Dissolved organic carbon[fresh water]	kg	7.46E-02
Fluoride[fresh water]	kg	3.20E-05
Heat, waste[fresh water]	kg	1.07E+01
Lead[fresh water]	kg	1.31E-06
Magnesium[fresh water]	kg	5.36E-02
Manganese[fresh water]	kg	4.19E-04
Mercury[fresh water]	kg	6.63E-08
Nickel, ion[fresh water]	kg	5.61E-06
Nitrate[fresh water]	kg	4.72E-03
Nitrite[fresh water]	kg	6.29E-04
Phosphate[fresh water]	kg	2.81E-03
Potassium, ion[fresh water]	kg	3.89E-04
Sodium, ion[fresh water]	kg	2.14E+01
TOC, Total organic carbon[fresh water]	kg	7.22E-03
Zinc, ion[fresh water]	kg	3.37E-05
Arsenic[Agr. soil]	kg	5.36E-08
Calcium[Agr. soil]	kg	1.37E-04
Carbon[Agr. soil]	kg	4.77E-03
Magnesium[Agr. soil]	kg	1.54E-04
Manganese[Agr. soil]	kg	7.22E-06

C-7: Overall emissions of sugarcane molasses based bioethanol

Substance	Unit	Emission /ha
Carbon dioxide[air]	kg	1.38E+02
Ammonia[air]	kg	4.18E-02
Carbon monoxide[air]	kg	1.60E-02
Nitrogen[fresh water]	kg	1.18E-01
Methane[air]	kg	6.19E-04
Nitrous oxide[air]	kg	9.65E-03
Nitrogen oxides[air]	kg	8.78E-02
Sulphur dioxide[air]	kg	1.23E-02
NMVOC, non-methane volatile organic compounds[air]	kg	2.49E-03

Particulates[air]	kg	4.19E-02
Glyphosate[Agr. soil]	kg	8.00E-04
Aldrin[Agr. soil]	kg	8.73E-03
Altrazine[Agr. soil]	kg	2.32E-03
Cadmium[Agr. soil]	kg	3.91E-04
Copper[Agr. soil]	kg	1.32E-02
Zinc[Agr. soil]	kg	1.04E-01
Lead[Agr. soil]	kg	1.87E-03
Nickel[Agr. soil]	kg	1.12E-02
Chromium[Agr. soil]	kg	5.36E-02
Mercury[Agr. soil]	kg	4.43E-05
Phosphorus[fresh water]	kg	2.87E-03
Arsenic[air]	kg	8.78E-07
Benzene[air]	kg	6.78E-04
Cadmium[air]	kg	1.40E-07
Chromium[air]	kg	3.32E-06
Heat, waste[air]	MJ	1.02E+03
Lead[air]	kg	2.08E-05
Mercury[air]	kg	2.48E-07
Nickel[air]	kg	7.70E-06
Toluene[air]	kg	2.25E-04
Zinc[air]	kg	2.48E-04
Calcium[air]	kg	4.83E-03
Copper[air]	kg	1.83E-05
Manganese[air]	kg	1.41E-04
Fluorine[air]	kg	4.12E-05
Magnesium[air]	kg	2.98E-04
Benzene ethyl[air]	kg	2.22E-05
Potassium[air]	kg	1.93E-02
Sodium[air]	kg	1.07E-03
Chlorine[air]	kg	1.48E-04
Acetaldehyde[air]	kg	5.07E-05
Phenol[air]	kg	5.95E-09
Phosphorus[air]	kg	2.47E-04
Ammonium, ion[fresh water]	kg	5.07E-04
Arsenic, ion[fresh water]	kg	2.56E-07
BOD5, Biochemical oxygen demand[fresh water]	kg	4.04E-04
Cadmium, ion[fresh water]	kg	2.53E-07
Calcium, ion[fresh water]	kg	2.00E-03
Chloride[fresh water]	kg	1.65E-03
Chromium VI[fresh water]	kg	1.54E-06
COD, Chemical oxygen demand[fresh water]	kg	1.24E-03

