

**DETERMINING ZAMBIA'S POTENTIAL FOR BIOETHANOL PRODUCTION AS A
MOTOR VEHICLE FUEL TO MEET CLIMATE OBJECTIVES BY 2040**

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DECLARATION

I, **Cosmas S. Mwanakaba**, do hereby declare that the contents of the thesis being submitted herein are my original work and they have not been previously submitted to any University for the award of a degree or any other qualification.

Signature.....Date.....

APPROVAL

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ABSTRACT

Zambia's transport sector is driven by imported and costly fossil fuels. Apart from the cost element, fossil fuels are finite. The source is depleting as it is being extracted continuously. Fossil fuels are also pollutants to environment. They contribute 70% of global carbon monoxide (CO) and 19% of global carbon dioxide (CO₂) emissions. These levels of emissions contribute to the global greenhouse gasses challenge. The greenhouse gasses are causing unpredictable weather patterns which have affected the agro business and general economic planning. This research looked at bioethanol as an alternative to gasoline in trying to mitigate the challenges highlighted in depending on fossil fuels for the transport sector. The research investigated three locally produced feedstocks namely sweet potato, cassava and sugarcane. The raw data for these crops was gathered at national level. These feedstocks were quantified and converted to bioethanol using appropriate mathematical ratios.

The period of assessment ranged from 2007 to 2017 and then forecast to 2040 which is seemingly a global benchmark to migrate from use of fossil fuels to alternative fuel sources preferably biofuels. As at 2018, Zambia was consuming 1.3 million liters of gasoline per day. Historical data showed gradual increases year by year from 2007 to 2017. Interestingly, when the total yields of sugarcane at Zambia Sugar (Nakambala), Kafue Sugar and Kasama Sugar as well as those of the national yields of sweet potato and cassava were converted to bioethanol, the results showed that quantities were moving in tandem up to 2023 with those of gasoline consumed and the curve separated thereafter due to the influence of the trend. The two tables compiled thus the total national gasoline consumption in 2007 was 165,040,279 liters while the converted bioethanol potential from all the feedstocks in the same year was 215,046,582. As at 2017, the national gasoline consumption was 461,427,680 liters while the converted bioethanol potential stood at 561,419,763.7 liters without considering the food requirements of the country. The other scenario of the research considered the food requirements of the country and the results as at 2007 for bioethanol potential was 45,173,085 and by 2017 the bioethanol potential was 113,485,818.

This research established that only quantities equivalent to the current yields of sugarcane, cassava and sweet potato (561,419,763.7 liters of bioethanol for 2017 potential) would suffice when converted to bioethanol to replace gasoline as a motor vehicle fuel. The research also established that after forecasting both bioethanol curves trailed lower than that of national gasoline consumption due to irregular increases on the bioethanol results with scenario number two curve moving at the same pace up to 2023 in magnitude and lost momentum thereafter to that of gasoline while scenario number one curve lied almost at bottom of the figure. The levelised cost of energy of all the feedstocks was calculated with molasses being most competitive at \$ 0.039/liter followed by cassava at \$ 0.062/liter, sugarcane at \$ 0.068/liter and sweet potato at \$ 0.304/liter

Key Words: Fossil fuel; Greenhouse Gasses; Gasoline; bioethanol; levelised cost of energy.

DEDICATION

I wish to dedicate this work to my wife Milimo and my children who suffered neglect due the fact that I spent much of my time during the period of research strictly towards this work. Without their support and sacrifice, this work could not have been possible. I appreciate their understanding and encouragement when the research was at its peak

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ABBREVIATIONS

CO	Carbon Monoxide
CO ₂	Carbon Dioxide
GHG	Greenhouse Gases
PLG	Liquified Petroleum Gas
ICE	Internal Combustion Engine
R&D	Research and Development
LCOE	Levelised Cost of Energy
HC	Hydrocarbon
FASOMGHG	Forest and Agricultural Optimization Model Greenhouse Gas
SI	Spark Ignition
CI	Compression Ignition
FC	Fermentable Carbohydrates
ISP	Industrial Sweet Potato
CCD	Central Composite Design
CSO	Central Statistics Office
ERB	Energy Regulation Board
RTSA	Road Transport and Safety Agency
PLC	Public Limited Company
MATLAB	Matrix Laboratory
HCL	Hydrochloric Acid
H ₂ SO ₄	Sulfuric Acid
PH	Potential Hydrogen

NOMENCLATURE

%	Percentage
R^2	Coefficient of Determination
e	Exponential
E	Energy
η	Conversion factor

CHAPTER 1

INTRODUCTION

1 Overview

Energy plays a pivotal role in the development of the nation though it has not been without challenges. The by-products of combustion of fossil fuels have continued polluting the environment and affecting known weather patterns to unpredictable ones. These trends have ultimately affected economic planning.

1.1. Background

Following the 2015 Paris Agreement on climate change, developed countries especially those in Europe have begun making pronouncements on migrating from using fossil fuels powered automobile engines to electrical powered engines by 2040. This development is intended to mitigate the effects of greenhouse gases on to the environment. Whilst this development is welcome, it is not possible for poor and developing countries like Zambia to move at the same pace as the bigger economies of the western world. In the Zambian scenario, an opportunity does exist to migrate to first generation bioethanol using the locally grown crops such as sugarcane, sweet sorghum, cassava and sweet potato as feedstocks. With sugarcane, collaboration with the sugar industry in the country is an important element of this research.

According to [1] today, the transportation sector worldwide is most entirely dependent on the petroleum-based fuels. It is responsible for 60% of the world oil consumption. In addition, transportation sector accounts for more than 70% of global carbon monoxide (CO) emissions and 19% of global carbon dioxide (CO₂) emissions. Carbon dioxide emissions from a gallon of gasoline are about 8kg. Around the world, there were about 806 million cars and light trucks on the road in 2007. These numbers are projected to increase to 1.3 billion by 2030 and to over 2 billion vehicles by 2050. These growths in the number of vehicles will affect the stability of the ecosystems and global climate as well as global oil reserves. The dramatic increase in the price of petroleum, the finite nature of fossil fuels, increasing concerns regarding environmental impact, especially related to greenhouse gasses (GHG) emissions, and health and safety considerations are forcing the search for new energy sources and alternative ways to power the world's motor vehicles.

An alternative fuel must be technically feasible, economically competitive, environmentally acceptable and readily available. Numerous potential alternative fuels have been proposed including bioethanol, biodiesel, methanol, hydrogen, boron, natural gas, liquefied petroleum gas (PLG), Fischer-Tropsch fuel, p-series, electricity and solar fuels.

Biomass-based fuels, also known as biofuels offer the following advantages over petroleum based fuels:

- 1) Biofuels are easily available from common biomass sources.
- 2) They represent a CO₂–cycle in combustion.
- 3) Biofuels have a considerable environmentally friendly potential.
- 4) There are many benefits for the environment, economy and consumers in using biofuels.
- 5) They are biodegradable and contribute to sustainability.

The use of biofuels can contribute to the mitigation of GHG emissions, provide a clean and therefore sustainable energy source, and increase the agricultural income for the rural poor in developing countries. Developing countries have a comparative advantage for biofuels production because of greater availability of land, favorable climate conditions for agriculture and lower labor costs.

However, there may be other socio-economic and environmental implications affecting the potential for developing countries to benefit from the increased global demand for biofuels. Large-scale production of biofuels offers an opportunity for certain developing countries to reduce their dependence on oil imports. In developed countries, there is a growing trend towards employing modern technologies and efficient bioenergy conversion using a range of biofuels, which are becoming cost-wise competitive with fossil fuels.

Biofuels are made from bio-based materials through thermo-chemical processes such as pyrolysis, gasification, liquefaction, supercritical fluid extraction, super critical water liquefaction and biochemical. Thermo-chemical reforming of biomass concerns the processes of catalytic and non-catalytic pyrolysis as well as the gasification, which aims at the maximization of the production of the energetically exploitable liquid and gaseous. Biofuels include bioethanol, biomethanol, vegetable oils, biodiesel, biogas, biosynthetic gas (bio-syngas) bio-oil, bio-char, Fischer-Tropsch liquids and bio-hydrogen. The term biofuels can refer to fuels for direct combustion for electricity production, but is generally used for liquid fuels for transportation sector. Renewable liquid biofuels for transportation have recently attracted huge attention in different countries all over the world because of its renewability, sustainability, common availability, regional development, rural manufacturing jobs, reduction of GHG emissions, and biodegradability.

Bioethanol is by far the most widely used bio-fuel for transportation worldwide. Bioethanol and bioethanol/gasoline blends have a long history as an alternative transportation fuels. It has been used in Germany and France as early as 1894 by the then incipient industry of internal combustion engines (ICEs). Brazil has utilized bioethanol as a fuel since 1925. By that time, the production of bioethanol was 70 times bigger than the production and consumption of petrol. The use of bioethanol for fuel was widespread in Europe and the United States until the early 1900s. Because it became more expensive to produce than the petroleum-based fuel, especially after World War II, bioethanol's potential was largely ignored until the oil crisis of the 1970s. Since the 1980s, there

has been an increased interest in the use of bioethanol as an alternative transportation fuel. To ensure that “good” bioethanol is produced, with reference to GHG benefits, the following demands must be met:

- 1) Bioethanol plants should use biomass and not fossil fuels.
- 2) Cultivation of annual feedstock crops should be avoided on land rich in carbon (above and below ground), such as peat soils used as permanent grassland.
- 3) By-products should be utilized efficiently in order to maximize their energy and GHG benefits.
- 4) Nitrous oxide emissions should be kept to a minimum by means of efficient fertilization strategies, and the commercial nitrogen fertilizer utilized should be produced in plants which have nitrous oxide gas cleaning.

In Zambia the production of bioethanol is not yet commercialized. It is still at R&D stage trying various feedstocks. However, the potential is high considering the availability of sugar plantations and a lot of research being undertaken using sweet sorghum. The research also ventures into other crops such as cassava and sweet potatoes which are grown in large quantities in the country. It is important to understand that Zambia’s fuel needs are dependent on imported fuel. The imports are at a greater cost to the nation using foreign currency. This research is exposing the possible solutions to this drain on the Zambian economy. It is equally believed that promoting bioethanol production would assist peasant farmers especially those growing and trading in sweet potatoes to have a well-defined market for their products unlike the current practice where these traders would line up on the highways trying to sell their merchandise to the road users. The result of such practices lead into loss of time for doing other productive activities and exposure to road traffic accidents. It is the intention of this research to bring out solutions and recommendations that would benefit the general populace and try to mitigate the use of modern existing in trading and selling agricultural produces. It is also equally a fact that fossil fuels will one day be depleted. Such a known outcome entails that Zambia as a nation must be ahead of the impending eventuality. It is from this background that this research is focusing on considering the locally produced feedstock as a strength in carrying out comparative cost benefits to Zambia. Looking at the whole venture, the actual major cost would be the importation of the processing equipment which can easily be recouped as production commences considering the demand motor vehicle fuels command worldwide.

The results obtained from this research are expected to give the country a startup direction in readiness for the 2040 climate objectives which would greatly contribute to predictable weather pattern and plan economic activities accordingly.

1.2. Problem statement

The use of fossil fuels in motor vehicle engines will by 2040 be phased out and be replaced with electrically powered motor vehicles by the European Union countries. For developing countries like Zambia, a gradual cheaper and sustainable migration can be use of biofuels like bioethanol in modified engines. As such, for Zambia, the potential for production of bioethanol from local feedstock varieties without affecting national food requirement to meet the anticipated local demand forecasting the 2040 increase in demand for bioethanol as a fuel should be determined.

1.3. Purpose of study

The purpose of this study is to determine Zambia's potential for bioethanol production to mitigate the impending migration from use of fossil fuels to meet the 2040 forecasted demand and climate change objectives.

1.4 Main Objective

To determine Zambia potential for bioethanol production using a variety of identified locally produced feedstocks and the levelised cost of each of the feedstocks considered.

1.5 Specific Objectives

1. To establish the production potential for bioethanol as an engine fuel in Zambia.
2. To determine the potential the existing sugar refineries can play in supporting the production of first generation bioethanol.
3. To establish so far the number of vehicles in Zambia using bioethanol as fuel.
4. To determine Zambia's potential for bioethanol production from such feedstocks as sweet potato, sweet sorghum and cassava.
5. To determine the Levelised Cost of Energy for each of the feedstocks considered under this research.

1.6 Research Questions

1. What is the production potential for bioethanol as a fuel for use in engines in Zambia?
2. What is the existing potential in the sugar refineries in Zambia to produce first generation bioethanol as a fuel?
3. What is the number of vehicles using bioethanol as fuel on the Zambian market?
4. What potential do other feedstocks such as sweet sorghum, sweet potatoes and cassava have in the production of bioethanol as a vehicle fuel in Zambia?
5. What is the Levelised Cost of Energy for each of the feedstocks considered under this research?

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

This Chapter presents a review of the literature of various players in the bioethanol production using different approaches and using a number of feedstocks focusing on environmental controls resulting from use of bioethanol as fuel in place of gasoline in Zambia.

2.2 Theory and Research Literature Specific to Research Topic

2.2.1 Theory

Bioethanol is an established fuel that is currently used in place of gasoline in many countries. It has a high octane number (108), which permits both the rising of the compression ratio and gives lower emissions. Octane number is a measure of the gasoline quality for prevention of early ignition, which leads to cylinder knocking. The fuels with higher octane numbers are preferred in spark ignition internal combustion engines. An oxygenate fuel like bioethanol provides a reasonable antiknock value. One of the famous feedstocks in this industry is sugarcane. This crop is one grown widely for production of sugar now grown in many countries. In Brazil a major source of bioethanol is now used as a fuel for modified flexi cars. According to [1] combustion of bioethanol reduces emissions by more than 90.9%. This reduction is enough to provide comparative advantage of bioethanol over gasoline. Remember fossil fuels are processed from hydrocarbons meaning that the carbon content is inherent in the raw hydrocarbon and cannot easily be separated from fossil fuels. Figure 2.1 shows the schematic diagram showing how sugarcane juice is processed to produce bioethanol. Sugarcane in this case is considered because it is one rich feedstock that Brazil has thrived on in the production of bioethanol. Figure 2.1 therefore the process stage by stage of bioethanol production. As indicated above, flexi car in Brazil runs on 100% ethanol benefiting from 90.9% CO₂ reduction. As can be clearly seen, the greenhouse gasses effect has grossly affected agricultural and economic planning to an extent of having unanticipated droughts and shifts in seasonal changes commencing.

Other crops in the Zambian context which at times go to waste by rotting are sweet potatoes and cassava. These two crops are grown in large quantities in Zambia and the commencement of processing them into bioethanol can motivate increased number of farmers to grow the same crops. This can result in commercial farmers getting involved in growing the crops for there can be ready market for products. This study looks at this approach as one way in reducing the cost of fuel in the country and boast quick economic growth.

Figure. 2.1 below is a simplified flowsheet of fuel ethanol production from sugarcane. The network shows general process of bioethanol production sugarcane

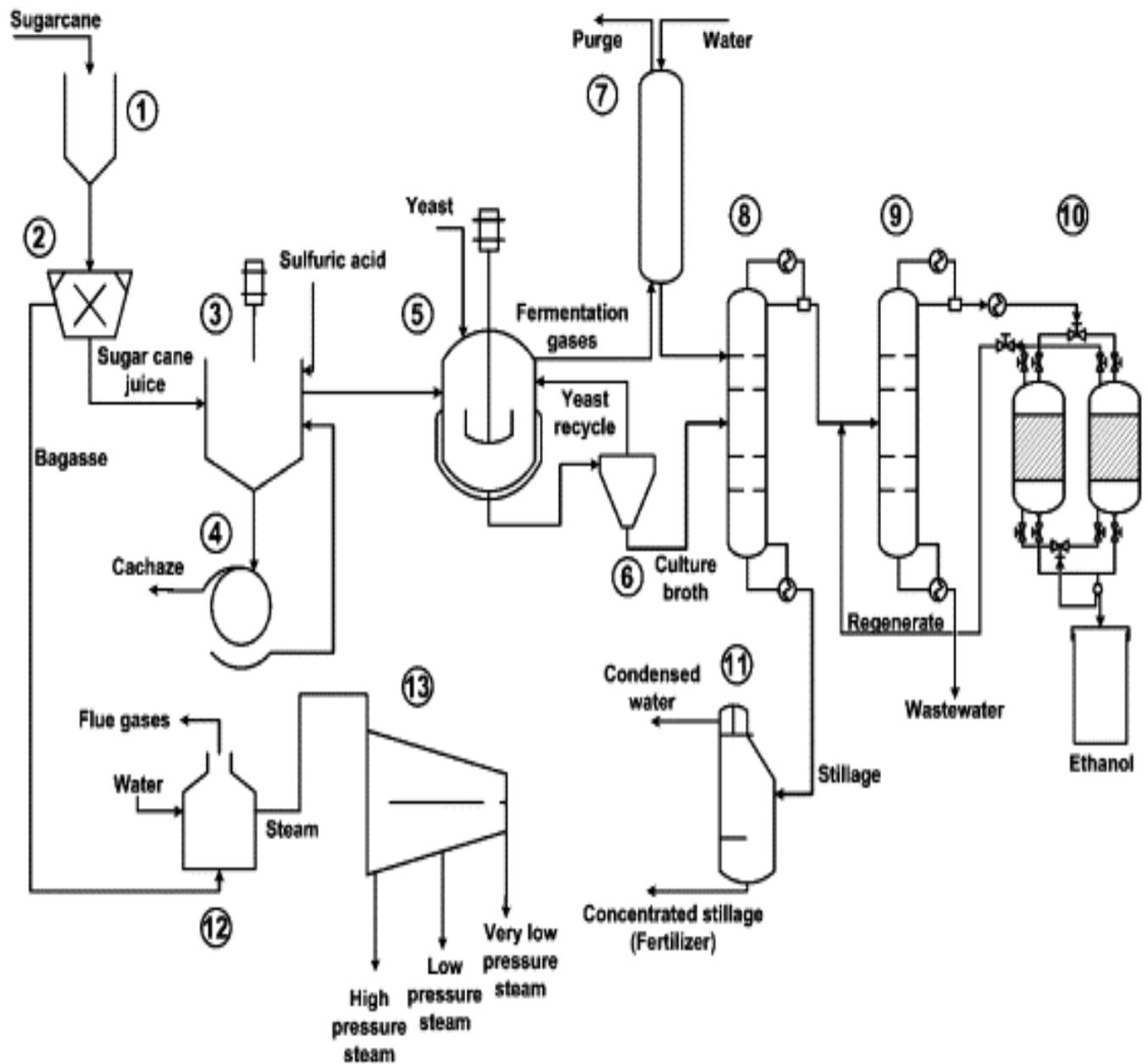


Figure 2.1, (Source: Energy 2008)

Figure 2.1: Simplified flowsheet of fuel ethanol production from sugarcane.

1. Washing tank, 2. Mill, 3. Clarifier, 4. Rotary drum, 5. Fermenter, 6. Centrifuge, 7. Ethanol absorber, 8. Concentration column, 9. Rectification column, 10. Molecular sieves, 11. Evaporator train, 12. Combustor, 13. Turbogenerator.

According to [2] there is emphasis on the many environmental effects that are poorly understood. Development of new metrics that measure specific resource input are under way. Further research into environment metrics is needed. For large scale production of ethanol to be enhanced, there is need to develop cellulosic technology. However important gains attained by using bioethanol over gasoline are not highlighted in this paper.

Looking at [3] the results indicate the high impact of cane productivity and bioethanol yield variations depending on the planting skills. The type of soil where cane is planted determines the actual yield at the end of the day. The research however lacks facts that combine environmental reductions and cost benefits especially for countries that are importing crude oil.

Considering [4] challenges of control of land use to ensure that tendencies that bleed GHG are put under strict scrutiny. It is established that indirect land use has effects on social and environmental responsibilities and actions taken. The paper has not pointed out on the activities that enhance GHG from land use. The implication is that the type soil where the cane is grown has an influence on the storage of carbon contents on the yields of cane. Basically scientific research and care must be considered each time sugarcane is planted. There must be thorough tests including soil tests. An analysis including carbon content of the soil must be carried out.

According to [5] blends of bioethanol and gasoline were the main focus used in the spark ignition engines. The positive results in terms of exhaust gasses reduction was highlighted. To evaluate this reduction in exhaust gasses, a four stroke, four cylinder engine was used to conduct the study. The results showed increases in brake power, torque, volumetric and brake thermal efficiencies and fuel consumption. There was remarkable decrease in the brake specific fuel consumption and equivalence air-fuel ratio. The CO and HC emissions concentrations in the engine exhaust decreased while the CO₂ concentration increased. The 20% volume of ethanol gave the best results of CO₂ reductions for all measured parameters at all engine speeds. However, this research is looking at 100% ethanol for it eliminates all aspects of carbon in operation unlike this one which was looking at blending.

[6] compared the benefits and environmental impacts of ethanol fuel was analyzed. An ecological footprint tool was developed by Wackernagel and Rees. A STELLA model to gauge possible outcomes as a function of variations in the ethanol production scenario. This helps in optimizing the production processes and coming up with the best practice in the production of bioethanol. This wastage is minimized and the quality of ethanol produced meets the required standards.

[7] Suggests that bioethanol from sugarcane is essentially a clean fuel and has several clear advantages over petroleum derived gasoline in reducing greenhouse gas emissions and improving air quality in metropolitan areas. Conversion technologies for producing bioethanol from cellulosic biomass resources such as forest materials, agricultural residues and urban wastes are under development and have not yet been demonstrated commercially. The report however does not give figurative and analytical advantages of using bioethanol over gasoline. Apart from the issues of greenhouse gasses, the economic advantages together with the ease of production of bioethanol

were not discussed. This approach does not give the advantage the changeover would bring about in fuel and oil industry in general.

Given [8], the research examined in detail technology and economics of substituting ethanol for gasoline focusing on three issues such as:

- i. The benefits of the ethanol/gasoline blends and the technical problems of large scale implementation of ethanol.
- ii. Ethanol production were examined in details from a variety of feedstocks and technologies. Common feedstocks are the starch/sugar crops and crop residues, while the technologies are corn wet mill, dry grind and lignocellulosic fermentation. The production possibilities allow the researchers to identify the extent of technological change, production costs, byproducts and GHG emissions.
- iii. Finally, agricultural model, FASOMGHG, is updated which predicts the market penetration of ethanol given technological progress, variety of technologies and feedstocks, market interactions, energy prices and GHG prices.

The above reference has not clearly brought out the levels of penetration of bioethanol use in the transport sector generally. This kind of information would be a factor in motivating the most required migration to modified engines in our situation in order to meet the climate change benchmarks. These benchmarks can be motivating in developing the bioethanol production industry.

[9] Discusses the production, characterization and current statuses of vegetable oil and biodiesel was discussed in this paper. The paper touches upon well-to-wheel greenhouse gas emissions, well-to-wheel efficiencies, fuel versatility, infrastructure, availability, economics, engine performance and emissions, effect on wear, lubrication oil. In the same review the properties and specifications of ethanol blended with diesel and gasoline fuel are also discussed. Special emphasis is placed on the factors critical to the potential commercial use of these blends. The effect of the fuel on the engine performance and emissions (SI as well as the compression ignition CI engines), and material compatibility is also considered. The challenge is that in the first place the paper did not elaborate the actual emission reductions from the discussed blends. Secondly the paper discusses blending whilst the interest of this research is a 100% use of bioethanol. Thirdly, the actual cost benefits for using bioethanol were not discussed in this presentation.

Figure 2.2 is a demonstration of annexing sugar/bioethanol production in one process. The system contains the distribution of the sugarcane juice with 50% going for sugar and the other 50% for bioethanol production.

2.3 Annexing Sugar and Bioethanol Production

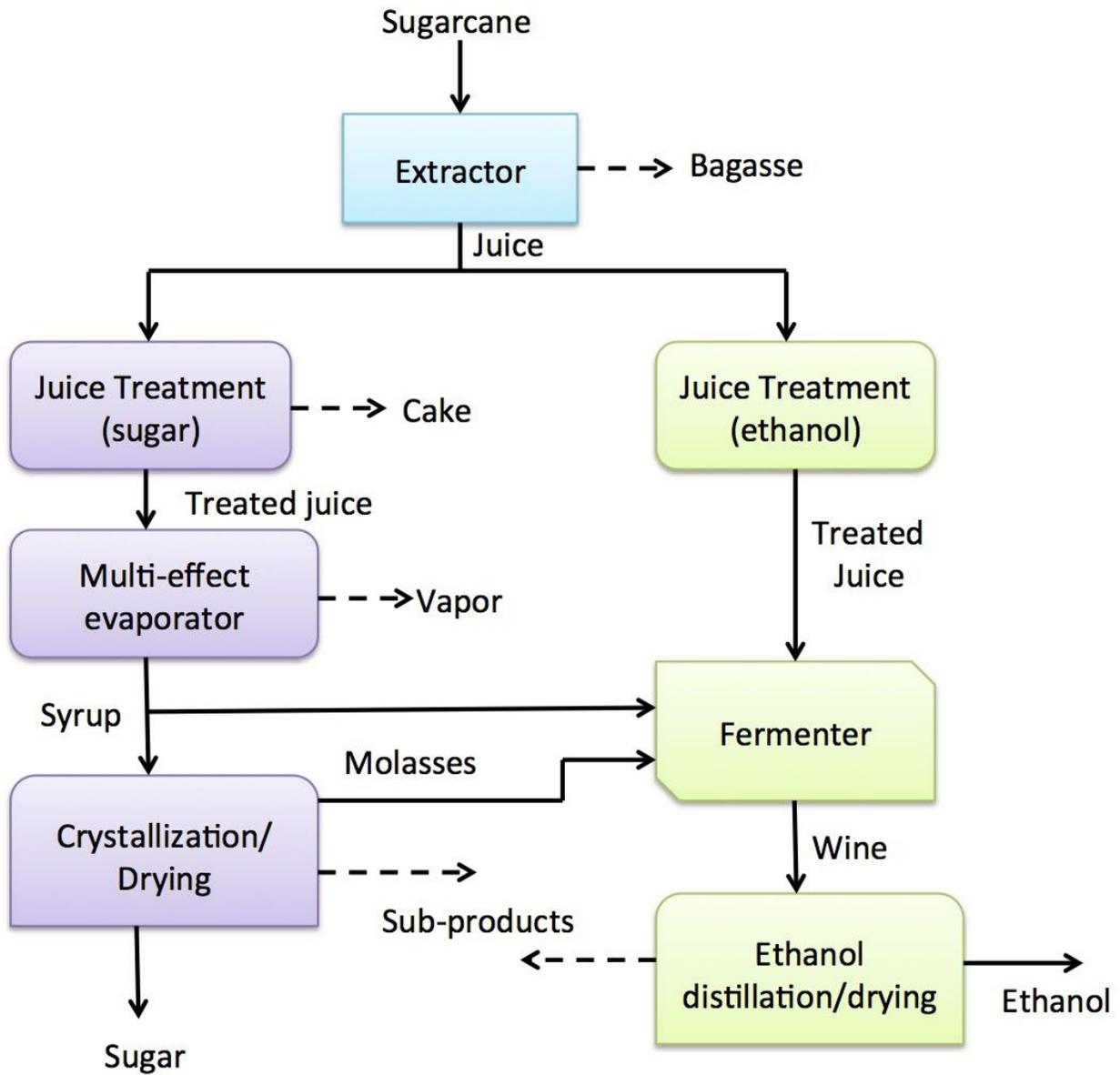


Figure 2.2 Source: e-Education Institute

To mitigate the challenges of competing demands for sugar (food) and bioethanol (Fuel), modern technologies allow for annexing the production of sugar and bioethanol. This process involves the sharing of the sugarcane juice to the production of both sugar and bioethanol.

The first step is sugarcane harvesting. Much of the harvesting is done with manual labor, particularly in many tropical regions. Some harvesting is done mechanically. The material is then quickly transported by truck to reduce losses.

The cane is then cut and milled with water. This produces a juice with 10-15% solids from which the sucrose is extracted. The juice contains undesired organic compounds that could cause what is called sugar inversion (hydrolysis of sugar into fructose and glucose). This leads to the clarification step in order to prevent sugar inversion. In the clarification step, the juice is heated to 115°C and treated with lime and sulfuric acid, which precipitates unwanted inorganics.

The next step for ethanol production is the fermentation step, where juice and molasses are mixed so that a 10-20% sucrose solution is obtained. The fermentation is exothermic; therefore, cooling is needed to keep the reaction under fermentation conditions. Yeast is added along with nutrients (nitrogen and trace elements) to keep yeast growing. Fermentation can take place in both batch and continuous reactors, though Brazil primarily uses continuous reactors.

Figure 2.2 shows a schematic of one process for ethanol production along with the option to produce refined sugar as well. Sugarcane contains the following: water (73-76%), soluble solids (10-16%), and dry fiber or bagasse (11-16%). It takes a series of physical and chemical processes that occur in 7 steps to make the two main products, ethanol and sugar.

Here is a list of the seven stages of the sugar cane process, followed by a step-by-step explanation of the seven stages:

Stage 1: Extraction

Stage 2: Juice Treatment (leading to sugar)

Stage 3: Juice Treatment (leading to ethanol)

Stage 4: Multi Effect Evaporator

Stage 5: Crystallization, Drying

Stage 6: Fermenter

Stage 7: Ethanol Distillation

Explanation of the seven stages beginning with Sugar Cane:

Stage 1 (Extraction) results in juice [also produces bagasse]. Juice is sent on to two possible stages: Stage 2 (eventually leading to sugar) or Stage 3 (eventually leading to ethanol).

Stage 2 produces Treated Juice [also produces cake].

Stage 3 produces Treated Juice. Treated Juice from Stage 3 is sent on to Stage 6 (Fermenter), while Treated Juice from Stage 2 is sent on to Stage 4 (Multi Effect Evaporator).

The result of Stage 4 (Multi Effect Evaporator) is syrup [this stage also produces vapor]. This

syrup is sent on in several possible directions.

Option 1. The syrup finishes at Stage 5 (Crystallization, Drying), where the syrup becomes sugar [or sub-products].

Option 2. The syrup passes through Stage 5 (Crystallization, Drying), where the syrup becomes molasses and then goes on to Stage 6 (Fermenter).

Option 3. The syrup goes directly to Stage 6 (Fermenter).

The result of Stage 6 (Fermenter) is wine. The wine is sent on to Stage 7.

The result of Stage 7 (Ethanol Distillation) is ethanol [this stage also produces sub-products].

So, why produce both sugar and ethanol? Both are commodity products, so the price and market of the product may dictate how much of each product to make. This is how Brazilian ethanol plants are configured. In order to have an economic process, all of the products, even the by-products, are utilized in some fashion.

As noted previously, one of the major by-products is the dry fiber of processing, also known as bagasse. Bagasse is also a by-product of sorghum stalk processing. Most commonly, bagasse is combusted to generate heat and power for processing industries. The advantage of burning the bagasse is lowering the need for external energy, which in turn also lowers the net carbon footprint and improves the net energy balance of the process. In corn processing, a co-product is made that can be used for animal feed, called distiller grains, but this material could also be burned to provide process heat and energy. The main drawback to burning bagasse is its high water content; high water content reduces the energy output and is an issue for most biomass sources when compared to fossil fuels, which have a higher energy density and lower water content.

2.4 Bioethanol Production from Sweet Sorghum

Another interesting feedstock for the purpose of bioethanol production is sweet sorghum. This crop generally grows in Zambia for its sweet juice if commercialized can assist in the area of biofuels. According to [10] this feedstock can be used under dry or hot conditions. It has higher tolerance to salt and drought compared to sugarcane. In addition, high carbohydrates content just like sugar cane. Due to its salt content sweet sorghum makes it easier for fermentation to ethanol. The focus of this research however is to check on the availability of this feedstock in preparation for migration to modified engines by 2040. Chaubey does not discuss the commercialization aspect and focusses on research and development.

Similarly[11] according to researchers Kalaluka Munyinda, Francis Davison Yamba and Hartley Walimwipi, bioethanol feedstocks in Africa include sugarcane, sweet potato, sweet sorghum and cassava. The report indicated that bioethanol potential in selected African countries for different use is estimated at 35EJ with The Democratic Republic of Congo and South Africa with the largest potential followed by Angola, Sudan, Zambia and Tanzania.

The report reveals that bioethanol production in Africa was 637 million liters in 2007. It also reveals that high production is South Africa followed by Egypt and Nigeria. It was noted that the biggest challenge in the development of biofuels markets in Southern Africa is that although

potential markets exist, and conventional technologies are available, feedstock is not available in sufficient quantities. It was observed that the main feedstock for bioethanol production in Africa is sugarcane but in the recent past the continent has seen an increasing interest in the new feedstocks types such as sweet sorghum.

The results for yields and sugar brix for eight exotic sweet sorghum varieties (TS1, Madhura, Praj-1, GE2, Wray, Cowley and Keller) were presented and compared to a local sweet sorghum variety “Sima”. The results showed encouraging yields averaging at 30 tons per hectare under the rain fed conditions. Sugar content in Brix% averaged at about 18% for medium maturing varieties (Keller, GE3 and Sima). The highest values of sugar content of sweet sorghum varieties are the same as those of sugarcane (18%).

[12], Discusses an analysis of the prospects for international bio-energy trade within the continent particularly regional integration and sustainable development in the region of Southern Africa. The focus being bioethanol processed from sugarcane and sweet sorghum. The focus of this research was looking at bioethanol production for blending with gasoline. The research also focused on the implications for alternative development paths and regional cooperation strategy was discussed and compared. The research emphasized the need for deliberate policies within the region to significantly increase suitable feedstocks in order to achieve economies of scale. It was observed that investment in this area would create new avenues in the region for export trade markets. The aspect of international trade protocols were equally discussed that would consider reducing tariffs and address trade barriers as well as promoting technology transfer and capacity building. Whilst this a good research its focus was bioethanol production for blending purposes. This research is looking at replacement of gasoline with bioethanol and use modified engines suitable to ignite and run on bioethanol.

[13] Reports the merits of sweet sorghum and sugarcane crops for the expansion of bioethanol sector in Nigeria. The research explains that from a number of perspectives, sugarcane molasses and sweet sorghum are major biomass sources for Nigerian fuel alcohol fermentations and findings indicate that sweet sorghum is the most suited in terms of environmental impact, sweet sorghum cultivation is more water efficient with less labor input, fertilization and agrochemical application.

The more of life cycle analysis was used to compare the environmental, social and economic aspects using sweet sorghum stalk juice and sugarcane molasses . Sweet sorghum represents a fairer biomass source and there is great potential for sustainable development and utilization sweet sorghum bioenergy production in Nigeria. However, the paper did not highlight the actual physical purpose of the study considering the fact Nigeria has a well-developed industrial base for the production and processes of fossil fuels. The paper did not in any way discuss blending or alternatively replacement of fossil fuels. The modified engines were not as well in the picture of this paper. The focus was to compare sweet sorghum juice and sugarcane molasses.

According to [14] developing bioethanol crops in Taiwan has many benefits. Four most popular alcohol crops in Taiwan are sweet potato, maize, sugarcane, and sweet sorghum. Sweet sorghum

stands strongly as a key crop in this regard. The advantage is its short period, low water requirement, large amount of biomass and high level of alcohol produced and greater income obtained from sweet sorghum cultivation. Whilst it is agreed that bioethanol is an alcohol, this research is far below the expectation with regards to using bioethanol as a fuel. The concentration of the report was the four crops converted to wine and variety of alcohol brands.

[15] Reported that sweet sorghum bicolor is similar to common grain sorghum with a rich sugar stalk. Sweet sorghum is characterized by wide adaptability, drought resistance, water logging resistance, salt resistance rapid growth, high sugar accumulation and biomass. Compared to sweet sorghum, lengthy growing period and high water requirements are the disadvantages in sugarcane and sugar beet (*Beta Vulgaris*), the main sources of sugar production in the world. This along with the comparative disadvantage of molasses (higher price, water and air pollution) are expected to increase the interest in sweet sorghum. This research thoroughly discussed the advantages of sweet sorghum over sugar beet and sugarcane. It has however not explained the production of bioethanol using sweet sorghum which is the focus of this research.

[16] Conducted a feasibility study was conducted in the southeastern United States through the representative countries in Mississippi. The research was studying and examining sweet sorghum production as a feedstock for ethanol production. The costs of production and transportation were estimated and the breakeven point established. These costs and breakeven cost were used to establish wholesale cost bioethanol as a final product. Using stochastic models the estimate profits for sweet sorghum bioethanol production were made and results showed losses. Clearly this report was experimental still under research and development in these regions of the United States.

[16] Further reported that sweet sorghum has been identified as a possible ethanol feedstock because of its high yield and its high concentration of readily fermentable sugars. Traditionally it has limited use because of poor post-harvests storage characteristics and a short harvest window in cooler climates. Transactions of the ASABE 51(2), 603-613) indicates that fermentable carbohydrates can be produced at less expense from sweet sorghum than from corn grain. The report indicated that economics of scale benefit larger milling equipment and boiler systems reducing fermentable carbohydrates (FC) more than 50% when increasing annual plant capacity from 37.9 to 379 million liters of storage of high moisture sweet sorghum in bunkers. This storage leads to significant losses of moisture and results in systems with net FC costs well above those of corn-derived FC. This report does not discuss the potential of bioethanol from sweet sorghum as a possible replacement for environmental pollutant fossil fuels.

According to [16] it is discovered that ethanol demand is increasing drastically in the present time due to its blending in automotive fuels which is desirable for getting clean exhaust and fuel sufficiency. The paper identifies the higher cost of cultivation of sugarcane/beets, highly sensitive molasses rates and instabilities in the price of ethanol price have created grounds to search for an alternative source of ethanol production. It was reported that sweet sorghum has shown potential as a raw material for fuel-grade ethanol production rapid growth rate and early maturity, greater

water use efficiency, limited fertilizer requirements total value and wide adoptability. It was emphasized that ethanol producing companies, research institutions, and government agencies can coordinate with each other to strategically develop value-added utilization of sweet sorghum. The report said Fuel-grade ethanol production from sweet sorghum syrup can significantly reduce India's dependence on foreign oil and also minimize the environmental threat caused by fossil fuels.

[17] examined the making of ethanol from the sugar extracted from the juice of sweet sorghum and/or from hemicellulose and cellulose in the residual sorghum bagasse was done. The paper indicated that the production of ethanol from the hemicellulose and cellulose in China was more favorable than burning it to make power, but the relative merits of making sugar from the juice was very sensitive to price of sugar in china. This result was confirmed by both process economics and analysis of opportunity commodity. Thus a flexible plant capable both sugar and ethanol from the juice was recommended. Generally, ethanol production from sorghum bagasse appeared very favorable, but other agricultural residues such as corn stoker and rice hulls would likely provide a more feedstock for making ethanol in the medium or long term due to their extensive availability in North China and their independence from other markets. The paper did not clearly discuss the wholly use of bioethanol to propel a motor vehicle as a fuel. Apparently that is where this research hinges with the purpose of minimizing environmental degradation caused by the combustion of fossil fuels.

Figure 2.3 layout shows the circuit in the production of bioethanol using sweet sorghum. This demonstrates that when sweet sorghum is harvested, the biomass is stored in the silos as animal feed. The grain goes through various processes. First it is used for poultry and animal feed. It also goes through the hydrolysis process, centrifugation then into a filter cake. The liquid content of the grain is fermented into alcohol. The juice is extracted from the stalk, fermented and turned into alcohol. The leaves, bagasse from the stalk and filter cake are all supplied as animal feed.

2.4.1 Layout of Bioethanol Production Plant Circuit

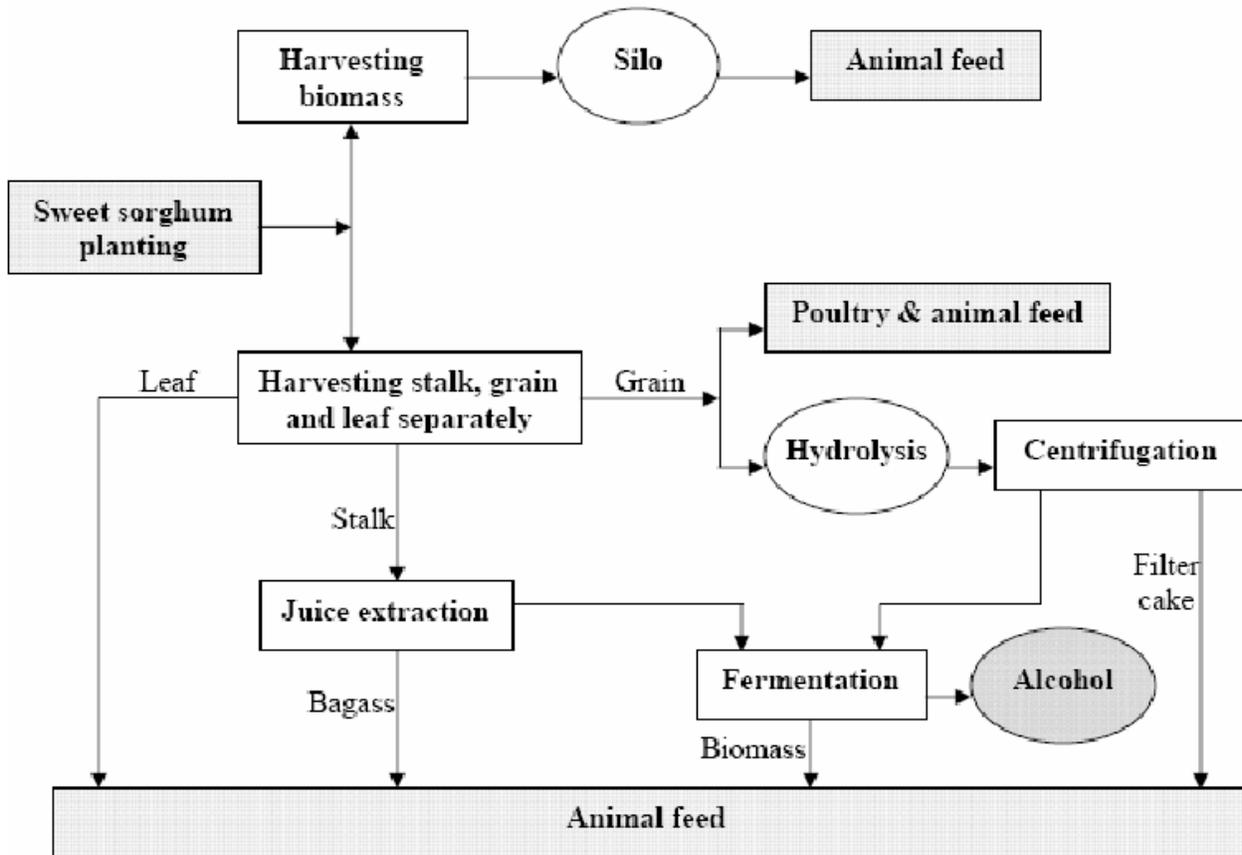


Figure 2.3: Bioethanol production layout from sweet sorghum. Source: Abas Almodares Dec, 20, 2016

2.5 Bioethanol Production from Sweet Potato

According to [18] a research was conducted on the bioprocess for bioethanol production from raw sweet potato by *saccharomyces cerevisiae* at laboratory, pilot and industrial scales. The report further discusses how the fermentation mode, inoculum size and pressure from different gases were determined in the laboratory. It was observed that sweet potato is an attractive feedstock for bioethanol production from both the economic standpoints and environmentally friendly. Whilst this research paper brought out important attributes of sweet potato towards bioethanol production such as the actual quantities of yields versus a given tonnage of sweet potatoes was not part of this research.

[18] Reported that the net energy ratio and net energy gain values were 1.48 and 6.55MJ/L respectively. It was further expressed that the most significant environmental impacts were eutrophication and acidification. The main sources contributing to energy consumption and environmental impact were analyzed. Also sensitive factors were identified, and improvement measures were discussed. The major interest of this research is to establish quantities in a given

tonnage not necessarily the energy produced. This paper lacks the important elements required for the focus the research constituted for.

[18] research paper, the effects of the dry matter ratio of sweet potato to water, the fermentation efficiency and sweet potato sugar content on the energy consumption thus steam and electricity were respectively evaluated. The best ratio of dry matter to total water to work with fresh sweet potato was found to be 0.2 kg dry sweet potato/kg water, as for greater ratios was not found a significant reduction in energy consumption. The drying of the sweet potato and its processing was also studied. It presented an energy consumption greater than the energy content of the bioethanol produced. Again here a situation where the direct utilization and production bioethanol was not discussed.

[19] Investigated the establishment of the hydrolysis of starch from fresh potato tubers by HCL and H₂SO₄ at different ratios of plant material to acid solution. Finally reducing sugars concentration in the hydrolysates depended on the type and concentration of acid and the ratio of plant material to acid solution but not on the type of potato. 94% is the highest dextrose equivalence which is the greatest reaction rate at a constant of 0.089⁻¹ and the 5-hydroxymethylfurfural (5-HMF) yield of 0.04g/L were achieved using 1M HCL at the ratio of plant material to acid solution of 1:2 (w/v). This paper showed a yield of 31g/L obtained in the fermentation prepared under the optimal hydrolysis conditions by commercial bakery yeast at 28°C for about 18h.

[20] Discussed the specialized sweet potato (K159) that it contains starch with low gelatinization temperature. It was equally observed that K159 mash containing high solid content was prepared by enzymatic viscosity reduction. As a result it was concluded that low temperature liquefaction was efficient for ethanol production from the K159 mash. The research majored on the K159 with clearly stating the comparative advantage over the other varieties of sweet potatoes. It does not equally indicate the quantities of bioethanol attained from a given tonnage of sweet potatoes. Secondly it was done in 2012 when migration from use of fossil fuels was not a serious issue.