Copper, ion[fresh water]	kg	1.37E-06
DOC, Dissolved organic carbon[fresh water]	kg	8.29E-04
Fluoride[fresh water]	kg	1.34E-07
Heat, waste[fresh water]	MJ	1.81E+01
Lead[fresh water]	kg	1.15E-07
Magnesium[fresh water]	kg	2.24E-04
Manganese[fresh water]	kg	1.76E-06
Mercury[fresh water]	kg	2.42E-07
Nickel, ion[fresh water]	kg	9.99E-07
Nitrate[fresh water]	kg	1.97E-05
Nitrite[fresh water]	kg	2.63E-06
Phosphate[fresh water]	kg	1.50E-05
Potassium, ion[fresh water]	kg	1.63E-06
Sodium, ion[fresh water]	kg	8.92E-02
TOC, Total organic carbon[fresh water]	kg	3.02E-05
Zinc, ion[fresh water]	kg	2.92E-07
Arsenic[Agr. soil]	kg	2.24E-10
Calcium[Agr. soil]	kg	5.75E-07
Carbon[Agr. soil]	kg	1.99E-05
Magnesium[Agr. soil]	kg	6.44E-07
Manganese[Agr. soil]	kg	3.02E-08
Benzene hexachloro[air]	kg	5.36E-12
Benzene(a) pyrene[air]	kg	3.69E-07
Bromine[air]	kg	4.92E-05
2,3,7,8 - tetrachlorodibenzo - p- dioxins[air]	kg	2.30E-11
Formaldehyde[air]	kg	9.95E-05
Xylene[air]	kg	8.87E-05
PAH, Polycyclic aromatic hydrocarbons[air]	kg	8.24E-06
Hydrocarbons, aliphatic, alkanes, unspecified[air]	kg	6.73E-04
Hydrocarbons, aliphatic, unsaturated, unspecified[air]	kg	2.30E-04
Hydrogen chloride[air]	kg	6.14E-06
Hydrogen fluoride[air]	kg	4.73E-06
Selenium[air]	kg	7.65E-16
Cobalt[air]	kg	1.40E-07
Sulphate[fresh water]	kg	2.04E-04
Aluminium[fresh water]	kg	4.58E-07
Chlorine[fresh water]	kg	3.55E-08
Butane[air]	kg	8.58E-06
Pentane[air]	kg	1.47E-05
Propane[air]	kg	2.57E-06
Chromium, ion[fresh water]	kg	7.41E-12

Appendix IV: Emissions in Sweet Sorghum Stalk Juice Bioethanol System

D-1: Emissions from sweet sorghum farming

Substance	kg/ha
Carbon dioxide[air]	7.90E+02
Nitrous oxide[air]	1.14E+00
Ammonia[air]	5.32E+00
Carbon monoxide[air]	7.61E-01
Methane[air]	1.75E-02
Nitrogen oxides[air]	1.26E+00
Sulphur dioxide[air]	7.61E-01
NMVOC, non-methane volatile organic compounds[air]	1.54E-01
Particulates[air]	8.15E-01
Nitrogen[fresh water]	1.60E+01
Phosphorus[fresh water]	1.26E+00
Aldrin[Agri. soil]	1.87E+00
Altrazine[Agri. soil]	4.93E-03
Glyphosate[Agri. soil]	1.70E-01
Cadmium[Agri. soil]	1.21E-05
Copper[Agri. soil]	3.26E+00
Zinc[Agri. soil]	2.85E-01
Lead[Agri. soil]	3.62E-03
Nickel[Agri. soil]	3.00E+00
Chromium[Agri. soil]	1.66E+01
Mercury[Agri. soil]	1.11E-02

D-2: Emissions from use of diesel for cultivation and transport of farm outputs

Substance	Tillage Emissions (kg/ha)	Transportation Emissions (kg/ha)	Total Emissions (kg/ha)
Carbon monoxide [air]	3.60E-02	1.60E+00	1.64E+00
Carbon dioxide [air]	1.33E+02	1.19E+02	2.52E+02
Methane [air]	1.80E-02	6.24E-03	2.42E-02
Nitrous oxide [air]	1.08E-03	6.24E-03	7.32E-03
Nitrogen oxides [air]	1.80E-01	1.92E+00	2.10E+00
Sulphur oxide[air]	6.24E-01	5.54E-01	1.18E+00
NMVOC, non-methane volatile compounds [air]	9.00E-03	3.20E-01	3.29E-01
Particulates [air]	6.70E-01	5.95E-01	1.26E+00

D-3: Heavy metal emissions from use of fertilizers

Substance	N-Fertilizer Emissions (kg/ha)	P-Fertilizer Emissions (kg/ha)	K-Fertilizer Emissions (kg/ha)	Total Emissions (kg/ha)
Cadmium [Agr, soil]	2.59E-04	1.23E-03	1.20E-06	1.49E-03
Copper [Agr, soil]	1.12E-03	2.82E-03	5.76E-05	4.00E-03
Zinc[Agr, soil]	8.77E-03	2.62E-02	7.44E-05	3.50E-02
Lead [Agr, soil]	2.37E-03	2.09E-03	9.60E-06	4.47E-03
Nickel [Agr, soil]	9.03E-04	2.75E-03	3.00E-05	3.69E-03
Chromium [Agr, soil]	3.37E-03	1.69E-02	6.96E-05	2.04E-02
Mercury [Agr, soil]	4.32E-06	9.36E-06	0.00E+00	1.37E-05