[20], Emphasis was on the worldwide need to find out new and less costly carbohydrate sources for production of bioethanol. The context under which this was discussed was an investigation in the use of mahula (*Madhuca latifolia* L) flowers by *saccharomyces cerevisiae* in solid state fermentation. It was reported that the moisture level 70% pH of 6.0 and temperature of 30°C were found optimum for maximum ethanol concentration (225.0±4.0g/kg flower) obtained from mahula flowers after 72h of fermentation. The results obtained were concomitant with highest ethanol concentration with the maximum ethanol productivity (3.13g/kg flower/h), yeast biomass (18.5*10⁸ CFU/g flower), the ethanol yield (58.44g/100g sugar consumed) and the fermentation efficiency (77.1%) were also obtained at these parametric levels. However, this feedstock is not known in Zambia.

[21] Focused on purple-fleshed industrial sweet potatoes (ISPs), a crop which is used for industrial purposes because it produces relatively high quantities of antioxidants in form of anthocyanins as well as high starch content for potential hydrolysis into fermentable sugars. Experimental extracts

and enzymatic hydrolysis analysis were conducted on purple-fleshed ISPs in order to evaluate the effects of solvent, extraction temperature and solid loading on recovery of anthocyanins and fermentable sugars. The research also included measurement of the total monomeric anthocyanin and phenolic concentrations of extracts. Residual solids from anthocyanin extraction were subsequently hydrolyzed for sugar production (maltotriose, maltose, glucose and fructose). The research also refers to the extraction temperature of 80°C using acidified methanol at 3.3 % (w/v) solid loading showed the highest anthocyanin recovery at 186.1 mg cyaniding-3-glucoside/100gfw.

The findings showed that acidified solvents resulted in 10-45% and 16-46% more anthocyanins than non-acidified solvents of ethanol and methanol respectively. On average, glucose production ranged from 268 to 395 mg/g dry ISP. Solid residues that went through extraction with acidified ethanol at 50°C at 17 % (W/V) solid loading had the highest average production of glucose at 395mg/g dry ISP. The findings also reported that residues from methanol solvents had lower glucose production after hydrolysis compared to those of ethanol based extraction.

It was further reported that fermentation of produced sugars from ISP residues was limited, where 38% less ethanol was produced from extraction residues compared to treatments that did not undergo initial extraction. All in all, purple-fleshed ISPs are amenable to anthocyanin and phenolic extraction, making it a suitable substrate for development of industrial coolants and dyes. This was a thorough research paper which looked at purple-fleshed sweet potatoes. However, the discussion on bioethanol production using sweet potatoes was not mentioned in this publication.

[14] looked at the global energy crisis and continual soaring prices of fossil fuels was done. The research emphasized that the crisis and costs of fossil fuels were forcing people to seek new and recycled alternative energy sources. Biodiesel oil as well as bioethanol fuel, as two new and clean fuels for environmental protection, have already been approved as substitutes for fuel or fuel additive. Some common bottlenecks for production of biodiesel crops have been found. In Taiwan developing bioethanol crops has many benefits. Four most promising alcohol crops i.e. sweet potato, maize, sugarcane and sweet sorghum have been discussed. The paper re-emphasizes that sweet sorghum can be strongly recommended as a key crop for alcohol production because of its short growing period, low water requirement, large amount of biomass and alcohol produced and greater income obtained from sweet sorghum cultivation.

[22] Observed that Zambia depends entirely on imports for its petroleum supply and considerations were underway to implement blending mandates for biofuels. The research showed the challenges that go along with this implementation. These challenges included production costs of biofuels, land requirements to meet the mandates and exploration of environmental benefits. The research was able to look at the cost range for bioethanol from US\$0.360 a liter to US\$0.680 a liter while the costs for biodiesel production range from US\$0.612 a liter to US\$0.952 a liter. The research analysis was that even if lower contents of biofuels were taken into account, biofuels were found to be cheaper than their petroleum counterparts. Since the biofuels have a cost benefit

over petroleum products and the availability of surplus agricultural land, Zambia was likely to benefit from the development of biofuel industry.

It was further observed that biofuels were expected to reduce Zambia's petroleum import bill which then stood at more than US\$700million and enhance food security by providing incentives to increase yields and increase affordability and accessibility to modern energy in the country where 77% of the population still lacks access to modern energy. This would also stimulate rural employment and development. The research however not look at 100% bioethanol as fuel for motor vehicle propulsion. This is the required scenario now as the first world countries are migrating to electrical cars, third world countries like Zambia will have to revert to biofuels in order to mitigate the negative environmental effect of combustion of fossil fuels.

[23] in their research looked at an approach which marries together value chain analysis with other stakeholders to ensure that analysis of opportunities and constraints get translated into actions that would facilitate commercial growth. Using Zambia's task force as an example, the paper described the value chain task force method and identifies elements critical to its effective implementation. This research focused on cassava and it shall be looked at in the next section.

2.6 Bioethanol Production from Cassava

Cassava is one of the crops that is widely used for bioethanol production. Various scholarly journals have shown that the crop cassava is an important resource and feedstock for bioethanol production. The advantage the crop has is its ability to grow even in drought prone conditions.

[24] Emphasized that cassava-based bioethanol has a negative net energy value with an energy ratio less than 1 indicating net energy loss. In the environmental performance area, the results showed that throughout the life cycle of bioethanol, the conversion stage contributes most to the environmental impacts which is due to the use of coal for power and steam production in the bioethanol plants. There was however a proposal to substitute coal with biogas produced from existing waste water treatment in order to significantly reduce environmental impact caused by coal. The paper did not come out as a successful research. It has not thoroughly demonstrated the application of bioethanol and its use.

[25] Studied and showed that spezyme level beyond 20.0 mg for a 10% (w/v) starch slurry was not critical for optimizing bioethanol yield from cassava starch, although a primary thinning of starch for 30 mins by spezyme facilitated saccharification-fermentation by stargen+ yeast system. The specific advantage of the new process was that the reaction could be completed within 48.5hrs at $30 \pm 1^\circ\text{C}$. This was another paper that was scientifically expressed but lacked the reality in terms of energy conversion from a given quantity of feedstock to the produced quantity of bioethanol.

[26] Reported cassava carbohydrates production in Maryland was poor yielding only 2.9 ha^{-1} . In Alabama the situation was different because the carbohydrate production from cassava averaged 10 ha^{-1} relative to carbohydrate production from corn in each location, sweet potato and cassava yielded approximately $1.5\times$ and $1.6\times$ as much carbohydrate as corn in Alabama, $2.3\times$ and $0.5\times$

for the Maryland site. In the event that economical harvesting methods and processing techniques could be developed, the given data suggested that sweet potato in Maryland and sweet potato and cassava in Alabama have greater potential as ethanol feedstock and sources than the existed corn systems, and as such, could be used to replace or offset corn as sources of biofuels. The research has not clearly demonstrated the technology application using sweet potato and cassava to produce bioethanol.

[27] Observed that the main and interaction effects of factors were subsequently evaluated based on a quadratic equation generated by central composite design (CCD) using response-surface methodology (RSM). It was further observed that under the optimized very high-gravity conditions, the final ethanol concentration obtained from the experiment increased from 8.21% (Wt. %) to 15.03% (wt. %) and was in good agreement with the model prediction. It was emphasized that by using two other commercial *Saccharomyces* strains, same results were obtained under similar optimized condition. The conclusion therefore was that final ethanol productivity ($V_{p/\max}$), glucose utilization ($Y_{G/s}$, $Y_{P/s}$) and fermentation efficiency (η_f) were enhanced or maintained under optimized condition of 40% gravity, 390 μ m particle size, initial pH 5.5, and 27°C fermentation temperature. The research however numerically lacked variable information that would allow clear estimates in the planning of bioethanol production.

[28] Carried out experiments and the results showed that the maximum methane yield (259.46mL/g-VS) of cassava residues was obtained through 12h of pretreatment by this microbial consortium which was 96.63% higher than the control (131.95 mL/g-VS). On top that, it was further found that the maximum methane yield is obtained when the highest filter paper cellulose (FPase), carboxymethyl cellulose (CMCase) and xylanase activity and soluble COD (sCOD) are produced. No mention was made about bioethanol production.

[29] Reports the results of the review process of the authors propose a simple and scalable two-step process that biologically converts the waste streams into valuable products. The first consideration in the process is fermentation and distillation of the cassava waste to produce ethanol. The other consideration is the anaerobic digestion of the fermentation byproducts with other waste streams including animal waste and human excrement to produce biogas and biological fertilizers. With the scalability of this application, the focus of the review was the development of a conceptual system for rural small scale businesses to achieve multiple beneficial outcomes which were treatment of multiple troublesome waste streams and production of a liquid biofuel including the provision of refrigeration through biogas powered absorption chillers and the co-production of organic fertilizer. Another good research but could not quantify the actual expected yield results.

In the similar vein, [30] reports that the potential in Ghana shows that biomass is the major energy source in that country contributing about 64% of Ghana's primary energy supply. Therefore, the paper gave an assessment of biomass resources and biofuels production potential in Ghana. The major and wide areas of energy crops, agricultural crop residues, urban wastes and animal wastes were part of this research. Animal wastes only cover and are only produced by domesticated

livestock. The agricultural residues was obtained and generated from sugarcane, maize, rice, cocoa, oil palm, coconut, sorghum, and millet processing. In the urban category, it was subdivided into municipal solid waste, food waste, sewage sludge or bio-solids and waste grease. These types of biomass were readily available together with brief description of possible biomass conversion routes, sustainability measures and there was research and development activities in Ghana. From the above discussion it was concluded that a large availability of biomass in Ghana gave great potential for biofuels production from the discussed resources. Another area clearly highlighting potential which is not figurative and perhaps at that time, there were no protocols to effect of phasing out fossil fuels hence everything was kept as academic R&D exercises.

[31] Highlighted that the highly politicized food versus energy debate becoming the relevant bottleneck for using potential food (such as cassava and other energy crops) for energy production. It suggested a paradigm shift and a more holistic and complementary view of food and biomass energy production. The research discovered that cassava and its biomass as the future crop for biogas production in Africa and especially in Southern Africa. During this research the actual direction of what could be produced out of cassava was not established though it was made clear that cassava is a good bioethanol feedstock.

[32] Observed that wide weather-induced fluctuations in maize production lead to recurrent food shortages in Zambia's maize consuming regions, while the cassava-growing regions of the north enjoy stable food production even in the years of severe drought. Understanding this striking correlation between drought vulnerability and prevalence of maize as a staple food, a growing array of agencies in Zambia had begun introducing highly productive new cassava varieties, developed in the north of the country, to more central and southerly regions in an effort to provide low-cost food security during drought years. It was also discovered that agro ecological conditions in these drought-prone regions differ significantly from the northern research stations where Zambian scientists developed new cassava varieties. It was however, not clear that the varieties or management practices that can work well in the north would prove optimal in other regions too.

Efforts were made to try to help farmers and agencies interested in expanding cassava as a food security crop in central Zambia. Trials were conducted over a period of three years in central Zambia. To curb the hunger threats, discussions were conducted with early adopting farmers. Out of this research, results from those investigations suggested that, with some modification of management practices recommended in the north, many of the new cassava clones offered a feasible means of mitigating lean season hunger and providing low-cost, in-kind drought insurance in rural households in central Zambia. Barratt mainly discussed cassava as a food crop. There was no mention of bioethanol production whatsoever. Such an approach does not enhance product growth rendering cassava to remain in the domains of the small scale farmers.

[23] Presented a method of operating for smallholder farmers is in vertical supply chains. It is therefore important to have an understanding of key opportunities and constraints up through the value chains become necessary for sustaining smallholder growth. Matters of market analysis were

of little value unless key private and public sector stakeholders agreed to implement necessary reforms. This work advocated an approach which combines together value chain analysis with a stakeholder task force to ensure that analysis of opportunities and constraints get translated into actions that will facilitate commercial growth. Using Zambia's cassava task force as an example, the paper describes the value chain task force method and identifies elements critical to its effective implementation. In terms of bioethanol production, this research did not provide any solution. However, in the Zambian scenario, this crop is one of those crops contributing effectively to well-being of the citizens as a staple food on the northern part of the country. One advantage it has is the drought resistance.

However, because cassava flour is widely used in certain parts of the country in place of maize, flour as staple food, much attention is given to its growth by the relevant authorities. This attention had resulted in researching for fast growing varieties targeting at those giving good yields of the crop. The Government of the Republic of Zambia had been involved in rendering support to farmers involved in growing this crop. This had resulted in motivating the farmers and each year the yields were increasing.

These increases were what would spearhead the bioethanol crusade since cassava gives good quantity and quality bioethanol production. Traditionally, other regions of the country do consider cassava as food and it is not cultivated in those regions. If bioethanol production commenced, cassava being one of the feedstocks, other farmers even in the regions where it is not popular would be compelled to grow it as a cash crop. While it is a fact that competing with food would not suffice in any given set up, the numbers obtained from the given environment would divide resources in the most equitable manner much to the benefit of the supplier and the nation as a whole.

It remains undisputed that one fossil fuels oil reserve would one day runout and that its pollutant nature remains harmful to the environment and humans. It is important that planning starts now to invest in other sources of fuel especially renewables because one day the country will be on standstill. Prevention remains important than cure.

2.7 Levelised Cost of Energy Considerations

[33] Observed that the cost of bioethanol production was determined by the entire performance of the supply chain from production to consumption. The process was broken down in components that costed separately, and looked at the cost element and profitability. However, the paper did not provide enough information on the process. The challenge was that the feedstocks were not discussed and costed accordingly. The paper therefore did not provide information that could easily be followed and relied on for the purpose of research.

[34], Presented the Indonesian scenario on the depletion of fossil fuels was considered. The paper looked at the estimates of depletion of source of energy with oil pegged to deplete in 12.8 years with natural gas and coal pegged at 30.8 and 59.8 years respectively. It was felt the depletion estimates were impacting negatively on the general energy security. The paper described coal as an equal pollutant like fossil fuels hence promoting biofuels in its publication. The paper therefore

identified biofuels and nuclear energy as the options to be considered in the technology transfer. Nevertheless, discussed and proposed the levelised cost of energy but without employing figures to work out the cost of energy.

[35], Looked at the viability of clean technology and the economic aspect was thoroughly discussed. The idea of the paper was to consider diminishing fossil fuels while financing mechanisms should be looked for to finance the development of clean energy. The paper emphasized on the technology transfer to enable biofuel penetrate especially the transport sector. The paper also discussed the resistance that came about moving from the traditional fossil fuels to biofuels. This however paper did not mention levelised cost with necessarily worked examples to provide the much needed comparison between fossil fuels and biofuels.

2.8 Critique of Literature Review

It was discovered that there was emphasis by the publishers above that the feedstocks were rich in bioethanol production. The challenge however was that none of the referenced authors came out with a well-articulated approach to bioethanol production relating quantity of feedstock to bioethanol quantity potential. After linking the yields to figurative bioethanol potential the authors could not tie the derived potential to the unit cost of each of the feedstocks under consideration. This research therefore was looking at the yields, convert to bioethanol potential and come up with the levelised cost of energy of each of the feedstocks of which outcome had to be compared to the current cost of gasoline.

CHAPTER 3: MATERIALS AND METHODS

This chapter presents Materials and Methods that were used to do this work. First of all, literature was reviewed in detail where worldwide sugarcane, sweet sorghum, sweet potato and cassava were being converted into bioethanol. With this analysis, it became imperative to take stock Zambia's capacity at national level for these crops over the years if they were to be used as feedstocks for local bioethanol production with the focus of using bioethanol as the replacement for gasoline in the running and operation of motor vehicles in Zambia.

This research was being done to provide the platform to meet the 2040 climate objectives. While the developed world countries were migrating to electric cars, third world countries like Zambia should resort to bioethanol if they were to contribute to pollution control mitigation measures as they developed the infrastructure for electric cars.

3.1 Data collected

The following data was collected from various organisations:

1. National gasoline consumption from 2007 to 2017 in Zambia.
2. Sugarcane yields in Zambia from 2007 to 2017.
3. Sweet potatoes yields in Zambia from 2007 to 2017.
4. Cassava yields in Zambia from 2007 to 2017.
5. Daily gasoline consumption in Zambia in the year 2018.
6. Conversion factors of molasses and starch to bioethanol.

3.2 Data collection sites

Table 3.1 below has the list of organizations where relevant data for this research was collected.

Table 3.1: List of organizations where data was collected

Number	Organization Visited And Contacted For Data	Location
1	Ministry of Energy	Lusaka
2	Ministry of Agriculture	Lusaka
3	Central Statistics Office	Lusaka
4	Energy Regulation Board of Zambia	Lusaka
5	Road Transport and Safety Agency	Lusaka
6	Zambia Sugar Plc	Mazabuka
7	Kafue Sugar	Nampundwe
8	Kasama Sugar	Kasama
9	Internet	UNZA

Please note that data from the above organisations was obtained formally by letters of introduction from School of Engineering and through a verbal interview data was given out.

3.3 Ministry of Energy

The Ministry of Energy is responsible for energy security in country by monitoring the energy status of the country at all times. The ministry provided information on the daily consumption levels of gasoline in the country. This information was obtained through a formal meeting after a letter of introduction from the school and data released through verbal interview. It was established that at this ministry that there was a technical committee set to look at the prospects of biofuels in Zambia. It was learnt at the Ministry of Energy that the ministry is quite aware of the impending challenges in continuing using fossil fuels in the country.

3.4 Ministry of Agriculture

The Ministry of Agriculture plays a major role in ensuring food security in the country. With this, the ministry carries out inventory of how the agriculture sector was performing in the country. At the Ministry of Agriculture, data on the national yields of cassava and sweet potato was obtained from 2007 to 2017. Apart from that, the crop survey unit provided data on how these crops were utilized for food and for sale including obtaining market prices. This ministry also provided information on the excess yields of cassava and sweet potato that can be converted to bioethanol without compromising the food security in the country.

3.5 Central Statistics Office

The Central Statistics Office which is responsible for providing information on the economic performance of the country. The areas of coverage include the cost of the food basket. Ability by the average household to have enough food on the table. Such responsibilities require to monitor how the agriculture sector is performing. At Central Statistics Office data was given on the crop harvests from 2007 to 2018. The data collected covered crops under this research apart from sweet sorghum. Each year had its own annual harvest making it easy to follow the trend of annual increases.

3.6 Road Transport and Safety Agency

Road Transport and Safety Agency is responsible for vehicle registration and monitor the road worthiness of registered vehicles in Zambia. This research sought to know whether under its registration the Agency had vehicles registered that were using bioethanol as fuel in Zambia.

3.7 Energy Regulation Board of Zambia

The Energy Regulation Board monitors the operations of energy utilities in the country on behalf of the Government of the Republic of Zambia. With this responsibility the Energy Regulation Board provided vital historical data on utilization of gasoline in country. The covered period ranged from 2007 to 2017 with annual gasoline consumption each year. This data provided direction and guidance to this research

3.8 Zambia Sugar PLC

Zambia Sugar is the oldest and biggest sugar plantation in Zambia. The data collected from this company was its sugarcane yields over the years. It was established that the company's sugarcane were part of the annual reports published by the company and were found on the official company website. The company had reports as way back as 2001. Since the baseline was 2007, data from 2007 to 2017 was obtained for purpose of this research.

3.9 Kafue Sugar

This is the second largest sugar plantations in country which is located along the Kafue flats. The company provided data on its sugarcane yields from 2007 to 2017. The company also shared vital information which was in tandem with this research. It was established that the company was in the process of diversifying the business operations to include bioethanol production from molasses. A plant so far was under construction.

3.10 Kasama Sugar

Kafue Sugar provided information on the contact details of Kasama Sugar. After contacting Kasama, data on the sugarcane yields for the period under review was provided. This saved costs and time that could have been incurred for travelling to Kasama.

3.11. MATLAB Tool

The MATLAB tool R2017A model was used to process the collected data. Specifically, curve fitting application tool was used. Using this tool it was possible to derive equations, extrapolate and finally come up with forecast graphs and lines of best fit in each case. When this tool is opened, it gives options of applications and in this case the exponential was identified as a suitable tool for this process. The tool was able to graphically plot the fed data and provide scenarios between the line of best fit and actual position according to the way data was flowing.

3.12. Computer Used

A personal acer laptop was used to install the MATLAB tool and prepare the thesis report with the following specifications:

- i. Processor-----i3
- ii. Processor Speed---2.0 GHz
- iii. RAM-----4 GB
- iv. Hard Disc----- 1000 GB

CHAPTER 4: DATA ANALYSIS BY SOURCE

This chapter consists of data that was collected in the course of assembling useful input information during this research. The nature of data that was collected is as set out in the objectives of this research in the order of the subtitles below.

4.1. Energy Regulation Board of Zambia

The data that was collected at the Energy Regulation Board provided the basis on which the whole research was leaning. Without the data below, the whole research had no starting point. The Board provided data on gasoline consumption in the country from 2007 to 2017

4.1.1 National gasoline consumption

Table 4.1 below consists of data collected from Energy Regulation Board on the national annual gasoline consumption from 2007 to 2017

Table 4.1: National Annual Gasoline Consumption (liters)

Year	National Annual Gasoline Consumption In Liters
2007	165,040,279
2008	191,372,721
2009	213,641,280
2010	216,655,049
2011	242,875,774
2012	297,172,159
2013	305,107,013
2014	412,141,590
2015	501,145,371
2016	463,021,018
2017	461,427,680

(Source: ERB, 2018)

4.2. Ministry of Energy

The Ministry of Energy provided data on the daily fuel consumption on average. The information obtained was that the country used **1,300,000** liters of gasoline per day and **2,800,000** liters of diesel per day in 2018. However, this information could not be used because it was given at mid of the year of data collecting and referred to Energy Regulation Board for historical information on gasoline consumption in Zambia.

4.3. Kafue Sugar

Kafue Sugar is a plantation based in Nampundwe along the Kafue River flats. Its business focus is sugar production. The same feedstock sugarcane used to produce sugar is also one of the feedstocks for bioethanol production. Also its byproduct “molasses” in the production of sugar can be processed into bioethanol. It was established during this research visit and data collection trip that the company had commenced construction of the bioethanol plant which would be using molasses as the feedstock to produce bioethanol. Table 4.2 below provides data on the sugarcane yields at Kafue Sugar from 2007 to 2017.

Table 4.2: Kafue Sugar Sugarcane yields in Tons

Year	Sugarcane Yields In Tons
2007	295,200
2008	297,000
2009	306,000
2010	309,000
2011	315,000
2012	324,000
2013	333,000
2014	342,000
2015	345,600
2016	349,200
2017	360,000

(Source: Kafue Sugar, 2018)

4.4. Zambia Sugar Plc

Just as it was at Kafue Sugar, sugarcane yields were collected at Zambia Sugar Plc. With this company, data was collected on their website since its public limited company, annual reports were always posted on their website. It is important to note that this data was obtained with the consent of the company. Data collected included yields from the sugarcane out growers supplying the company. Table 4.3 below provides sugarcane yields at Zambia Sugar Plc from 2007 to 2017.

Table 4.3: Zambia Sugar sugarcane yields in tons

Year	Sugarcane Yields In Tons
2007	1,573,000
2008	1,860,000
2009	1,626,000
2010	2,612,000
2011	3,103,000
2012	3,039,000
2013	3,246,000
2014	3,300,000
2015	3,500,000
2016	3,250,000
2017	5,000,000

(Source: Zambia Sugar, 2018)

4.5. Kasama Sugar

In the similar manner data of the sugarcane yields were collected at Kasama Sugar. This is an upcoming sugar company based in North Zambia. Table 4.4 is a representation of the sugarcane yields at Kasama Sugar from 2007 to 2017.

Table 4.4: Kasama Sugar Sugarcane yields in tons.

Year	Sugarcane Yields In Tons
2007	12,560
2008	15,000
2009	15,000
2010	15,500
2011	17,000
2012	19,000
2013	22,000
2014	23,500
2015	30,000
2016	33,500
2017	35,000

(Source: Kasama Sugar, 2018)

4.6. Ministry of Agriculture & Central Statistics Office

Some of feedstocks considered under this research are sweet potato and cassava. What was interesting was that both the Ministry of Agriculture and Central Statistics Office had the same data indicating high levels of collaboration between the two government entities.

It is important to note that sweet sorghum, an important feedstock for bioethanol production was not officially accounted for in Zambia by the Ministry of Agriculture. However, sweet sorghum,

being a non-food crop stands out as the ideal feedstock for bioethanol production. Table 4.5 provides data on sweet potato yields between 2007 and 2017. Also Table 4.6 provided data on National cassava yields during the period under review.

Table 4.5: National sweet potato yields in tons

Year	Sweet Potato Yields In Tons
2007	86,276
2008	93,283
2009	100,824
2010	104,036
2011	111,054
2012	117,081
2013	124,513
2014	173,213
2015	213,091
2016	224,310
2017	236,127

(Source: Ministry of Agriculture & Central Statistics Office, 2018)

Table 4.6: National cassava yields in tons.

Year	Cassava Yields In Tons
2007	599,361
2008	657,015
2009	683,714
2010	798,171
2011	790,412
2012	801,520
2013	854,393
2014	819,497
2015	923,795
2016	1,114,583
2017	1,178,516

(Source: Ministry of Agriculture & Central Statistics Office, 2018)

4.7 Internet

Table 4.7 below shows the conversion ratios from the quantities of crop yields to bioethanol and biodiesel.

Table 4.7: Conversion relationships from a variety of feed stocks to bioethanol and biodiesel [36].

Sugarcane	Sweet Sorghum	Jatropha
<ul style="list-style-type: none"> • 1 ton of sugarcane produces 10 liters of ethanol (via the molasses route). • 4% of the sugarcane yield is molasses (1 ton of cane produces 40 liters of molasses). • 1 ton of molasses produces 250 liters of ethanol. • 1 ton of sugarcane produces 80 liters of ethanol by direct conversion. 	<ul style="list-style-type: none"> • 1 ton of sweet sorghum produces 55 liters of ethanol by direct conversion. 	<ul style="list-style-type: none"> • The oil content of jatropha seed is 30-35%. • The conversion ratio from oil to bio-diesel is 1:1. • 1 ton of jatropha seed produces 300 liters of Bio-diesel

(Source: WWF Report, 2011)

CHAPTER 5: RESULTS AND DISCUSSION

This chapter presents the results of the research. The results were obtained strictly in accordance to the objectives of the study. The raw data was collected from various companies in sugar production business which included Zambia Sugar, Kafue Sugar and Kasama Sugar. The other set of raw data was collected from government agencies such as Ministry of Agriculture, Ministry of Energy, Central Statistics Office and Energy Regulation Board. The raw data as presented in each table was fed in the MATLAB model and produced curves of best fit versus the actual and the governing equation automatically was derived in each case. The equation was used to forecast up to 2040 using exponential regression tool. Each organization visited provided data which was assembled in each of the tables.

There were two scenarios considered in processing this raw data. The first scenario took into account that the feedstocks being considered are food sources in Zambia. With this in mind it was decided that in the case of sugarcane, molasses be used to assess the potential from this resource and in the case of cassava and sweet potato, the potential extracted starch was considered for the remainder from the food requirement. The second scenario took a holistic approach where the total yield in each case was processed and calculated into bioethanol.

The assembled data was fed to the MATLAB model produced the relationships for each set of data according to trend. This trend on each table which determined the direction and behavior of the curve produced. There was a difference between the actual curve and the curve of best fit. Where the data in the table presented a predictable flow, the line of best fit and the actual line were produced close to each other. In the case where the flow of data in the table comes out in an irregular manner, the two lines were far from each other sometimes giving negative readings. During data gathering, sugarcane related industries gave big quantities of sugarcane because of the commercial nature of the industries.

Zambia Sugar being the oldest and biggest plantation in the country gave comparatively large amounts of sugarcane being produced by the company and the surrounding out growers of which yields are bought by the company. Kafue Sugar was the second largest sugar company in the country but growing at a fast rate. Kasama Sugar is also an upcoming expanding equally at a faster rate. The company's expansion program was done ambitiously and with time it will soon reach the current levels of Kafue Sugar. Cassava also showed greater signs of potential in the country with its growth showing a smooth curve. There was emphasis on its growth in the country as such the Ministry kept clear and consistent data about it. The only challenge is that there is no known and prominent entity investing in it.

Data on national sweet potato yields was provided by Central Statistics Office. Again this is the feedstock without any prominent investor on it. The data collected was irregular and that is why

the curve appeared reasonably irregular. The Ministry of Energy provided current data on fossil fuels consumption while the Energy Regulation Board provided historical data on fuel consumption in the country. It was from this background that the results were assembled as contained in the tables and graphs presented in this chapter. This data was processed using known mathematical methods (MATLAB) and it is important to note that each feedstock has its own conversion factor used in the formulae. It is also important to note that sweet sorghum could not provide statistical data under the Zambian scenario because the feedstock is not categorized as food under the Ministry of Agriculture and any other organ set to document food security information.

5.1. National gasoline consumption

The national gasoline consumption is key to proving the benchmarks to this research without which there can be no basis for the process. Table 5.1 is presented in this regard to provide the basis for this research it presents the annual gasoline consumption from 2007 to 2017. As can be seen, there was a continuous growth in the fuel consumption from 2007 up to 2015. From 2015 going towards 2017 there was a record decrease in fuel consumption in the country. This can be attributed to the performance of the economy since fuel consumption is directly proportional to economic performance. However the decline was so insignificant that it could not affect the growth of the curve upwards as can be seen in Figure 5.1 below. The effect of this development was that the gasoline consumption in the country had continued growing over the years.

Table 5.1: National Gasoline consumption

Year	National Annual Gasoline Consumption In Liters
2007	165,040,279
2008	191,372,721
2009	213,641,280
2010	216,655,049
2011	242,875,774
2012	297,172,159
2013	305,107,013
2014	412,141,590
2015	501,145,371
2016	463,021,018
2017	461,427,680

The 2018 data obtained from the Ministry of Energy was a daily consumption of 1,300,000 liters of gasoline per day giving an anticipated annual consumption of 474, 500,000 liters of gasoline in 2018. This figure is indicative of an increase in 2018 from the 461,427,680 liters of gasoline in 2017. These huge quantities of gasoline were procured at a huge cost bearing negatively on the Zambian economy. What makes it even more challenging is that these huge quantities are imported using foreign exchange to a larger extent depleting the National foreign exchange reserves.

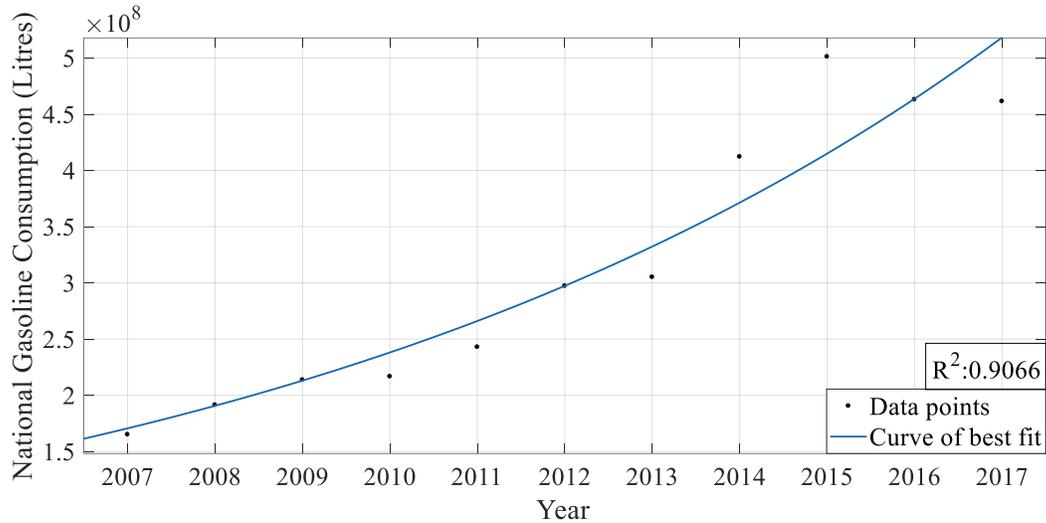


Figure. 5.1: National gasoline consumption from 2007 to 2017 curve.

The coefficient of determination (R^2) is 0.9066

The national gasoline consumption data of Table 5.1 was fed on to the MATLAB tool R2017A for purpose of finding the curve of best fit which in this regard represents the ideal situation following the trend as presented in Table 5.1. Using the curve of fitting application and exponential regression, the plotting was able to obtain the actual location of the data points versus the curve of the best fit. The coefficient of determination (R^2) is 0.9066.

From the results so far the presentation is a smooth curve giving a good result. However, this result was the benchmark where the rest of the research results were compared to. What this meant was that the closer the results were to these figures the successful the research was and the lower the figures were from these figures then suggestions by this research needed to be made to mitigate the inadequacy of the feedstocks under consideration.

In terms of resources, it was discovered that the feedstocks under consideration constituted to a very serious extent foodstuff in the Zambian scenario. Under these circumstances, it was decided that the research be considered in two categories which looked at extraction of molasses from the sugarcane yield quantities and excesses of cassava and sweet potatoes after consumption and the other conversion was that of the total yields without taking into account the food requirements of the general populace.

5.2. Scenario Number One: Using Molasses and Excess Sweet Potato and Cassava

Table 5.2 is a summation of sugarcane yields and molasses from the three sugar companies in Zambia namely: Zambia Sugar, Kafue Sugar and Kasama Sugar. Take note that 4% of sugarcane yields is molasses in liters hence each year, the molasses is tabulated.

Table 5.2: Sugarcane and Molasses Conversion

Year	Sugarcane Yields In Kgs	Molasses In Liters
2007	1,880,760,000	75,230,400
2008	2,172,000,000	86,880,000
2009	1,947,000,000	77,880,000
2010	2,936,500,000	117,460,000
2011	3,435,000,000	137,400,000
2012	3,382,000,000	135,280,000
2013	3,601,000,000	144,04,0000
2014	3,665,500,000	146,620,000
2015	3,875,600,000	155,024,000
2016	3,632,700,000	145,308,000
2017	5,395,000,000	215,800.000

Taking into consideration that sugarcane in Zambia is primarily grown for the purpose of producing sugar which plays an important role as a foodstuff amongst many Zambian households, it became important that part of this research focusses on molasses, which is a by-product in the process of producing sugar. For the purpose of this assessment, it was decided that the yields of sugarcane by the plantations where data was collected should be summed-up and converted to molasses.

In theory, every quantity of sugarcane that is converted to sugar produces 4% of molasses in liters. Using that conversion factor, all the quantities of sugarcane yields from 2007 to 2017 were converted to liters of molasses as shown in Table 5.2. As can be seen the quantities of molasses increased according to increase in the sugarcane yield. Another interesting scenario in Table 5.2 is the fact that sugarcane yield increased progressively from 2007 to 2017.

The meaning of the results obtained in Table 5.2 was that sugarcane production in Zambia was continuously increasing. Looking at the location of Zambia Sugar Plc and Kafue Sugar versus a distance of 1000km to Kasama where Kasama Sugar is located shows that the Zambian weather pattern is conducive for sugarcane production in most parts of country. In this case new investment avenues can be promoted even for the purpose of bioethanol production.

Figure 5.2 below gives the conversion ratios of sugarcane to molasses.

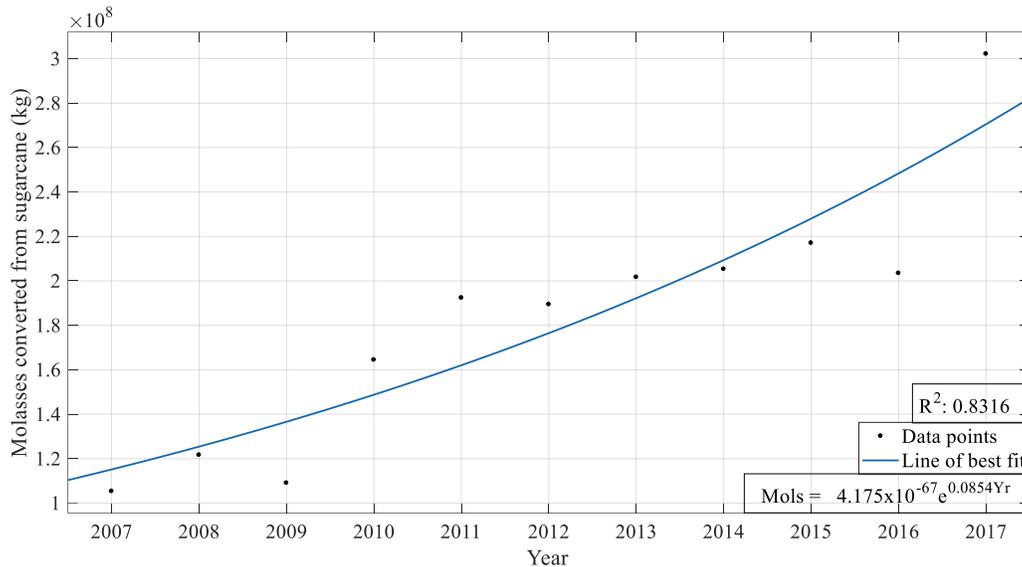


Figure 5.2: Molasses conversion from sugarcane.

The data contained in Table 5.2 was fed in the MATLAB model. The model produced a figure with a smooth curve. The curve provided a line of best fit represented by a smooth curve whilst the actual data route is represented by the dots on the graph.

The coefficient of determination (R^2) is 0.8316

The **coefficient of determination** (denoted by R^2) is a key output of regression analysis. It is interpreted as the proportion of the variance in the dependent variable that is predictable from the independent variable.

The equation E that was derived by the MATLAB model as the data was factored in the model is as follows:

$$E = 4.175 \times 10^{-67} e^{0.0854yr} \dots\dots\dots 1$$

When data is fed on to the MATLAB model using exponential regression tool, the outcome is a figure of the nature of Figure 1 and an equation as Equation 1. Equation 1 manually can be used to plot Figure 5.2. The process was similar in each case.

The above equation was used by the MATLAB model to plot Figure 5.2.

Table 5.3 contains information on the national sweet potato yields in Zambia from 2007 to 2017 obtained from the Ministry of Agriculture and Fisheries. It was established at the ministry that out of each yield, 28.7% of sweet potatoes is retained for consumption by the farmers themselves, 39.23% is sold to other consumers both in rural and urban areas and that the other 32.07% end up getting rotten and dry because it is neither sold nor consumed. This is the quantity that can be considered for bioethanol production. Table 5.3 shows actual sweet potato yields less consumption quantities

Table 5.3: Sweet Potato excess quantity

Year	Actual Sweet Potato Yield In Tons	32.07% Of Actual Yield In Tons
2007	86,276	27,668.7
2008	93,283	29,915.86
2009	100,824	32,334.26
2010	104,036	33,364.34
2011	111,054	35,615.02
2012	117,081	37,547.88
2013	124,513	39,931.32
2014	173,213	55,549.41
2015	213,091	68,338.28
2016	224,310	71,936.22
2017	236,127	75,725.93

Information obtained at the Ministry of Agriculture, Crop Survey Unit showed that out of the total yields of sweet potato, on average 32.07% was excess that could be used for other purposes. With bioethanol research project in mind, it was decided that this excess should be considered for bioethanol conversion. This was done in order to take into consideration the food requirements of the people especially the rural parts of Zambia. In this case, out of yields from 2007 to 2017, only 32.07% were considered for bioethanol research each progressive year.

Further the data assembled was factored using MATLAB to compile Figure 5.3 below.

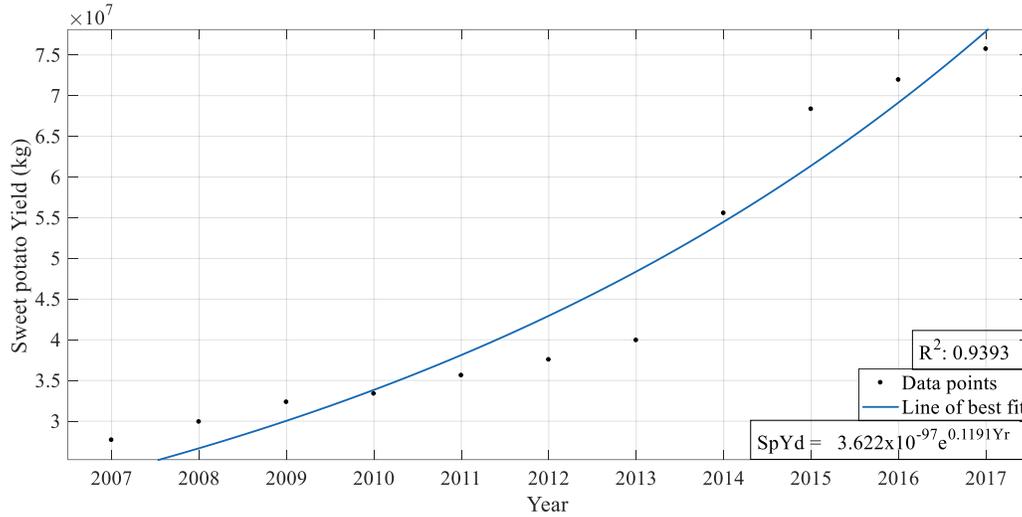


Figure 5.3: Exponential curve on the excess sweet potato after food considerations.

The excess sweet potato yields according to the calculations were fed to the MATLAB model. A smooth exponential curve was derived representing a line of best fit while the data points according to the data in Table 5.3 are represented by dots.

The coefficient of determination (R^2) is 0.9393.

The curve was plotted by the following equation:

$$E=3.622 \times 10^{-97} e^{0.1191 \text{yr}} \dots\dots\dots 2$$

The Table 5.4 contains collected data of cassava yields in country in the period under review. The information provided by the Ministry of Agriculture Crop Survey Unit is as follows:

- I. 31% of the yield is used as food.
- II. 40% is sold to the brewery industries
- III. 29% normally remain unsold and this is the quantity that can be converted to bioethanol.

Table 5.4: Actual Cassava yields Less Consumption

Year	Actual Cassava Yields In Tons	29% Of The Actual In Tons
2007	599,361	173,814.69
2008	657,015	190,534.35
2009	683,714	198,277.06
2010	798,171	231,469.59
2011	790,412	229,219.48
2012	801,520	232,440.8
2013	854,393	247,773.97
2014	819,497	237,654.13
2015	923,795	267,900.55
2016	1,114,583	323,229.07
2017	1,178,516	341,769.64

Just like sweet potato, the Ministry of Agriculture crop survey unit provided information on the approximate distributions of cassava yields each year. It was established that 29% of the cassava was normally excess above domestic requirements and available for bioethanol production. As a result of this information, 29% of cassava was calculated from each year’s yield so establish the quantities available for bioethanol conversion.

Figure 5.4 below is a compilation of data contained in Table 5.4.

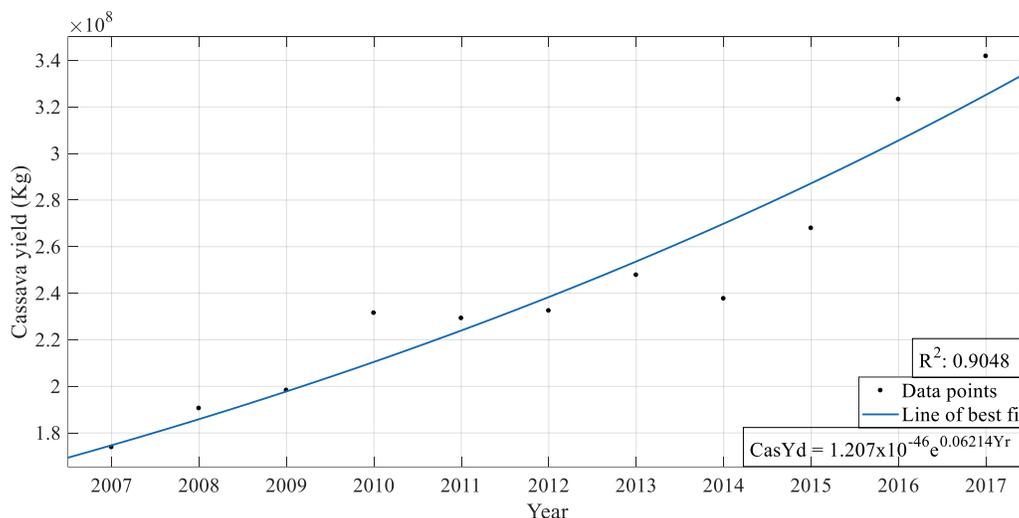


Figure 5.4: Exponential curve on the cassava yields after food requirements considerations.

In the similar manner the data from Table 5.4 was factored in the MATLAB model.

The coefficient of determination (R^2) is 0.9048.

$$E=1.207 \times 10^{-46} e^{0.06214 \text{yr}} \dots\dots\dots 3$$

5.2.1. Conversion of Feedstocks to bioethanol

According to [37] Molasses Tanks are specially made extra duty tanks for storage of heavy molasses or similar liquids (1 liter molasses = 1.4kg). This means that a 1,000 liters will weigh 1,400 kg

Also we are aware the relationship that $E=\eta \times S$

Where:

E=the amount of ethanol in liters

S= molasses in kg

η for molasses =250/1000 from table 4.7

$\eta=0.25$

This part of research is the major reason why this research was constituted. The calculated molasses conversions were tabulated in tubular form and converted to bioethanol according to Table 5.5.

Table 5.5: Conversion of molasses to bioethanol

Year	Mass Of Molasses In Kgs	Bioethanol Potential Liters
2007	105,322,560	26,330,640
2008	121,632,000	30,408,000
2009	109,032,000	27,258,000
2010	164,444,000	41,111,000
2011	192,360,000	48,090,000
2012	189,392,000	47,348,000
2013	201,656,000	50,414,000
2014	205,268,000	51,317,000
2015	217,033,600	54,258,400
2016	203,431,200	50,857,800
2017	302,120,000	75,530,000

What is interesting even in this case is the progressive manner in which the bioethanol potential figures were growing showing that the country has a greater potential even when the bioethanol production was to lean and rely on molasses only.

This route if enhanced would not pose any challenges with regards to availability of sugar for consumption in the country. Even if the country resorts to specific plantations for bioethanol production, molasses would still play a role in bioethanol production. The other advantage molasses has is the pretreatment it comes with in process of producing sugar. Molasses is applied directly in the production of bioethanol without any further treatment because enzymes are already used in the production of sugar and chains are already broken.

Figure 5.5 below gives the bioethanol potential from molasses in Zambia.