D-4: Emissions from bagasse combustion in boilers

Substance	Emissions (kg/ha)
Ammonia[air]	5.07E-02
Particulates[air]	1.31E+00
Methane[air]	1.30E+00
Carbon monoxide[air]	9.24E-01
Cadmium[air]	2.03E-05
Arsenic[air]	2.92E-05
Copper[air]	6.41E-04
Lead[air]	7.26E-04
Nitrogen oxides[air]	1.02E+01
Sulphur dioxide[air]	9.85E-02
Zinc[air]	8.73E-03
Nitrous oxide[air]	1.30E-01
Phosphorus[air]	8.73E-03
Toluene[air]	8.73E-03
Benzene[air]	4.61E-03
Chromium V[air]	1.16E-06

D-5: Emissions from bioethanol conversion

Substance	Unit	Emissions (kg/ha)
Acetaldehyde[air]	kg	5.35E-03
Ammonia[air]	kg	1.52E-01
Arsenic[air]	kg	8.73E-05
Benzene[air]	kg	7.15E-02
Benzene, ethyl-[air]	kg	2.35E-03

Benzene, hexachloro-[air]	kg	5.63E-10
Benzo(a)pyrene[air]	kg	3.91E-05
Bromine[air]	kg	5.24E-03
Cadmium[air]	kg	6.12E-05
Calcium[air]	kg	5.10E-01
Carbon dioxide[air]	kg	1.64E+04
Carbon monoxide[air]	kg	5.49E-01
Chlorine[air]	kg	1.57E-02
Chromium[air]	kg	3.46E-04
Chromium VI[air]	kg	3.50E-06
Copper[air]	kg	1.93E-03
Dinitrogen monoxide[air]	kg	2.01E-01
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin[air]	kg	2.43E-09
Fluorine[air]	kg	4.36E-03
Formaldehyde[air]	kg	1.02E-02
Heat, waste[air]	MJ	3.43E+04
Hydrocarbons, aliphatic, alkanes, unspecified[air]	kg	7.15E-02
Hydrocarbons, aliphatic, unsaturated[air]	kg	2.43E-01
Lead[air]	kg	2.18E-03
Magnesium[air]	kg	3.16E-02
Manganese[air]	kg	1.50E-02
Mercury[air]	kg	2.62E-05
Methane[air]	kg	3.40E-02
m-Xylene[air]	kg	9.40E-03
Nickel[air]	kg	5.24E-04
Nitrogen oxides[air]	kg	7.71E+00
NMVOC, non-methane volatile organic compounds, unspecified origin[air]	kg	4.79E-02
PAH, polycyclic aromatic hydrocarbons[air]	kg	8.62E-04
Particulates[air]	kg	3.52E+00
Phenol, pentachloro-[air]	kg	6.34E-07
Phosphorus[air]	kg	2.62E-02
Potassium[air]	kg	2.05E+00
Sodium[air]	kg	1.14E-01
Sulphur dioxide[air]	kg	2.18E-01
Toluene[air]	kg	2.35E-02
Zinc[air]	kg	2.62E-02