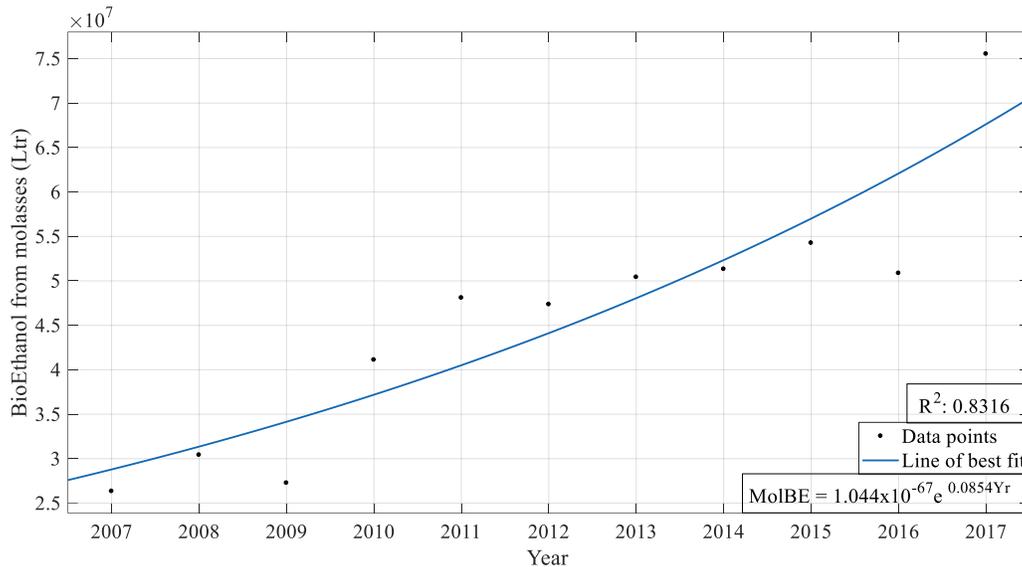


Figure 5.5: Exponential curve on bioethanol potential from molasses.

Molasses is a by-product of sugar production.

The results on bioethanol potential each year was factored in the MATLAB model and produced a curve of the line of best fit which is a smooth curve. As can be seen the line best fit highest point lie below that of the highest actual dot.

The curve was plotted from the following equation:

$$E = 1.044 \times 10^{-67} e^{0.0854 \text{yr}} \dots \dots \dots 4$$

The coefficient of determination (R^2) is 0.8316 which is lower percentage representation.

5.3 Sweet potato and Cassava

Sweet potato and Cassava technologies of extracting ethanol are different from those of sugarcane. The two crops processing is by hydrolysis and fermentation where starch is converted to useful sugars. In this case the mass in use is the mass of starch. According to [18] the maximum yields of starch from a given mass of sweet potato is 25% and for cassava is 28%. The yields for sweet potato presented in Table 4.5 are broken down into those ratios and presented in Table 5.6. In the same vain [38] gives the starch and bioethanol relationship. The relationship is such that 170L ethanol from one ton of sweet potato and 363L ethanol from one ton of cassava.

Therefore using $E = q \times S$

q for sweet potato is 0.17L/kg and for cassava is 0.363L/kg

5.3.1 Conversion of excess sweet potato to bioethanol

Table 5.6 provides information and process of converting excess sweet potato to bioethanol.

Table 5.6: Converting sweet potatoes to bioethanol

Year	Sweet Potato In Kgs	25% Starch In Kgs	Bioethanol In Liters
2007	27,668,700	6,917,175	1,175,919.75
2008	29,915,860	7,478,965	1,271,424.05
2009	32,334,260	8,083,565	1,374,206.05
2010	33,364,340	8,341,085	1,417,984.45
2011	35,615,020	8,903,755	1,513,638.35
2012	37,547,880	9,386,970	1,595,784.9
2013	39,931,320	9,982,830	1,697,081.1
2014	55,549,410	13,887,352.5	2,360,849.925
2015	68,338,280	17,084,570	2,904,376.9
2016	71,936,220	17,984,055	3,057,289.35
2017	75,725,930	18,931,482.5	3,218,352.025

The remainders from consumption and other domestic uses of sweet potatoes were converted to bioethanol and produced results as shown in Table 5.6. This was another typical result showing continuous increase in the feedstock yields giving a corresponding increase in the bioethanol potential. These increases meant that going forward the country will have reciprocal increase in the excess of the feedstock.

With the feedstock's potential for bioethanol production targeting the replacement of gasoline with bioethanol, this feedstock has the potential to attract commercial investors in its production. The other interesting factor was that the demand for this feedstock would go up and following the law of supply and demand and the fetching price the feedstock automatically would go up.

In the Zambian scenario this crop is considered as women's preserve. Its commercialization can attract the participation of men in growing the feedstock and increase production further. In this situation the excess is likely to even be higher than that reserved for consumption and other domestic uses. This together with other government generated promotion interests can result in the feedstock not to necessarily compete with food.

Figure 5.6 below gives the bioethanol potential from excess sweet potato in Zambia.

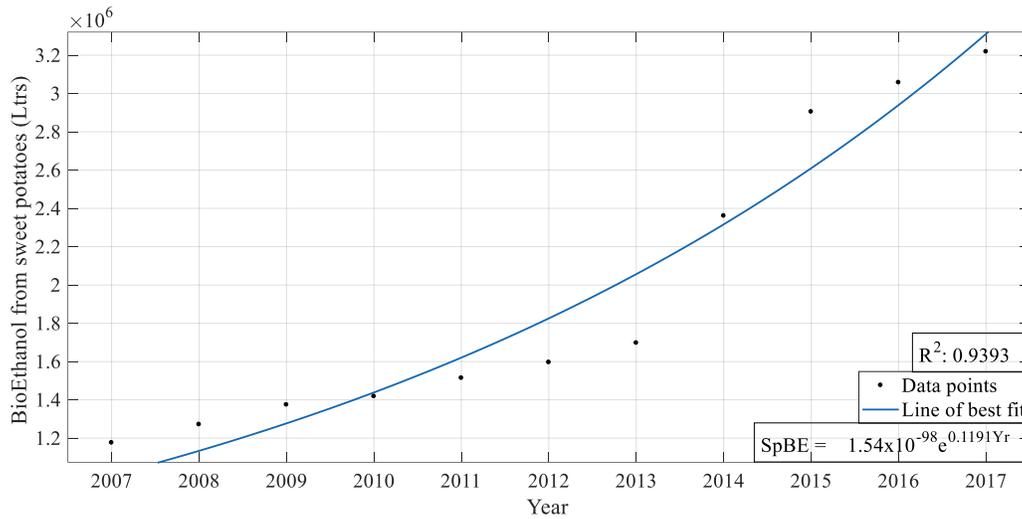


Figure 5.6: Exponential curve on the bioethanol potential from the excess sweet potato in the country.

In the similar manner, the bioethanol potential calculated was factored to the MATLAB model and plotted the line of best fit and actual points.

The coefficient of determination (R^2) is 0.9393.

The derived equation is as follows:

$$E = 1.54 \times 10^{-98} e^{0.1191 \text{yr}} \dots \dots \dots 5$$

5.3.2. Conversion of excess cassava to bioethanol

The Table 5.7 presents data on the processes after converting cassava into bioethanol.

Table 5.7: Converting cassava to bioethanol

Year	Cassava In Kgs	28% Starch In Kgs	Bioethanol In Liters
2007	173,814,690	48,668,113.2	17,666,525.09
2008	190,534,350	53,349,618	19,365,911.33
2009	198,277,060	55,517,576.8	20,152,880.38
2010	231,469,590	64,811,485.2	23,526,569.13
2011	229,219,480	64,181,454.4	23,297,867.95
2012	232,440,800	65,083,424	23,625,282.91
2013	247,773,970	69,376,711.6	25,183,746.31
2014	237,654,130	66,543,156.4	23,792,165.77
2015	267,900,550	75,012,154	27,229,411.9
2016	323,229,070	90,504,139.6	32,853,002.67
2017	341,769,640	95,695,499.2	34,737,466.21

The excess of cassava equally converted to bioethanol. Cassava being cultivated at a reasonably higher scale in Zambia than sweet potatoes hence the higher figures of bioethanol potential. This feedstock is mainly cultivated in northern part of Zambia and was historically considered as a staple food in that part of the country. With this development, a lot of research in early maturing varieties is going on in the country with government taking a keen interest.

Figure 5.7 below gives the bioethanol potential from excess cassava in Zambia.

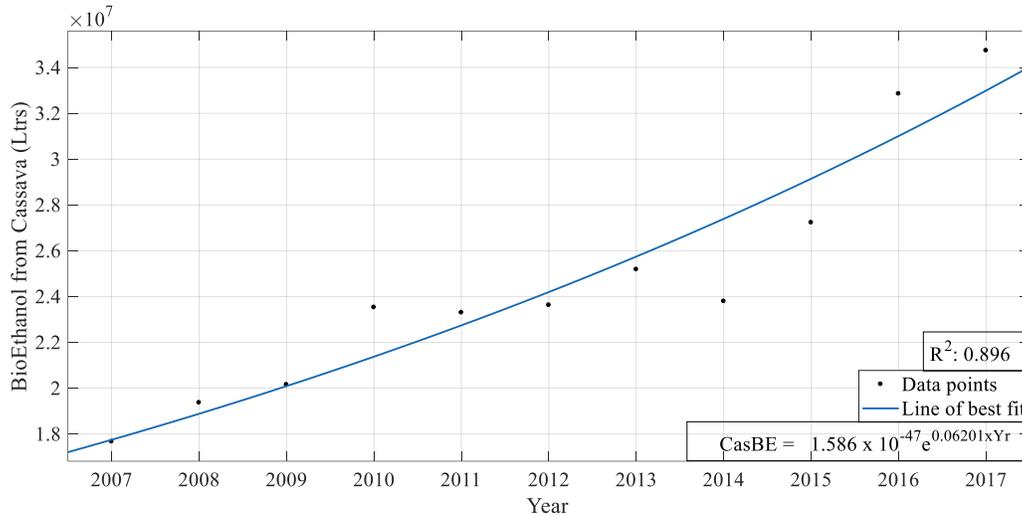


Figure 5.7: Exponential curve on the bioethanol potential from excess cassava

The converted bioethanol was factored in the MATLAB model and derived an equation that plotted the line best fit in the form of a curve which is a smooth curve. The actual points were also dotted within the figure.

The coefficient of determinant (R^2) is 0.896

The equation E derived to plot the graph is as follows:

$$E = 1.586 \times 10^{-47} e^{0.06201 \times \text{yr}} \dots \dots \dots 6$$

5.3.3 Summation of bioethanol potential from all the feedstocks under scenario number one

Table 5.8 sums up bioethanol potential from all the feedstocks under the first scenario

Table 5.8: Total Bioethanol Potential from all the feedstocks

Year	Consolidation Of Bioethanol Potential From All The Feedstocks In Liters
2007	45,173,084.84
2008	51,045,335.38
2009	48,785,086.43
2010	66,055,553.58
2011	72,901,506.3
2012	72,569,067.81
2013	77,294,827.41
2014	77,470,015.7
2015	84,392,188.8
2016	86,768,092.02
2017	113,485,818.2

At the end of the first scenario in which the food requirements were taken into consideration, it became important to sum up the obtained bioethanol potential from molasses and excesses from cassava and sweet potatoes conversions. Comparing these results with gasoline consumption from 2007 to 2017, it was observed that these results are far much lower and cannot replace gasoline as the situation is now. Quantitatively, the bioethanol potential gathered under this scenario stands at 25% to 27% of the national gasoline demand. Such a situation can not suffice for the national fuel requirements targeting bioethanol as a replacement for gasoline.

However, it is important to note that the three feedstocks combined in the manner they were considered can still be, going forward and be part of the feedstocks considered for bioethanol production in the country. The fact is that as long as there is sugar production, there will always be molasses to be converted to bioethanol. In this case, even if the nation resorts to direct investment in the business of feedstocks for bioethanol production, this combination will still have to supplement in the production of bioethanol to prepare the country for the impending migration to biofuels. The quantities so far exhibited in Table 5.8 cannot sustain the national fuel requirements and eventually replace gasoline. The results however show that with increase in the feedstock quantities, the bioethanol also increases. Deliberate approach methods should be devised to enhance the growth of these feedstocks.

Figure 5.8 below gives the bioethanol potential under scenario number one.

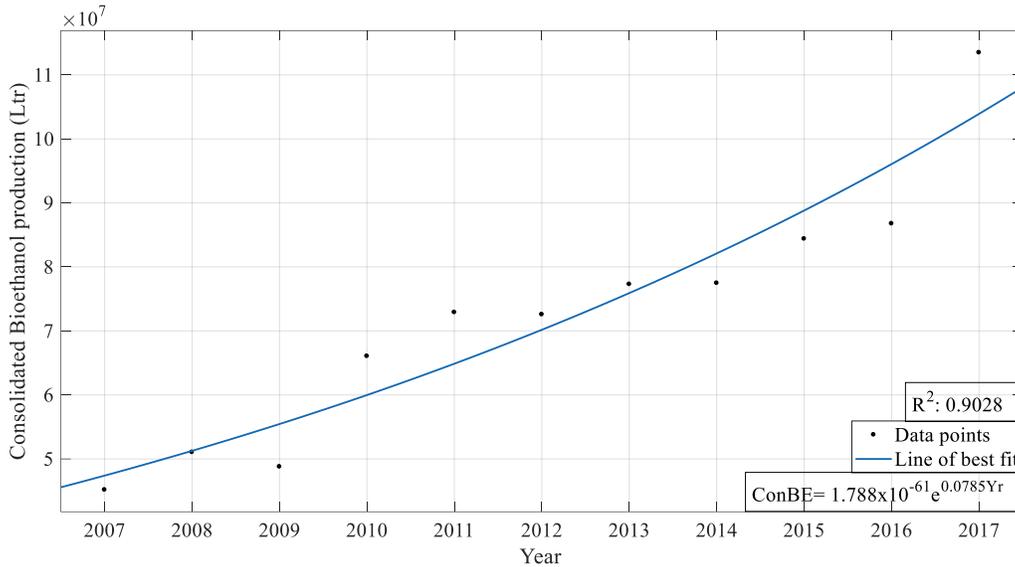


Figure 5.8: bioethanol potential from the quantities considered under scenario number one

The consolidated bioethanol potential from all the feedstocks was factored in the MATLAB model according to data contained in table 5.8. The line of best fit was plotted in the form of a curve and the actual points were using dots. It is important to note that the results produced a smooth curve representing good data distribution.

The coefficient of determination (R^2) is 0.9028

The equation that formulated the plotting of the graph is as follows:

$$E = 1.788 \times 10^{-61} e^{0.0785yr} \dots\dots\dots 7$$

5.4. Scenario Number Two: Using the actual yields of sugarcane, sweet potato and cassava

This scenario looks at the bioethanol potential yielded from total production of the feedstocks under consideration. As a nation, it is important to assess the potential contained within the activities in the country visa-vie the feedstocks grown for other uses. This potential once accurately assessed will give Zambia the levels of investment required to meet the national bioethanol quantities required to replace gasoline. In this case, feedstocks were converted directly to bioethanol potential without due regards to food requirements of the country. All these assessments were compared to the principle, which is the compiled national gasoline consumption.

5.4.1. Sugarcane production by Kafue Sugar

Kafue Sugar Company was visited and provided information so helpful in determining Zambia's potential for bioethanol production. Table 4.2 is repeated here as Table 5.9 for convenience and shows data on annual sugarcane yields at Kafue Sugar obtained at Kafue Sugar in Nampundwe.

Table 5.9: Raw data on sugarcane yields at Kafue Sugar

Year	Sugarcane Yields In Tons
2007	295,200
2008	297,000
2009	306,000
2010	309,000
2011	315,000
2012	324,000
2013	333,000
2014	342,000
2015	345,600
2016	349,200
2017	360,000

Kafue Sugar, a company based in Nampundwe running a sugarcane plantation and a sugar manufacturing plant. The company provided information of its annual yields of sugarcane over the period of time under this research. The information compiled in Table 5.9 showed a fast growing company. All these tonnages of sugarcane were primarily grown for sugar production.

It was these quantities that this research took into consideration to base Zambia's potential for bioethanol production. These production levels provide information of what ought to be done at national level in order to mitigate the effects of the environmental pollution caused by continued burning of fossil fuels. It is important to understand the drastic changes on the weather patterns worldwide and disasters caused by upsets in the weather general behavior caused by pollutants especially those caused by mobile equipment with no means of capturing it for other uses.

Figure 5.9 gives a representation of sugarcane yields at Kafue Sugar.

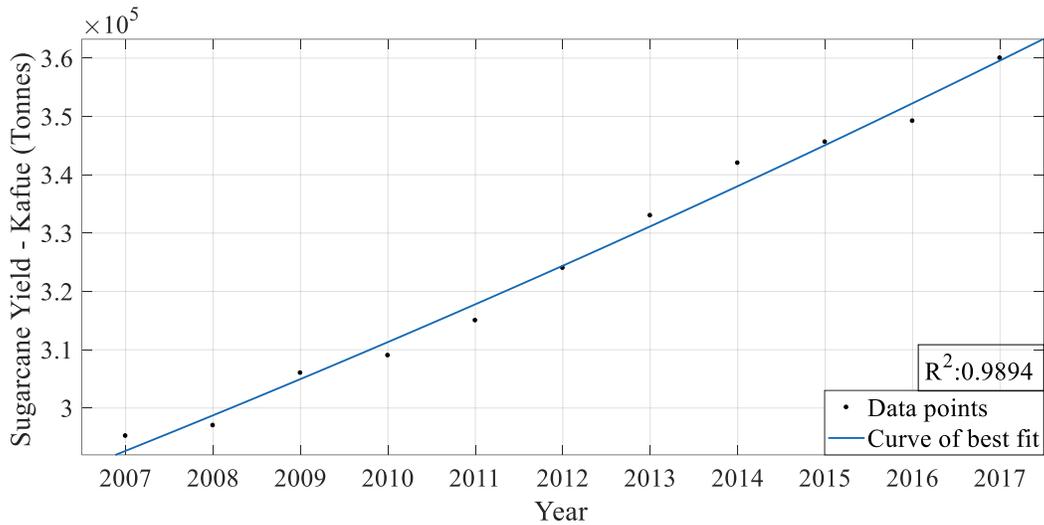


Figure 5.9: Sugarcane yields at Kafue Sugar with an almost straight curve.

As at 2017 the yield stood at 360,000 tons per annum

The data contained in Table 5.9 was also factored in the MATLAB model. This resulted in the plotting of the line of best fit. This curve of best fit was almost a straight line. Looking at the location of actual point's dots and the curve of best fit, it was observed that both followed the same profile meaning that it was a good curve. The trend of yield was evenly distributed and predictable.

The coefficient of determination (R^2) at 0.9894.

Because of the profile of the curve of best fit and the actual points, the coefficient of determination (R^2) is almost 100%. This means the two roots data compilation was almost parallel to each other showing that Kafue Sugar has a well-defined growth plan of sugarcane. Effectively, the growth plan follow well determined rate.

The equation derived to plot the curve is as follows

$$E=3.26 \times 10^{-13} e^{0.0206 \text{yr}} \dots \dots \dots 8$$

The equation provided the platform in which the curve of best fit and the actual data points were plotted on the figure.

5.4.2. Sugarcane production by Zambia Sugar

Zambia Sugar PLC provided information on the annual sugarcane yields as provided in table 5.10. Table 5.10 therefore is a repetition of Table 4.3 and shows data on sugarcane yields at Zambia Sugar.

Table 5.10: Zambia Sugar annual reports for the years represented

Year	Sugarcane Yields In Tons
2007	1,573,000
2008	1,860,000
2009	1,626,000
2010	2,612,000
2011	3,103,000
2012	3,039,000
2013	3,246,000
2014	3,300,000
2015	3,500,000
2016	3,250,000
2017	5,000,000

Zambia Sugar is largest sugarcane plantation lying on 17000 hectares of land and runs the biggest sugar refinery in the country. As can be seen from 2007 through to 2017 the yield levels were quite high already that this company is highly commercialized and its investment levels can only be equated to other investments on the international market. This is the type of investment that can sustain business targeted at producing fuel to run the transport system in a country like Zambia.

These tonnages of sugarcane combine both with the cane produced by the company and that which was supplied by out growers dotted around the company. The idea was to emulate such investments and reciprocate the same approach to consider setting up plantations for the purpose of bioethanol production. It is important to understand the damage caused by pollution as a result of combustion processes of fossil fuels.

As at 2017 the yield levels rose from 3,250,000 tons in 2016 to 5,000,000 tons. This is not a small increase in terms of sugarcane yields. Such tonnages converted to bioethanol impact positively on the objectives of this research. It is clear that naturally the demand for fuel is higher than that of sugar hence such an investment in the fuel industry would grow even at higher rate compared to that of the sugar industry. The motivation for every business venture is the ability to meet its objectives and have sustainability.

Those that spend resources in any business undertaking do not want to recoup their investment only but also realize a profit at the end of the day. If anything, businesses are attractive if only they have room to expand. This is the situation related to the sugarcane plantation and can be related to bioethanol production. In any case, it is a matter of fact that fuel business already supported by about a million fleet of cars on the Zambian streets cannot lose market of its product.

Figure 5.10 is a representation of sugarcane yields at Zambia Sugar.

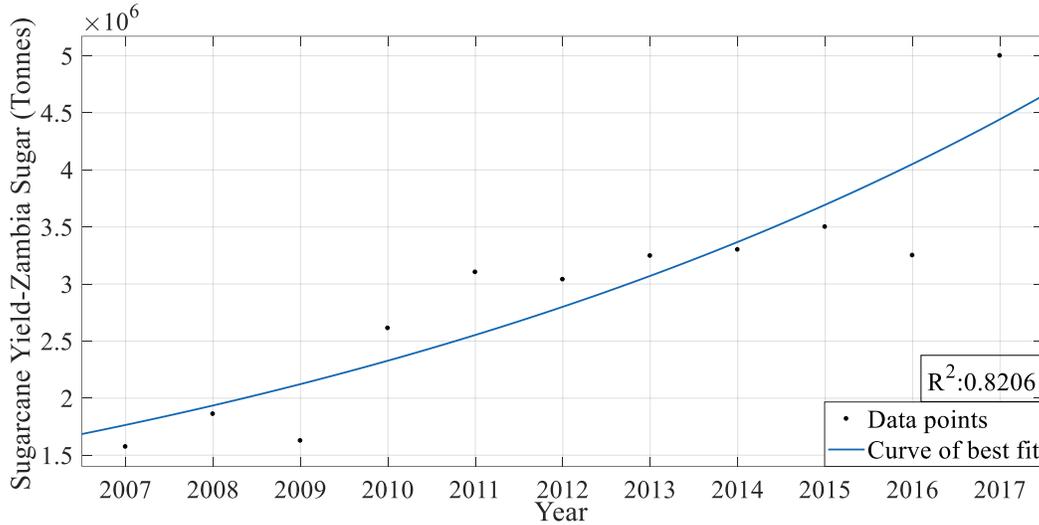


Figure 5.10: Sugarcane yields at Zambia Sugar with a smooth exponential growth over the years.

As at 2017 the yields of sugarcane were at **5000 000 tons per annum**

The data contained in Table 5.10 was in the similar manner factored on to the MATLAB model and the derived equation automatically plotted Figure 5.10 curve and actual points. The curve of best fit and the actual points were not moving in tandem because business activities at Zambia Sugar were not adjusted using a regular trend. Since 1992, due to privatization, the company has changed hands and each investor who took over the company ploughed in some capital and that caused the company to have irregular investment levels. What was interesting was that yields kept on increasing and by 2017, the yield had hit the highest mark in the history of the company at five million tons.

The coefficient of determination (R^2) stands at 0.8206

The coefficient of determination (R^2) is reasonably lower at 82% because of the irregular levels of growth though indeed the growth was huge upswing each time.

The equation that was automatically derived by the MATLAB model as follows:

$$E=2.801 \times 10^{-6} e^{0.3063 \text{yr}} \dots \dots \dots 9$$

5.4.3. Sugarcane production by Kasama Sugar

Kasama Sugar Company provided information on their sugarcane yields per annum during the period under review. Table 5.11 is the repetition of Table 4.4 providing raw data on sugar yields at Kasama Sugar as provided by Kasama Sugar

Table 5.11: Kasama Sugar sugarcane yields

Year	Sugarcane Yields In Tons
2007	12,560
2008	15,000
2009	15,000
2010	15,500
2011	17,000
2012	19,000
2013	22,000
2014	23,500
2015	30,000
2016	33,500
2017	35,000

Kasama Sugar, strategically located in the far north of Zambia, running a cane plantation and a sugar manufacturing plant. Between 2007 and 2017 it yields had tripled showing that the company was on the growth path. These are Zambian Scenarios showing that a large portion of the country can support sugarcane production.

Figure 5.11 is a representation sugarcane yields at Kasama Sugar.

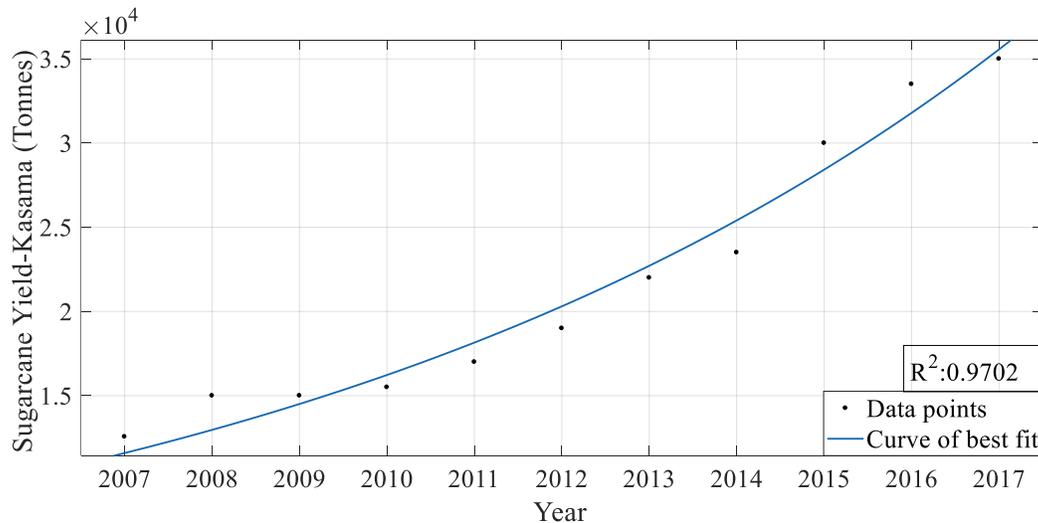


Figure 5.11: Sugarcane yields at Kasama Sugar exponential curve.

The coefficient of determination (R^2) stands at 0.9702 another distribution between the curve of best fit and the actual points moving in tandem

The derived equation $E=2.295 \times 10^{-94} e^{0.3063yr}$ 10

5.4.4. National Sweet potato production

The national sweet potato production record was provided by the Ministry of Agriculture and Central Statistics Office. Table 5.12 is a repetition of Table 4.5 and shows raw data on the national sweet potato yields as provided by the Ministry of Agriculture.

Table 5.12: National sweet potato yields.

Year	Sweet Potato Yields In Tons
2007	86,276
2008	93,283
2009	100,824
2010	104,036
2011	111,054
2012	117,081
2013	124,513
2014	173,213
2015	213,091
2016	224,310
2017	236,127

Sweet potato, a crop mainly grown in Zambia by the women has never been commercialized in Zambia. It is mainly grown and taken as food and never processed beyond consumption levels. What is interesting however is the fact the Ministry of Agriculture through Crop Survey Unit has always been able to account for the annual yields of this crop. Important to note was that by 2017, the yield had trebled compared to what it was in 2007.

Nevertheless, sweet potato is a preserve of rural farmers and huge quantities are normally traded along the highways. This crop is one of the rich feedstocks for bioethanol production. Its identity as a feedstock for bioethanol production places its growth at a greater opportunity considering the important role fuel plays to propel the economy. Therefore, linking it to fuel production can increase its market value and following the law of supply and demand its production becomes attractive not only to peasant farmers but commercial farmers too.

It is therefore necessary that the cultivating of such feedstocks is enhanced especially that it does not amount to one of the staple foods in the country. The idea in this case is to deal with the escalating fuel prices by promoting local feed stocks to spearhead fuel production. The other important element to note is that the current fossil fuels in use are imported at great prices where as countries that import have no control of what the price should be at a given time. This deprives the countries of their hard earned foreign exchanges and even affects nation reserves. The savings from such huge expenditures would go towards poverty reduction by boosting agriculture and providing incentives for local manufacturing industry including bioethanol industry.

Figure 5.12 is a representation of sweet potato yields in Zambia.

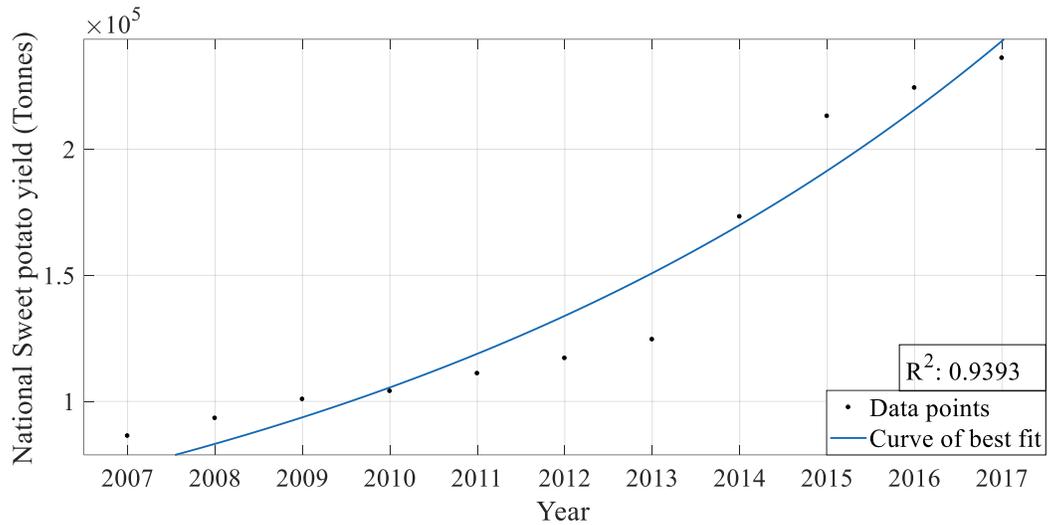


Figure 5.12: Exponential curve on the national sweet potato yields

As at 2017 the yields stood at **236,127 tons** of sweet potatoes per annum.

The data contained in Table 5.12 was factored in the MATLAB model and produced a curve of best fit which ran in tandem with the actual points of the table. In this situation it means that the growth trend was evenly distributed. That is why the coefficient of determination (R^2) was at 0.9393 which is a reasonably higher percentage.

The coefficient of determination (R^2) at 0.9393.

The exponential equation that assisted in plotting the curve is as follows:

$$E=1.13 \times 10^{-99} e^{0.1191 \text{yr}} \dots\dots\dots 11.$$

5.4.5. National Cassava Production

The national cassava yields from 2007 to 2017 was collected at the Ministry of Agriculture and supported Central Statistics Office. Table 5.13 is a replica of Table 4.6 and shows raw data on the national cassava production as provided by the Ministry of Agriculture and Central Statistics Office.

Table 5.13: National cassava yields

Year	Cassava Yields In Tons
2007	599,361
2008	657,015
2009	683,714
2010	798,171
2011	790,412
2012	801,520
2013	854,393
2014	819,497
2015	923,795
2016	1,114,583
2017	1,178,516

Table 5.13 provides information on the national cassava yields within the years under review. This feedstock attracts a lot of attention at national level because of its localized and staple nature. Official national associations are in place to enhance its production and marketing. Looking at its figures it shows that it was growing at a fast rate and clearly it was developed.

Early maturing varieties were being developed and all to increase production of the feedstock. Historically, it served as a staple food especially in Luapula Province of Zambia. Indigenous people there have not migrated to other crops even when the traditional type takes three years to mature and new varieties being developed take at least one year to mature.

Through this research it was discovered to have rich properties for bioethanol production. With already indications of its development in the country, it can play a vital role in the bioethanol production as a motor vehicle fuel. So far, the farmers through the association are struggling to find good market for the commodity. It is through the bioethanol ventures that such resources and farmers can be supported and protected.

Figure 5.13 represents national cassava yields in Zambia

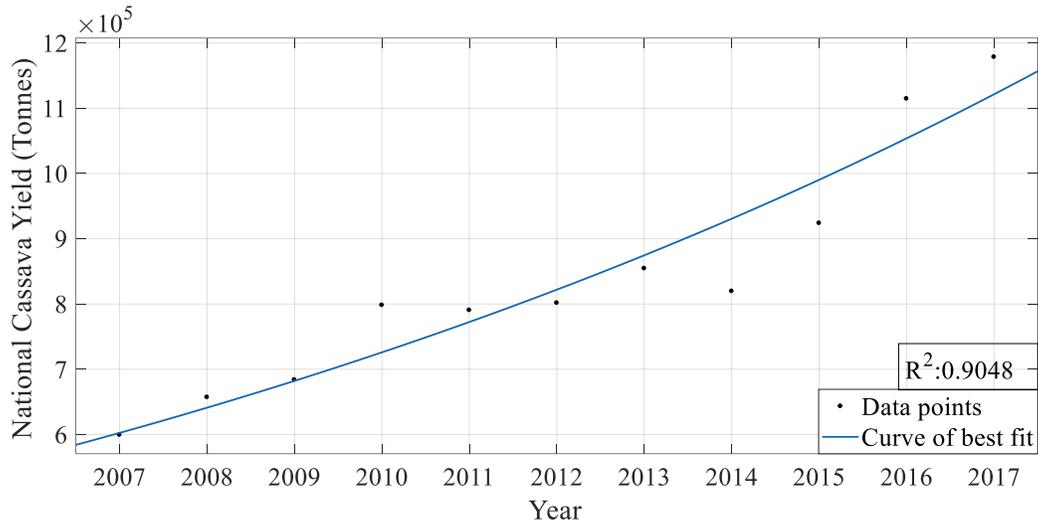


Figure 5.13: Exponential growth of national cassava yields.

The data contained in Table 5.13 was factored in the MATLAB model and the curve of best fit and the data points plotted on to Figure 5.13.

The coefficient of determination (R^2) is 0.9048.

And the exponential equation derived and that plotted Figure 5.13 is as follows:

$$E=4.163 \times 10^{-49} e^{0.06214 \text{yr}} \dots\dots\dots 12.$$

5.5. Converting Sugarcane Yields to Bioethanol

Sugarcane production in Zambia through the sugar refineries has been commercialized and the sugar industry in the country is one of the ever growing industries. It is from this strength that bioethanol production in the country cannot be discussed without considering the sugarcane plantations. In this regard the potential for bioethanol production in Zambia cannot be assessed outside the existing sugarcane plantations.

Table 5.14 which is a replica of Table 4.7 provides information on various conversion ratios for biofuels including bioethanol. These ratios help in assessing quantities of biofuels a variety of feedstocks in terms of yields that can be realized.

According to [36] the following Table 5.14 gives the conversion ratios:

Table 5.4: Conversion ratios of feedstocks to bioethanol

Sugarcane	Sweet Sorghum	Jatropha
<ul style="list-style-type: none"> • 1 ton of sugarcane produces 10 liters of ethanol (via the molasses route). • 4% of the sugarcane yield is molasses (1 ton of cane produces 40 liters of molasses). • 1 ton of molasses produces 250 liters of ethanol. • 1 ton of sugarcane produces 80 liters of ethanol by direct conversion. 	<ul style="list-style-type: none"> • 1 ton of sweet sorghum produces 55 liters of ethanol by direct conversion. 	<ul style="list-style-type: none"> • The oil content of jatropha seed is 30-35%. • The conversion ratio from oil to bio-diesel is 1:1. • 1 ton of jatropha seed produces 300 liters of Bio-diesel

Taking the bullet on direct conversion of sugarcane, we note that 1 ton of sugarcane produces 80 liters of ethanol.

Using the relationship of $E=q \times S$,

Where:

E=the amount of ethanol in liters

S= Sugarcane in kg

$q= 0.08L/kg$ in this case

With this information Tables 5.14 to 5.19 are expanded to include bioethanol converted each year.

All the entries are converted to kilograms and then converted to bioethanol in liters

Table 5.15 below gives the conversion sugarcane yields at Kafue Sugar to bioethanol.

Table 5.15: Kafue Sugar sugarcane yields converted to bioethanol in liters.

Year	Sugarcane Yields In Kgs	Bioethanol In Liters
2007	295,200,000	23,616,000
2008	297,000,000	23,760,000
2009	306,000,000	24,480,000
2010	309,600,000	24,768,000
2011	315,000,000	25,200,000
2012	324,000,000	25,920,000
2013	333,000,000	26,640,000
2014	342,000,000	27,360,000
2015	345,600,000	27,648,000
2016	349,200,000	27,936,000
2017	360,000,000	28,800,000

Sample Calculation,

$$E=q \times S$$

$$E= 0.08 \times 295,200,000 = 23,616,000$$

Bioethanol potential establishment is the main focus of this research. The idea is to see if what this research was able to gather is enough to replace gasoline. With this information Kafue Sugar yields calculated from 2007 to 2017 resulted in bioethanol potential ranging from 23,616,000 liters in 2007 to 28,800,000 liters in 2017. As at 2018, information obtained at the Ministry of Energy showed that Zambia was consuming 1,300,000 liters of gasoline per day. The implication is that the quantity of bioethanol would only run the gasoline propelled vehicles for a period ranging from 18 days to 22 days.

However, the potential was encouraging since it was coming from the second largest sugar plantations in the country. At the rate the company was producing, there is a possibility that by now company yields have grown further. Kafue Sugar was in the process of establishing a bioethanol plant with molasses being the targeted feed stock. This compliment to their business means that the company will have to multiply further its yields in order to tandemly manage both the sugar and bioethanol businesses. Given the above information, the bioethanol potential in the country is very high. All it requires is enhancement by establishing independent sugarcane plantations for bioethanol production working together with the existing sugar refineries and use molasses for the same purpose.

Figure 5.14 is a representation of bioethanol potential from Kafue Sugar.

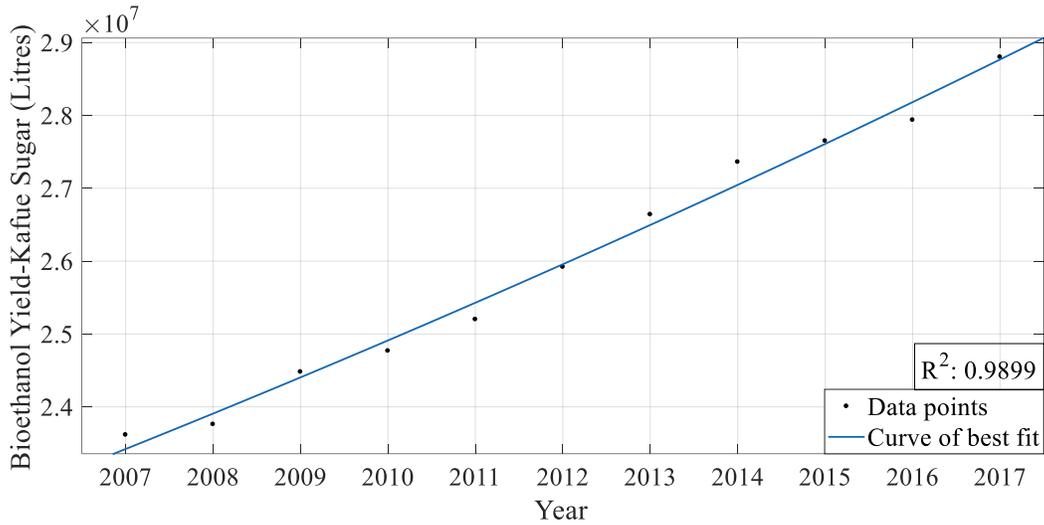


Figure 5.14: Kafue Sugar bioethanol potential exponential growth.

Coefficient of determination (R^2) at 0.9899

The calculated bioethanol potential was factored in the MATLAB model to obtain the curve of best fit and to establish the location of actual data points. As established during discussions on Kafue Sugar yields, the Kafue Sugar data was evenly distributed such that the curve of best fit and the data points followed the same profile. That is the reason why the coefficient of determination (R^2) is at 0.9899 which is almost 100%.

The exponential regression equation is given as follows:

$$E=2.828 \times 10^{-11} e^{0.02056yr} \dots\dots\dots 13$$

The above equation was used by the MATLAB model to plot the curve of best fit and the data points.

Table 5.16 below provides conversion of Zambia sugar yields of sugarcane to bioethanol potential.

Table 5.16: Zambia Sugar sugarcane yields converted to bioethanol in liters

Year	Sugarcane Yields In Kgs	Bioethanol In Liters
2007	1,573,000,000	125,840,000
2008	1,860,000,000	148,800,000
2009	1,626,000,000	130,080,000
2010	2,612,000,000	208,960,000
2011	3,103,000,000	248,240,000
2012	3,039,000,000	243,120,000
2013	3,246,000,000	259,680,000
2014	3,300,000,000	264,000,000
2015	3,500,000,000	280,000,000
2016	3,250,000,000	260,000,000
2017	5,000,000,000	400,000,000

Zambia Sugar Company PLC was focal in this research because of the high yields the company continued recording during the period under review. To a greater extent the Zambia Sugar yields provided an idea as to what levels of investment was required to consider in setting up a bioethanol processing plant. Looking at the situation closely, with good planning, a plantation of the magnitude of Zambia Sugar can sustain the plan of replacing gasoline with bioethanol for purpose of the transport network in the country. What this would mean is that the company is allowed to grow at the pace it is doing so far. The production of bioethanol is then commenced before the actual changeover with the produce being stored in the strategic storage reserves. When the reserves are reasonable enough, the changeover to modified engines is effected.

Generally, the results from Zambia Sugar showed that the potential for Zambia to migrate to modified motor vehicle engines is attainable. Since the fuel supply borders on national security and economic emancipation of any given country, two plantations of the size of Zambia Sugar would manage to supply the sugarcane requirements for bioethanol conversion. The benefits to the country are enormous because they include the chance to reduce cost of fuel since in this regard, fuel can be locally produced unlike the current situation where fuel is strictly imported.

The need for migration is a combination of important factors which include the environmental degradation mitigation which is continuously caused by combustion processes of fossil fuels. This has resulted in greenhouse gases exerting high temperatures on the surface of the earth. These environmental changes are generally altering the known weather patterns. These alterations on the weather patterns have normally affected economic planning especially agriculture related negatively and this negativity is escalating the poverty levels in many countries with Zambia inclusive.

Figure 5.14 is a representation of bioethanol potential from Zambia Sugar sugarcane yields.

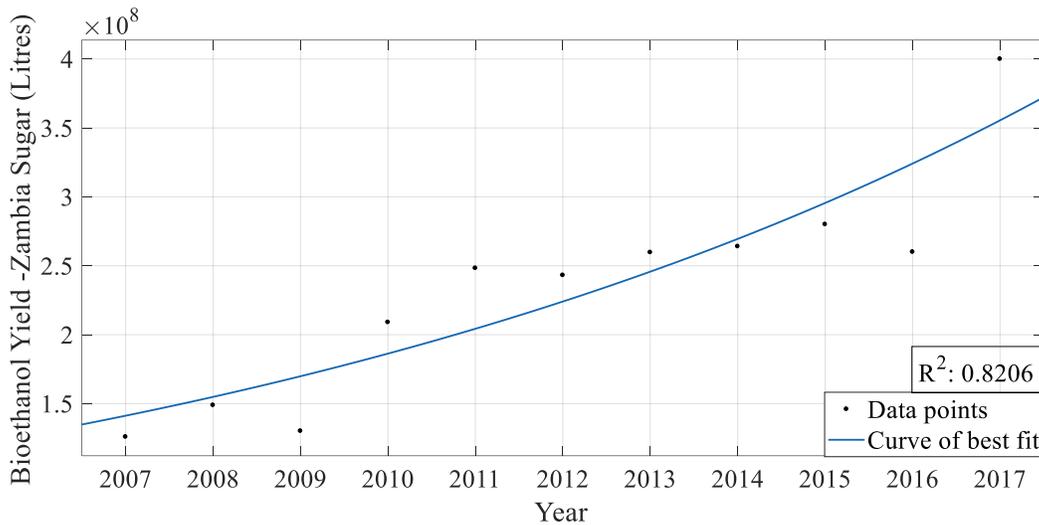


Figure 5.15: Zambia Sugar bioethanol potential exponential growth.

The data contained in Table 5.16 on the bioethanol potential at Zambia Sugar was factored in the MATLAB model and derived the exponential equation as follows.

$$E = 4.609 \times 10^{-73} e^{0.09234 \text{yr}} \dots \dots \dots 14$$

Using equation 14 above, the curve of best fit was plotted.

Also the data points were plotted by the model.

The irregular presentation between the data points and the curve of best fit was as a result of the irregular manner yields were increasing at Zambia Sugar. Important to note about Zambia Sugar is that the company is not wholly dependent on its own yields. They have a substantial quantity of sugarcane supplied by the out-growers which makes it difficult for the company to regulate its supply of sugarcane.

The coefficient of determination (R^2) is 0.8206.

This coefficient of determination is low due to the irregular growth pattern at Zambia Sugar.

Table 5.17 below gives the bioethanol potential from sugarcane yields at Kasama Sugar.

Table 5.17: Kasama Sugar sugarcane yields converted to bioethanol in liters.

Year	Sugarcane Yields In Kgs	Bioethanol In Liters
2007	12,560,000	1,004,800
2008	15, 000,000	1,200,000
2009	15,000,000	1,200,000
2010	15,500,000	1,240,000
2011	17,000,000	1,360,000
2012	19,000,000	1,520,000
2013	22,000,000	1,760,000
2014	23,500,000	1,880,000
2015	30,000,000	2,400,000
2016	33,500,000	2,680,000
2017	35,000,000	2,800,000

Another company where yields were converted to bioethanol potential is Kasama Sugar. Being so far the smallest company included in this research, the bioethanol converted from the yields were lower than that of the other two sugar companies assessed earlier on. However, the yields continued to grow and between 2007 and 2017 the yields had doubled.