D-6: Overall emissions of sweet sorghum stalk juice based bioethanol

Substance	Unit	kg/ha
Carbon dioxide[air]	kg	1.75E+03
Nitrous oxide[air]	kg	6.42E-01
Ammonia[air]	kg	2.50E+00
Carbon monoxide[air]	kg	7.08E-01
Methane[air]	kg	3.26E-02
Nitrogen oxides[air]	kg	5.66E+00
Sulphur dioxide[air]	kg	4.81E-01
NMVOC, non-methane volatile organic compounds[air]	kg	9.98E-02
Particulates[air]	kg	2.74E+00
Nitrogen[fresh water]	kg	7.13E+00
Phosphorus[fresh water]	kg	5.66E-01
Aldrin[Agri. soil]	kg	8.33E-01
Altrazine[Agri. soil]	kg	2.20E-03
Glyphosate[Agri. soil]	kg	7.57E-02
Cadmium[Agri. soil]	kg	5.39E-06
Copper[Agri. soil]	kg	1.45E+00
Zinc[Agri. soil]	kg	1.27E-01
Lead[Agri. soil]	kg	1.62E-03
Nickel[Agri. soil]	kg	1.34E+00
Chromium[Agri. soil]	kg	7.40E+00
Mercury[Agri. soil]	kg	4.95E-03
Acetaldehyde[air]	kg	3.54E-03
Arsenic[air]	kg	5.93E-05
Benzene[air]	kg	4.72E-02
Benzene, ethyl[air]	kg	1.55E-03
Benzo(a)pyrene[air]	kg	2.57E-05
Bromine[air]	kg	3.46E-03
Cadmium[air]	kg	4.54E-05
Chlorine[air]	kg	1.03E-02
Chromium[air]	kg	2.30E-04
Chromium VI[air]	kg	2.33E-06
Copper[air]	kg	1.27E-03
2,3,7,8 - tetrachlorodibenzo - p - dioxins[air]	kg	1.60E-09
Fluorine[air]	kg	2.87E-03
Formaldehyde[air]	kg	6.82E-03
Heat, waste[air]	MJ	2.33E+04
Hydrocarbons, aliphatic, alkanes unspecified[air]	kg	4.68E-02
Hydrocarbons, aliphatic, unsaturated, unspecified[air]	kg	1.60E-01
Lead[air]	kg	2.32E-05
Magnesium[air]	kg	2.08E-02
Manganese[air]	kg	9.85E-03
Mercury[air]	kg	1.73E-05

Xylene[air]	kg	6.19E-03
Nickel[air]	kg	4.46E-04
PAH, polycyclic aromatic hydrocarbons[air]	kg	5.66E-04
Phenol, pentachloro[air]	kg	4.16E-07
Phosphorus[air]	kg	1.72E-02
Potassium[air]	kg	1.35E+00
Sodium[air]	kg	7.49E-02
Zinc[air]	kg	1.73E-02
Toluene[air]	kg	1.55E-02
Benzene, hexachloro[air]	kg	3.69E-10
Hydrogen chloride[air]	kg	2.24E-04
Hydrogen fluoride[air]	kg	8.33E-04
Phosphate[fresh water]	kg	6.46E-04
Ammonium ion[fresh water]	kg	2.42E-03
Cobalt[air]	kg	5.12E-06
Mercury[fresh water]	kg	4.77E-05
Zinc, ion[fresh water]	kg	2.96E-05
Cadmium, ion[fresh water]	kg	4.95E-05
Nickel, ion[fresh water]	kg	1.92E-04
Lead[fresh water]	kg	2.15E-05
Arsenic, ion[fresh water]	kg	4.95E-05
Chromium, ion[fresh water]	kg	2.49E-04
Acetone[air]	kg	2.31E-05
Chloride[fresh water]	kg	2.04E-02
Copper, ion[fresh water]	kg	2.54E-04
Hydrogen[air]	kg	7.49E-04
Bromate[fresh water]	kg	3.72E-04
Chlorate[fresh water]	kg	2.85E-03
Chlorinated solvents[fresh water]	kg	8.15E-07
Sulphate[fresh water]	kg	1.07E-02
Butane[air]	kg	3.14E-04
Pentane[air]	kg	5.39E-04
Propane[air]	kg	9.40E-05

Appendix V: Production costs for sugarcane molasses-based bioethanol System

Operations/Chemicals	Units	Quantity /ha	Unit price (Kshs)	Total cost (Kshs/ha)	Total cost (Kshs /L bioethanol)
Cultivation/harvesting					
Ploughing	ha	1	8460	4.62E+02	9.48E-01
Harrowing	ha	1	6005	2.92E+02	6.00E-01
Furrowing	ha	1	3025	1.65E+02	3.39E-01
Confidor pesticide	Litres	0.034	4200	7.80E+00	1.60E-02
Follicur fungicide	Litres	0.4	2200	4.81E+01	9.86E-02
NPK Blend 1 fertilizer	Bags	5	2850	7.79E+02	1.60E+00
NPK Blend 2 fertilizer	Bags	5	2945	8.05E+02	1.65E+00
Dual Gold herbicide	Litres	3.9	2270	4.84E+02	9.92E-01
Human labour	Man-days	36	280	5.51E+02	1.13E+00
Harvesting	tons	65	256	9.09E+02	1.87E+00
Cane transportation	tons	65	502	1.78E+03	3.66E+00
Milling					
Sulphur	kg	6.5	66	2.34E+01	4.81E-02
Lime	kg	65	21	7.46E+01	1.53E-01
Juice flocculant	kg	0.195	650	6.93E+00	1.42E-02
Bioethanol conversion					
Sulphuric acid	kg	1.56	46	71.76	1.47E-01
Urea	kg	1.95	53	103.35	2.12E-01
Yeast	kg	0.02	860	17.2	3.53E-02