In the manner of sugar production, bioethanol production must also be spread in many parts of country in order to minimize the cost of transporting bioethanol far from the source of production. Looking at the localities of companies where these feedstocks were identified, it is clear that much of Zambia's environment is friendly to the production of sugarcane.

At national level, it is important to come up with a plan to enhance the production of these feedstocks such that the quantity of yields is enough for both sugar and bioethanol. Sugarcane as a crop is friendly to Zambian soils because throughout the country, it is grown by small scale farmers and sold to the public for its sweet juice. Once it is identified that it can be commercialized for fuel production apart from sugar, other players can come onboard.

This business is not only about the production plant supported by the plantation, it is about it being identified as a viable business and then the out-growers provide the feedstock. A good example are milling companies that are producing mealie meal, they do not own maize farms. The farmers know that there is business for maize in the country and the feedstock is supplied by the farmers. Since maize is a staple food in Zambia, farmers normally grow enough for sale and leave some for their own consumption.

Figure 5.16 represents bioethanol potential from sugarcane yields at Kasama Sugar

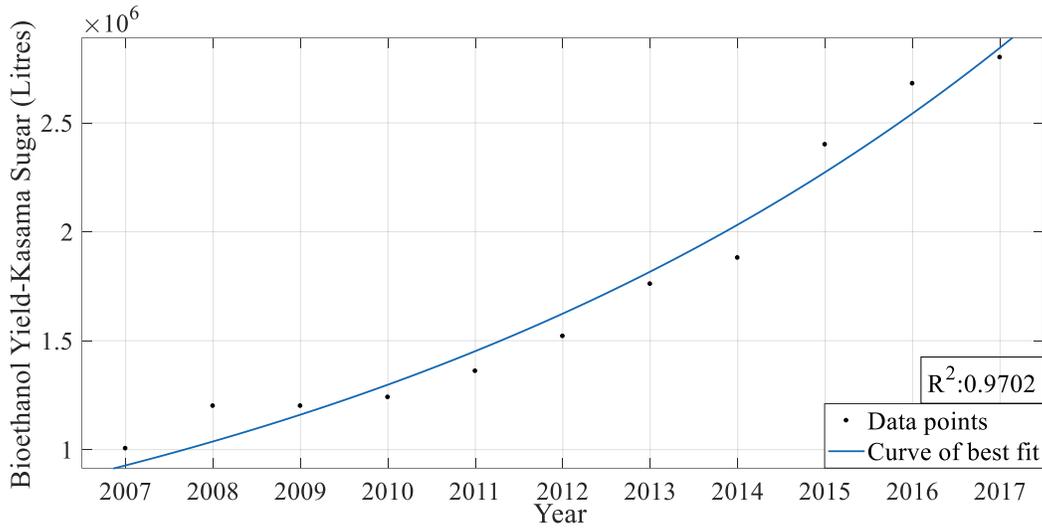


Figure 5.16: Exponential growth of bioethanol potential at kasama sugar.

The growth rate at Kasama Sugar was consistent and predictable. That is why the when factored in the MATLAB model, the profile of the curve of best fit and data points both follow the same gradient. The other factor that made the profiles both the curve of best fit and the data almost consistent was when the company was at its infancy and the growth rate was just a trickle increase. This means that the increase has less impact graphically.

$$E=1.836 \times 10^{-92} e^{0.1121 \text{yr}} \dots \dots \dots 15$$

The coefficient of determination (R^2) at 0.9702.

As can be seen from the coefficient of determination, it is high percentage at 97% meaning that the rate of growth was consistent.

Table 5.18 is a summation bioethanol potential from the three sugar companies.

Table 5.18: Consolidated bioethanol potential from the three sugar companies.

Year	Total Sugarcane Yields In Kgs	Bioethanol In Liters
2007	1,880,760,000	150,460,800
2008	2,172,000,000	173,760,000
2009	1,947,000,000	155,760,000
2010	2,936,500,000	234,968,000
2011	3,435,000,000	274,800,000
2012	3,382,000,000	270,560,000
2013	3,601,000,000	288,080,000
2014	3,665,500,000	293,240,000
2015	3,875,600,000	310,048,000
2016	3,632,700,000	290,616,000
2017	5,395,000,000	431,600,000

The sugar companies in Zambia provided the major resource as feedstock for bioethanol potential in Zambia. Because of its commercialization nature, the feedstock was yielded in large quantities providing a high potential that sugarcane has in the country for conversion into other finished products. The fact that sugar companies are able to invest at such huge scales means that any other sector in the economy should be able to venture in other business activities.

This research therefore has identified sugarcane as the most available feedstock for this purpose. Efforts must be made to enhance its production since it is easy to grow in most parts of the country. On the business front, just like in sugar refineries, out-growers voluntarily or by support schemes should be able to participate in supplying the set industries with the much needed feedstock in this case sugarcane.

It must be understood that the use of fossil fuels is slowly being discarded by developed countries because of environmental degradation the fuels are causing. The greenhouse gasses emissions coupled with their impact on global warming is causing great damage to natural resources. This has resulted in economies of many countries downgrading and general increase in poverty levels of the masses in the affected countries.

Zambia has not been spared from these challenges and with poverty levels already high, the environmental degradation is causing lower crop yields resulting in government providing relief food in most parts of the country. This effectively affects the developmental agenda of the country because resources are being diverted towards consumption.

Figure 5.17 is a representation of bioethanol potential from the three sugar companies

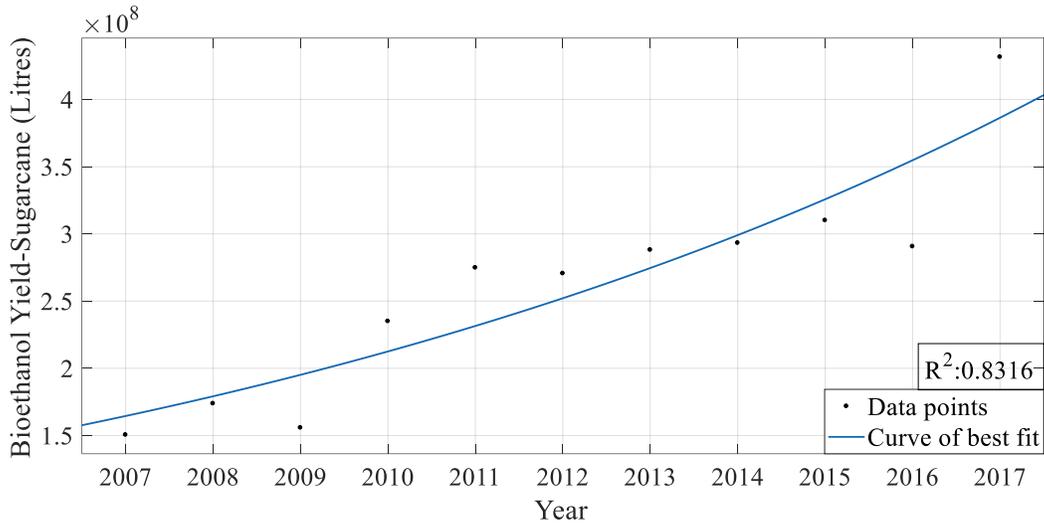


Figure 5.17: Exponential growth of bioethanol potential by the sugar companies in the country.

Coefficient of determination (R^2) is lower at 0. 8316

The consolidated results from the sugar companies were factored in the MATLAB model. Using the model, the curve of best fit and data points were plotted.

The following exponential equation was derived:

$$E=6.028 \times 10^{-67} e^{0.0854 \text{yr}} \dots \dots \dots 16$$

The coefficient of determination (R^2) is 0.8316 which is low and greatly influenced by the Zambia Sugar results.

5.6. Converting Of Sweet Potato and Cassava Yields to Bioethanol

Sweet potato and Cassava technologies of extracting ethanol are different from that of sugarcane. The two crops processing is by hydrolysis and then fermentation where starch is converted to useful sugars. In this case the mass in use is that of starch. According to [18] the maximum yields of starch from a given mass of sweet potato is 25% and for cassava is 28%. The sweet potato conversions to bioethanol is as shown in Table 5.19.

In the same vain [38] gives the starch and bioethanol relationship. The relationship is such that 170L of ethanol per ton of sweet potato and 363L per ton of cassava.

Therefore using $E=q \times S$

q for sweet potato is 0.17l/kg and for cassava is 0.363L/kg

Sample calculation for sweet potato

$$E=q \times S$$

$$E=0.17L/kg \times 21569000kg=3,666,730.$$

Table 5.19: National sweet potato yields converted to bioethanol

Year	Sweet Potato Yields In Kgs	25% Starch In Kgs	Ethanol In Liters
2007	86,276,000	21,569,000	3,666,730
2008	93,283,000	23,320,750	3,964,527.5
2009	100,824,000	25,206,000	4,285,020
2010	104,036,000	26,009,000	4,421,530
2011	111,054,000	27,763,500	4,719,795
2012	117,081,000	29,270,250	4,975,942.5
2013	124,513,000	31,128,250	5,291,802.5
2014	173,213,000	43,303,250	7,361,552.5
2015	213,091,000	53,272,750	9,056,367.5
2016	224,310,000	56,077,500	9,533,175
2017	236,127,000	59,031,750	10,035,397.5

Sweet potato has good bioethanol production properties. The process has a stage of extracting starch from sweet potatoes and then the extracted starch is converted to bioethanol. The results so far show a production potential of two days' supply to about eight days. So far, this is the smallest feedstock resource feedstock compared to sugarcane and cassava quantities and it requires enhancement.

This feedstock has never been commercialized in Zambia and so far there are no attempts to do so. However one of its important properties is that it has rich properties for bioethanol production. Normally it is grown by women in Zambia and traded by small scale traders. With this situation, the crop is scantily accounted for by the Ministry of Agriculture. Nevertheless, it is important to note that every attempt is being made to account for it for the purpose of managing the poverty situation in the country.

The fact that this feedstock is associated with bioethanol production, and once decisions are made to migrate from using gasoline to bioethanol, this feedstock can cease to be a preserve of women. Other players can come on board including commercial undertakings. It remains important that decisions should be made especially that some of these feedstocks are not staple in nature in the country. The data was further compiled as shown in Figure 5.18 below.

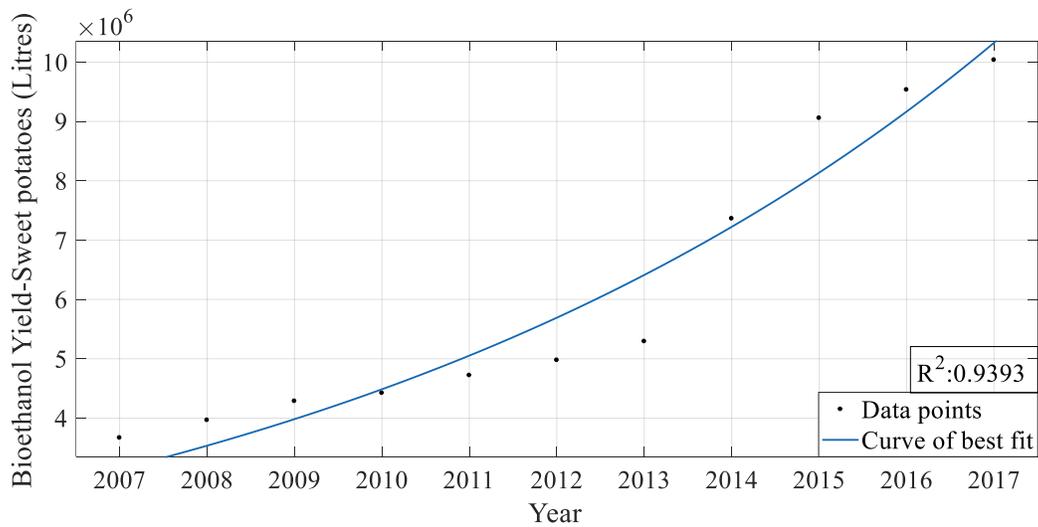


Figure 5.18: National sweet potato bioethanol potential exponential growth.

The results of bioethanol potential in Table 5.19 were factored in the MATLAB model and plotted the curve of best fit and the data points. This is another situation where the curve of best fit and data points were developed in tandem. The curve was smooth, a clear indication of good results.

The exponential equation that was used by the MATLAB model to plot the equation is as follows:

$$E=4.801 \times 10^{-98} e^{0.1191 \text{yr}} \dots \dots \dots 17$$

The coefficient of determination (R^2) is 0. 9393.

The η for cassava is 0.363L/kg and ethanol conversion is as shown in Table 4.13.

Table 5.20: National cassava yields converted to starch in kilograms and ethanol in liters.

Year	Cassava Yields In Kgs	28% Starch In Kgs	Bioethanol In Liters
2007	599,361,000	167,821,080	60,919,052.04
2008	657,015,000	183,964,200	66,779,004.6
2009	683,714,000	191,439,920	69,492,690.96
2010	798,171,000	223,487,880	81,126,100.44
2011	790,412,000	221,315,360	80,337,475.68
2012	801,520,000	224,425,600	81,466,492.8
2013	854,393,000	239,230,040	86,840,504.52
2014	819,497,000	229,459,160	83,293,675.08
2015	923,795,000	258,662,600	93,894,523.8
2016	1,114,583,000	312,083,240	113,286,216.1
2017	1,178,516,000	329,984,480	119,784,366.2

Cassava yields were assessed in the similar manner like sweet potato by first calculating the starch potential from the yields. It was the calculated starch to which the bioethanol potential was based and according to literature the conversion stands at 28% of cassava quantity is starch. It is important to note that this feedstock provided the second largest yield quantities after sugarcane.

In terms accountability, the Ministry of Agriculture has more collaborating data on cassava yields than sweet potato. This is from the background that this feedstock was traditionally a staple food for people of Luapula Province and up to now some of the people are clinging to it as their staple food. The government of the Republic of Zambia in collaboration with co-operative societies and research institutions in country are developing fast maturing varieties.

This feedstock has properties for bioethanol production. With this seemingly lucrative opportunity, its application for bioethanol production can in the similar manner attract more players on the market including commercial undertakings. The fetching prices for this feedstock now by the brewery companies is considered exploitative by the farmers themselves. Bringing in another dimension to its use has the potential to boost the fetching prices for the feedstock. The collected data was further computed using MATLAB to produce Figure 5.19 below.

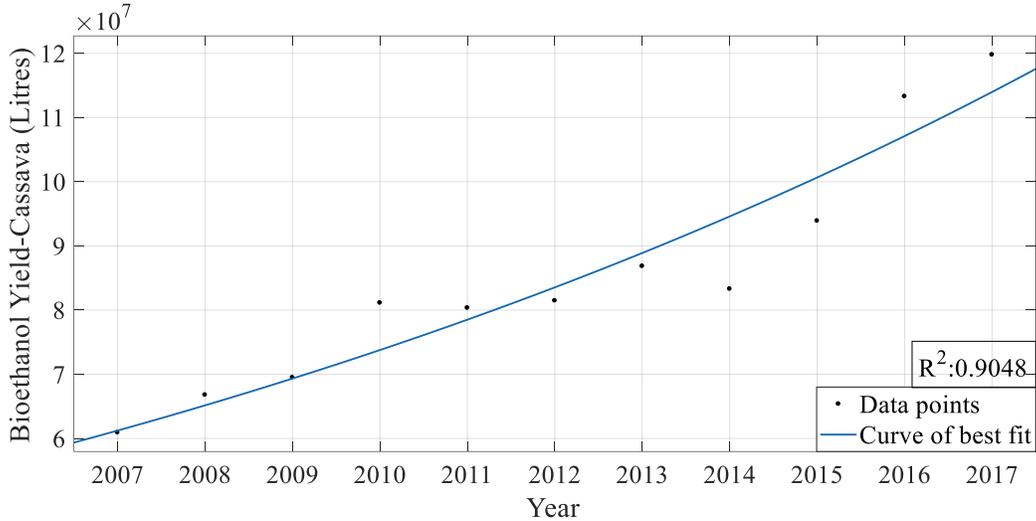


Figure 5.19: Exponential curve for cassava yields bioethanol potential in the country.

The growth rate is represented by an exponential curve with data points according to Table 5.20.

The results that were obtained on the bioethanol potential from the national cassava yields were factored in the MATLAB model. That resulted in the plotting of the curve of best fit and the data points. Somehow, the curve of best fit and the data points are aligned and in tandem.

Out of factoring the results in the MATLAB model, the exponential equation which plotted the data points was derived as follows:

$$E=4.231 \times 10^{-47} e^{0.06214 \text{yr}} \dots \dots \dots 18$$

The coefficient of determination (R^2) is 0.9048.

5.7. Hydrolysis Process

It is important to note that the process of converting starch extracted from sweet potato and cassava is by way of the hydrolysis process. The hydrolysis process involves the use of enzymes diluted into the starch solution and subjected to high temperatures of about 78°C for a minimum of two hours to breakdown the solution to usable sugars which is referred to as the liquification process. Thereafter the temperature is increased further to about 90°C for a minimum of forty five minutes which is the saccharification process and cool down the solution to room temperature of which process converts it to glucose. The glucose is then fermented for three to seven days before distilling it into bioethanol.

Table 5.21 was thereafter compiled to establish the potential of bioethanol production under scenario number two.

Table 5.21: Summation of annual bioethanol potential for Zambia under scenario 2

Year	Summation Of Annual Bioethanol Potential From All Feedstocks In Liters In Scenario 2
2007	215,046,582
2008	244,503,532.1
2009	229,537,711
2010	320,515,630.4
2011	359,857,270.7
2012	357,002,435.3
2013	380,212,307
2014	383,895,227.6
2015	412,998,891.3
2016	413,435,391.1
2017	561,419,763.7

The results of the second scenario were summed up and the outcome is as shown in Table 5.21. The second scenario gave an indication of what it would take the country to replace gasoline with bioethanol. The results contained in Table 5.21 compared to Table 5.1 which is the obtaining national gasoline consumption shows how much of the sugarcane, sweet potato and cassava the country needs to effect the migration.

At national level, decisions have to be made to know what needs to be done in order to move in tandem with the rest of the world. It remains undisputed fact that the whole world is working towards finding lasting solutions to the challenges posed by combustion of fossil fuels. Zambia cannot lag behind while the rest of the world is making headways in alleviating the situation.

What is important to note is the fact that these feedstocks are locally produced and the cost is one that Zambia as a country can regulate. So far the cost of fuel in the country is high and its high cost is affecting the rest of the national activities since fuel is a prime mover of economic activities in any country. The solution to Zambia lies in moving to biofuels as the main stay fuel for motor vehicles in country. The only costly venture in this case can be the importation of the bioethanol processing equipment and the rest such as feedstocks are locally acquired.

It should be noted that crude oil and sometimes processed fuel are all imported in the country and Zambia has to find the foreign exchange to make these transactions at a great cost. This has tended to impoverish the country because generally, the resources are being channeled towards these costly importations at the expense of poverty alleviation activities.

The results of the above summation was compiled in MATLAB and produced Figure 5.20 below.

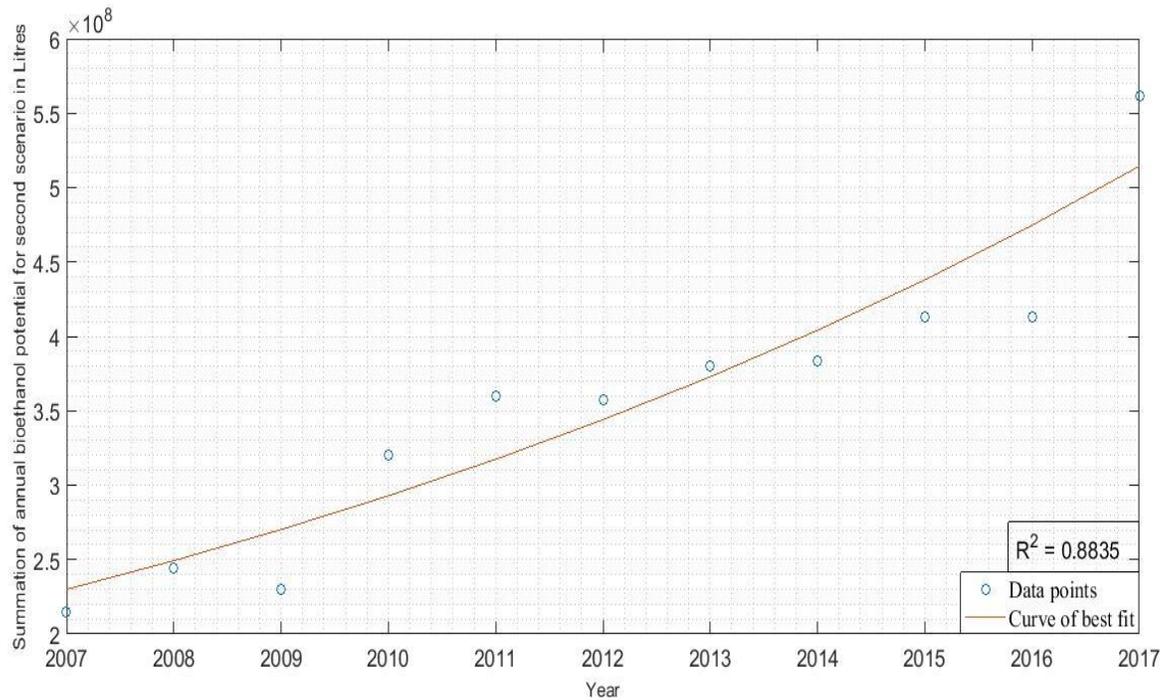


Figure: 5.20: Summation bioethanol potential Exponential Curve from all the feedstocks under Scenario 2

The results obtained from scenario two were summed up in Table 5.21 and fed into the MATLAB model to produce a smooth of line of best fit against the circled points for the actual data points.

The coefficient of determination R^2 is 0.8835

Exponential equation $E=1.569 \times 10^{-62} e^{0.0805yr}$19

5.8. Bioethanol from Sweet Sorghum

Sweet Sorghum by the Zambian agriculture system is not accounted for by the Ministry of Agriculture. The reason is that it is not considered as one of the stocked food crops. Research during literature review shows that sweet sorghum is widely used in other countries for bioethanol production. Checking references from Munyiinda, Yamba and Walimwipi (2012) to Gnansounou, Dauriat and Wyman (2005), it was established that sweet sorghum is one crop widely used for bioethanol production in countries such as Egypt, South Africa, Sudan, Angola, Tanzania, Nigeria, Taiwan, China, Brazil and the United States of America. In Zambia a lot of research is going on as contained under references 10 to 17 on the potential of sweet sorghum to produce bioethanol. The results obtained and presentations that followed showed rich yields of bioethanol.

According to the Zambian scenario, and considering the main feedstocks of this research, all the feedstocks are foodstuffs and converting them directly to bioethanol would affect the food basket for the general public in the country. This scenario gives sweet sorghum a comparative advantage

over other feedstocks. Therefore, processing sweet sorghum into bioethanol would not in any way deprive the people of Zambia their food source and requirement. This research considered that sweet sorghum to be taken as the main stay in bioethanol processes. It was discovered during research that the crop is drought resistant and is grown in all parts of Zambia.