Appendix VI: Production Costs for Sweet Sorghum Stalk Juice-based Bioethanol System

Operations/Chemicals	Units	Quantity/ha	Unit price (Kshs)	Total cost (Kshs)/ha	Total cost (Kshs) /L bioethanol
Cultivation/harvesting					
Ploughing	ha	1	8460	6.85E+03	1.54E+00
Harrowing	ha	1	6005	4.33E+03	9.73E-01
Furrowing	ha	1	3025	2.45E+03	5.50E-01
Dual Gold herbicide	Litres	2.4	2270	4.41E+03	9.90E-01
Seeds	kg	6.4	850	4.41E+03	9.89E-01
NPK Mavuno fertilizer	Bags	2.4	2500	4.86E+03	1.09E+00
Mavuno top dress fertilizer	Bags	2.4	2500	4.86E+03	1.09E+00
Human labour	man-days	39	280	8.85E+03	1.99E+00
Harvesting	tons	55.88	256	1.16E+04	2.60E+00
Transportation	tons	55.88	502	2.27E+04	5.10E+00
Milling					
Lime	kg	39.12	21	5.48E+02	1.23E-01
Juice flocculant	kg	0.006	650	2.60E+00	5.84E-04
Bioethanol conversion					
Sodium hydroxide	kg	4.46	116	3.12E+02	7.00E-02
Yeast	kg	22.3	860	1.16E+04	2.60E+00
Urea	kg	6.7	53	2.14E+02	4.81E-02

Appendix VII: Machinery costing on land preparation

In determination of machinery costing on land preparation, two costs are involved, fixed costs and operating costs. Fixed costs include depreciation rate, interest rate, insurance and shelter. Operating rates include repair and maintenance, labour, fuel consumption, oil and lubricants. Fuel consumption on land preparation depend on model of tractor used as well as the type of operation, but the variations are insignificant on the overall operating rates.

(a) Determination of fixed costs

(i) $$\text{Annual average depreciation (AAD)} = \frac{\text{Cost price} - \text{Salvage value}}{\text{Useful life}}$$

E.g. Cost price = Kshs 6,600,000

Useful life = 6 years

Salvage value = 30% of the cost price

= Kshs 1,770,000

$$\text{AAD} = \frac{6,600,000 - 1,980,000}{6}$$

= Kshs 770,000/year

(ii) Interest rate

Interest for each year = P (1+r) – P

P = Principal amount = 6,600,000

r = rate = 14.5%

Total interest = Kshs 4,021,657

Average interest rate per year = $\frac{4,021,657}{6}$

= Kshs 670,276

(iii) Insurance

Annual charge assumed to be b 3% of the cost price

$$= \frac{3 \times 6,600,000}{100}$$

= Kshs 198,000/year

(iv) Shelter

Shelter as cost incurred at the rate of 1.5% of the total cost

$$= \frac{1.5 \times 6,600,000}{100}$$

= Kshs 99,000/year

Total fixed costs per year

Depreciation	Kshs 770,000
Insurance	Kshs 198,000
Shelter	Kshs 99,000
Interest	Kshs 670,276
Total	Kshs 1,737,276

(b) Determination of operating costs

(i) Fuel consumption = consumption/ha x surface x unit price x days in a year

= 25 x 7 x 90 x 260

= Kshs 4,095,000/year

(ii) Oil and lubricants – At 15% of fuel consumption

$$= \frac{15 \times 4,095,000}{100}$$

= Kshs 614,250/year

(iii) Repair and maintenance (R&M) = $\frac{\text{Principal cost(P)} \times \text{Repair cost factor(r)}}{\text{Useful life}}$

For tractor r = 1.0 and implements r = 1.2

For tractor, R&M = $\frac{6,600,00}{6}$ = Kshs 1,100,000

For implement = $\frac{2,500,000 \times 1.2}{6}$

= Kshs 500,000

(iv) Labour – assumed at two operators

Salary = Monthly pay x 12 months x 2

= 29,019 x 12 x 2

= Kshs 696,456

Total operating costs

Fuel	Kshs 4,095,000
Oil & lubricants	Kshs 614,250
R&M - Tractor	Kshs 1,100,000
R&M - Implement	Kshs 500,000
Labour	Kshs 696,456
Total costs	Kshs 7,006,206

Operating rates for pre-harrow = $\frac{\text{Fixed cost + Operating cost}}{\text{Machine capacity}}$

$= \frac{1,737,246+7,006,206}{7\times260}$

= Kshs 4,804,095

At 25% markup = 1.25 x 4,804,095

= Kshs 6,005