Market players in the production of bioethanol can be encouraged to consider establishing supporting estates in sweet sorghum production to provide feedstock in bioethanol production. Stock assessment should include out-growers especially peasant farmers who grow it just for its sweet juice. As elaborated during discussing other feedstocks, any feedstock that is identified with fuel production (sweet sorghum inclusive) would have both its demand and price escalate upwards. The fact is that the crop would attract investment by commercial and small scale entities. It is therefore important that at national level decisions are made on this noble policy direction so that non conflict crops like sweet sorghum are enhanced. Such an approach would boost the economy and save the much scarce foreign exchange.

Bioethanol being the most probable alternative energy fuel many poor African countries would migrate to, it can provide an opportunity for the country to be the major exporter of fuel to neighboring countries and in return earn foreign exchange. Such a move would to a very large extent boost the economy and drastically reduce cost of living in the country.

With the above views whilst so far the country is not able to account for sweet sorghum yield, its characteristics make it the ultimate alternative

5.9. Levelised Cost of Energy

The levelised cost of energy or LCOE is similar to the concept of the payback for energy systems. However, instead of measuring how much is needed to recoup the initial investment, the LCOE determines how much money must be made per unit of a particular energy to recoup the lifetime costs of the system. This includes the initial capital investment, maintenance costs, the cost of feedstock for the system (if any), any operational costs and the discount rate.

The LCOE is one way of determining whether or not a firm will build a project because if the project will not break even then it will not be built. The LCOE is a useful tool because it can combine both the fixed costs and variable costs into a single measurement to simplify analysis. To determine the LCOE, a firm will determine the necessary parameters such as the lifetime of the system, how much bioethanol it will produce and the input costs.

According to [39], the bioethanol production plant able to take all the feedstocks has the following parameters:

Investment Cost =USD \$ 500,000,000.

Overhead and Maintenance costs at 15% of Investment cost.

Plant Capacity stands at 450,000,000 liters of bioethanol per year.

Plant life span=30 years.

Capacity Factor=90%.

The following sample calculations were based on the 2017 yields for each feedstock.

1) Total Sugarcane yields

Yield = 5,395,000 tons/year

Bioethanol Potential= 431,600,000 Liters/year (Table 5.18, 2017)

Cost of Sugarcane= \$40/ton

Using the above information, Levelised Cost of Energy (LCOE) for sugarcane is as follows:

$$\text{LCOE} = \frac{\text{investment} + \text{operations \& maintenance cost} + \text{variable cost}}{\text{Annual energy} \times \text{plant factor} \times \text{plant life}}$$

$$\text{LCOE} = \frac{500,000,000 + 75,000,000 + (40 \times 5,395,000)}{431,600,000 \times 0.9 \times 30}$$

$$\text{LCOE} = 0.06786$$

$$\text{LCOE} = \underline{\underline{\$0.06786/\text{liter}}}$$

According to [40] the following plant to carter for the rest of the feedstocks and the plant parameters are as follows:

Investment Cost= US \$ 50,000,000

Overhead and Maintenance costs at 15% of Investment cost.

Plant Capacity stands at 150,000,000 liters of bioethanol per year.

Plant life span=30 years.

Capacity Factor=90%.

2) National Cassava Yields

Yield=1,178,516,000kg/year

Bioethanol Potential= 119,784,366.2 Liters/year (Table 5.20, 2017)

Cost of Cassava= \$0.08/kg + \$0.04/kg for hydrolysis process

Using the above information Levelised Cost of Energy (LCOE) for cassava is as follows:

$$\text{LCOE} = \frac{\text{investment} + \text{operations \& maintenance cost} + \text{variable cost}}{\text{Annual energy} \times \text{plant factor} \times \text{plant life}}$$

$$\text{LCOE} = \frac{50,000,000 + 7,500,000 + (0.12 \times 1,178,516,000)}{119,784,366.2 \times 0.9 \times 30}$$

$$\text{LCOE} = 0.062$$

$$\underline{\text{LCOE}} = \underline{\$0.062/\text{Liter}}$$

3) Molasses

Yield=302,120,000kg/year

Bioethanol Potential=75,530,000Liters/year (Table 5.5, 2017)

Cost of Molasses= \$0.07/kg

$$\text{LCOE} = \frac{\text{investment} + \text{operations \& maintenance cost} + \text{variable cost}}{\text{Annual energy} \times \text{plant factor} \times \text{plant life}}$$

$$\text{LCOE} = \frac{50,000,000 + 75,00,000 + (0.07 \times 302,120,000)}{75,530,000 \times 0.9 \times 30}$$

$$\text{LCOE} = 0.039$$

$$\underline{\text{LCOE}} = \underline{\$0.039/\text{Liter}}$$

4) National Sweet Potato Yields

Yields=236,127,000kg/year

Bioethanol Potential= 10,035,397.5 Liters/year (Table 5.19, 2017)

Cost of sweet potato=\$0.07/kg+ \$0.035/kg for hydrolysis process

$$\text{LCOE} = \frac{\text{investment} + \text{operations \& maintenance cost} + \text{variable cost}}{\text{Annual energy} \times \text{plant factor} \times \text{plant life}}$$

$$\text{LCOE} = \frac{50,000,000 + 75,00,000 + (0.105 \times 236,127,000)}{10,035,397.5 \times 0.9 \times 30}$$

$$\text{LCOE} = 0.304$$

$$\underline{\text{LCOE}} = \underline{\$0.304/\text{Liter}}$$

Important in the energy production planning whatever the energy is the levelised cost of energy. The fact is that every investment has a recovery period in which the investment and running costs are recouped. This particular cost analysis component looks at a unit cost of energy required to recoup the cost of setting up and running the plant over a period of 30 years.

In this case, the levelised costs of energy (LCOE) of the four feedstocks under consideration namely: sugarcane, molasses, sweet potato and cassava were calculated. Observations were made during these calculations. The determining factor during these calculations was the annual energy which is the denominator of the equation. From all the years' assessments of bioethanol potential, 2017 was taken as a baseline year for the purpose of sample calculations for levelised cost of energy.

$$\text{LCOE} = \frac{\text{investment} + \text{operations \& maintenance cost} + \text{variable cost}}{\text{Annual energy} \times \text{plant factor} \times \text{plant life}}$$

The variable cost also influences the outcome because it is the product of the cost of the feedstock and the total yield.

The sugarcane total yields gave the most competitive levelised cost of energy at a cost of \$0.06/liter. This was from the total bioethanol potential of 431, 600,000 liters per year as obtained in Table 5.18. Compared to the current cost of gasoline in Zambia which is at \$1.2/liter, this results would lower the cost of fuel in the country and also lower the cost of doing business. There was need to scale down on the size of the plant to cater for other feedstocks. The quantities of cassava yields also provided a competitive levelised cost of energy. At the rate of total cassava yields, the levelised cost of energy stands at \$ 0.062/liter which also is far much lower than the retail price of gasoline in the country at \$1.2/liter

Molasses which is a by-product of sugar production provided another interesting levelised cost of energy result. At the cost of \$ 0.039/Liter which is even further below the cost of gasoline in the country. Sweet potato gave a levelised cost energy at \$0.304/liter which is the only feedstock remaining uncompetitive due to lower yields.

It is known that if bioethanol replaced gasoline in the country, it is a fact that there would be transport, transit and profit markup costs. From the results however, the overall cost of bioethanol can still be far below the current cost gasoline in the country. Clearly this is the route to go for the country. The benefits for the country are twofold. Firstly the cost of fuel in the country would go down which lowers the cost of doing business and the cost of living. The second benefit is that the country would lower the pollution of the environment by over 90%. Additionally, this would save the foreign exchange currently being spend to import crude oil from afar outside the country

5.10. Forecasting of Gasoline consumption and Bioethanol Production up to 2040

The major idea of this research was to establish how fuel consumption behavior scenario has been from 2007 to date. The trend when extrapolated helped to forecast the gasoline consumption up to 2040. Information on the annual gasoline consumption during the period under review was provided by The Energy Regulation Board of Zambia and the Ministry of Energy, Directorate of

Petroleum. In the similar manner, the bioethanol potential in Zambia from the individual feed stocks and the overall was processed mathematically. The obtained results of the national bioethanol potential were compared with the national gasoline consumption to ascertain the ability of Zambia to potentially migrate from using gasoline to bioethanol. This assessment was carried out using two scenarios. The first scenario considered molasses from the sugar companies that provided the yields and the leftovers from consumption of sweet potato and cassava in the country. The second scenario converted bioethanol from the total yields of sugarcane from three sugar companies in Zambia and those of the yields of cassava and sweet potato in the country as provided by the Ministry of Agriculture and Central Statistics Office.

Data gathered and extrapolated was compiled on the same graph and table below to provide a platform to discuss the results. The compilation and extrapolation up to 2040 included the gasoline consumption from 2017 and then extrapolated to 2040. The same method was used to process bioethanol potential for both scenarios and similarly extrapolated to 2040. It was these results that were considered for discussion in this chapter in relationship to the main objectives of this research.

At national level it was also of paramount importance to establish if at all there are vehicles in Zambia currently using bioethanol as fuel. Official inquiry was tendered at Road Transport and Safety Agency (RTSA) and it was established that there was none. This means that this kind of fuel is not known in the country and it will require promotions for society to accept. The other important aspect in this research is the modifications required in the carburation and ignition systems of the various cars using gasoline. These modifications are minor and cost effective compared to electric cars which is a new phenomenon all together. The cost of carrying out carburetor and ignition modifications is by far less costly compared to acquiring a new electric car. Table 5.22 below is an extrapolation of gasoline consumption and bioethanol potential from the two scenarios. The same data was fed on to the MATLAB Model to produce Figure 5.21.

Table 5.22: gasoline consumption, and bioethanol potential from both scenarios forecast up 2040

Year	National Gasoline Consumption (Gigalitres)	Bioethanol Potential From All Feed Stocks Without Taking Consumption Into Consideration (Gigalitres)	Bioethanol Potential From All Feed Stocks After Taking Consumption Into Consideration (Gigalitres)
2007	0.1663	0.2300	0.0473
2008	0.1858	0.2493	0.0512
2009	0.2077	0.2702	0.0554
2010	0.2321	0.2928	0.0599
2011	0.2594	0.3174	0.0648
2012	0.2898	0.3440	0.0701
2013	0.3239	0.3728	0.0758
2014	0.3620	0.4041	0.0820
2015	0.4045	0.4380	0.0887
2016	0.4520	0.4747	0.0960
2017	0.5051	0.5145	0.1038
2018	0.5645	0.5576	0.1123
2019	0.6308	0.6043	0.1214
2020	0.7049	0.6550	0.1314
2021	0.7878	0.7099	0.1421
2022	0.8803	0.7694	0.1537
2023	0.9838	0.8339	0.1662
2024	1.0994	0.9038	0.1798
2025	1.2286	0.9796	0.1945
2026	1.3729	1.0617	0.2104
2027	1.5343	1.1507	0.2276
2028	1.7146	1.2472	0.2461
2029	1.9160	1.3517	0.2662
2030	2.1412	1.4651	0.2880
2031	2.3928	1.5879	0.3115
2032	2.6740	1.7210	0.3369
2033	2.9882	1.8653	0.3645
2034	3.3393	2.0216	0.3942
2035	3.7317	2.1911	0.4264
2036	4.1702	2.3748	0.4612
2037	4.6602	2.5738	0.4989
2038	5.2078	2.7896	0.5396
2039	5.8198	3.0234	0.5837
2040	6.5036	3.2769	0.6314

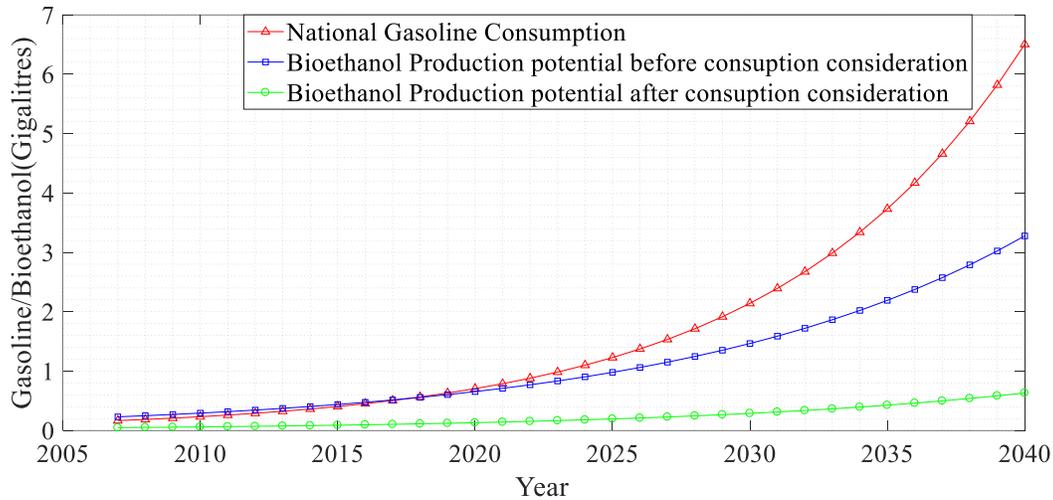


Figure 5.21: Gasoline consumption, and bioethanol potential from both scenarios forecast up 2040

5.10.1. National Gasoline Consumption Forecasting Up to 2040

The National Gasoline consumption was key to the outcome of the results obtained from the potentials of the feedstocks under this consideration. What came out clearly was the rate of growth of consumption each progressive year from 2007 to 2017. This same rate of growth was used to extrapolate gasoline consumption up to 2040. As at 2007, the annual gasoline consumption stood at 166,300,000 liters meaning that on daily basis in 2007 consumption stood at 455,616.44 liters. The consumption continued increasing and as at 2017, the annual consumption stood at 505,100,000 liters giving a daily consumption of 1,383,835.62 liters of gasoline. The growth in consumption of gasoline between 2007 and 2017 was approximately three (3) times. The trend between each progressive year from 2007 to 2017 was used to extrapolate and escalate the consumption up to 2040. These figures might not be accurate but they provide a framework for planning purposes looking into the future. All figures going forward were calculated using the following equation derived using MATLAB:

$$E=2.415 \times 10^{-89} e^{0.1111 \text{yr}} \dots \dots \dots 20$$

And coefficient of determination $R^2=0.9066$

The above variables were used to extrapolate and predict the gasoline consumption situation in Zambia up to 2040. According to the prediction, the annual gasoline consumption in 2040 will be 6,503,600,000 liters giving a daily consumption of 17, 818, 082.19 liters of gasoline compared to current consumption of about 1,400,000 liters of gasoline per day. This would only be attained at a colossal cost of an imported product.

This research was looking at the potential inherent within the country using feedstocks which are grown within the country and stand well with the Zambian weather patterns. Replacing gasoline with an alternative locally produced fuel would save the country a lot of foreign exchange and in

return, earn even more foreign exchange by exporting the same bioethanol to neighboring countries. Worldwide efforts are being made to manage the environmental pollution caused by the combustion of fossil fuels. With the potential daily consumption of gasoline standing at 17, 818, 082.19 liters by 2040, the level and extent of environmental pollution will equally be as high. Graphically, the National Gasoline Consumption is well elaborated in Figure 6.1 represented by a red curve. The curve for gasoline consumption is exponentially growing faster and higher than the rest of curves on the graph meaning that decisions have to be made to curb the situation.

Generally Zambia has a variety of feedstocks that can be converted to biofuels and all it requires is the motivation of investment in the processing of these fuels. The only costly venture in this area is the purchase of the processing brewing plant which can be bought using tax concessions provided by government. This is necessary because the arrangement is a serious transformation in the energy sector of the country. The environment pollution does affect the economy of the country and now it is an international challenge. Protocols and treaties are being entered at international level trying to find lasting solutions to the challenge caused by the combustion processes of fossil fuels. While the developed countries are resorting to electric cars, biofuels remain a lasting solution for the poor countries like Zambia because the modifications required for technology transfer are cheaper compared to electric cars where people have to buy new cars all over again.

The transformation is a serious undertaking because it would require overhauls of certain industrial installations which could have been acquired at a great cost. What has happened over the years is that the pollution has caused greenhouse gasses (GHG) which in effect has affected the weather patterns throughout the world. These changes in weather patterns are affecting economic and activity planning of many countries Zambia inclusive. The weather pattern especially the rain cycle remain unpredictable. This has caused a lot of uncertainties on investing in the agriculture sector particularly peasant farmers who have no capacity to venture in mechanized farming methods. It therefore remains cardinal to consider changing the type of fuels the country uses to try to propel the economy of the country.

A lot has to be done in terms of investment and planning to alleviate the challenges brought about by the environmental degradation in our countries. Undoubtedly the cost of this technological migration is exorbitant but it has far reaching benefits in terms of hearth and national/regional development.

5.10.2. Scenario Number one: Forecasting Bioethanol Production Potential after Consumption is considered Up to 2040

The feedstocks under consideration in this research are all food stuff and have a bearing on what would become of the food requirements of the country if everything is diverted to bioethanol production. Looking at the demand existing for fossil fuels in the country, it was felt replacing gasoline with bioethanol would mean the transferring of the existing demand for gasoline to bioethanol. The resultant effect would be that the marketing of these feedstocks incline towards bioethanol production due to fetching prices of fuel production related raw materials with the cost of fuel being a determinant. Considerations were seriously made at the continuous nature of

demand for fuel meaning that these feedstocks would be required throughout the year. Remember, production of fuel is not only for daily national requirements but includes strategic reserves to maintain supply during the equipment down time.

The competing effects of food requirements were given serious consideration. This was in order to curb the scarcity that would be caused by this competition. In any given situation, production of products is never done at the expense of the food requirements of the citizenry. Matters of poverty reduction hinge on the social-corporate responsibility. The state will always protect citizens from being plunged in poverty due to diversion of food stuff raw materials to other lucrative business activities. This was considered serious especially if the diversification is based on the product that has been traditionally used as food by the society over a long period of time. Considering that as at 2018, the daily gasoline demand in Zambia stood at 1.3 Million liters, it was observed that the exploration of these crops into bioethanol would demand beyond total yields of each given year.

However, it is important to note that once the demand for these crops become equal to the demand of gasoline or its replacement, the number of participants in production of these crops would increase. What is being produced by peasant farmers now would attract commercial farming entities. The investment in the bioethanol processing plants would in return create demand for the feedstocks under consideration. Following the law of demand and supply, the existing demand would bring about scarcity of the feedstocks in question and this scarcity eventually causing prices of these crops escalate upwards.

This behavior has far reaching financial gains to the farmers and motivating other players to invest in the production of these feedstocks. Nevertheless, it remains important on one part of this research to consider evaluating the existing demand for food in the country before converting the feedstocks in question to bioethanol. That way, the results of this research would not risk the lives of citizens by attracting investment in bioethanol production ignoring people's food requirements. The sugarcane conversion to molasses was the easiest to attain. The information is that to every sugarcane yield there is 4% molasses. The effect was that all the yields from Kafue Sugar, Zambia Sugar and Kasama Sugar quantities year by year from 2007 to 2017 were converted to molasses at the rate of 4%. The results were compiled in a tabular form and graphically according to Table 6.1 and Figure 6.1. However the compiled representation show a low yield of bioethanol. What is clear from this research is that bioethanol production is directly proportional to sugarcane yield. An increase in sugarcane yield can translate to an increase in bioethanol production.

Looking at the graph, the green curve represents bioethanol yields lying almost at the base of the graph. This curve is not only for molasses but combined with excess cassava and sweet potato bioethanol potentials after food considerations. When the green curve was compared with the red curve which represents the current gasoline consumption in the country, it is clear that the path of excess food and molasses would not in any way take Zambia closer to replacing gasoline with bioethanol.

The Ministry Agriculture, Crop Survey Unit provided vital information on cassava and sweet potato general distribution. It was reported that above consumption by the producers and other consumers, 29% and 32.07% of cassava and sweet potato respectively are excess available for bioethanol conversion in Zambia. The above quantities combined with the 4% representation for each quantity of sugarcane fell below the required quantities enough to replace gasoline with bioethanol.

Scenario number one looks promising in implementation and free from any conflict with regards to food requirements of the citizenry. However, the bioethanol yields from this scenario can only suffice for gasoline/bioethanol blends at 10% ethanol which retains a huge amount pollutants and does still contaminate the environment. The results therefore obtained fell far below the benchmark which would make the country consider replacing gasoline with bioethanol. The only way these results could be enhanced upwards was to increase the production of the crops under consideration. The effect is that the excess above food requirements and the 4% for every sugarcane yield would swing upwards giving higher bioethanol conversions.

Nevertheless, fuel supply is big business with shortages of fuel in some parts of the world due to ever increasing demand for fuel. The number of vehicles are increasing every day on the Zambian market. The demand for fuel as a commodity is ever increasing every day. With this increase in the demand of fuel, any feedstock identified as a raw material for any form of motor vehicle fuel would attract a large number of farmers and traders due to emerging demand. Therefore, the business nature of that feed stock would attract even commercial entities to consider investment in it. Remember replacing gasoline with bioethanol is a business decision. Business has market at play and bioethanol as a fuel can easily find its place on the market. Feedstocks can automatically come up due to existing demand on the market.

5.10.3. Scenario Number Two: Forecasting Bioethanol Production Potential before Consumption is Considered Up to 2040

The results obtained in the second scenario are closer to what would make economic sense to migrate from use of gasoline to bioethanol. Observing both Table 6.1 and Figure 6.1 it shows that the blue curve for bioethanol production potential from total yields and the red curve for gasoline consumption were moving in tandem from 2007 to 2023. This means that the sugarcane yields from the three major sugar companies in the country combined with the national yields of cassava and sweet potato under the same period could be converted to bioethanol and produce enough bioethanol to replace gasoline as a motor vehicle fuel.

From the results, it was observed that the two curves separate from 2024 with the forecast on the National Gasoline consumption going much higher such that by 2040 the gap between the two curves is much pronounced. This difference was caused by the trend in the actual results obtained from 2007 to 2017. The results for sugarcane were consistently going up. The challenge was when the bioethanol potential from sugarcane was blended with that of cassava and sweet potato potentials. Cassava and sweet potato had lower growth rates. Their lower growth rate when

blended with that of sugarcane caused distortion in the growth rate of scenario number two in general.

However, seriously considering scenario number two provides an idea of what ought to be done in order to attain the levels at which gasoline is being consumed in Zambia. In this scenario, it is evident that the levels of sugarcane yields in the country were adequate enough to provide the required bioethanol potential to replace gasoline to propel motor vehicles. If at all there could be any shortfall, it would require a small increase in the sugarcane yields in the country.

Considering that the sugarcane yields being discussed were specifically grown to manufacture sugar and the quantities of cassava and sweet potato for consumption, it is of paramount importance to plan using direct investment using the yields in the sugar companies to determine the levels of investment. As indicated before, fuel for motor vehicles is big business. Planning should not be limited by what is existing. Alternative sources of sugarcane, cassava and sweet potato should be planned for.

The problem at hand is that the current fossil fuels being used are pollutants to the environment. The extent of this problem is that the world is now facing challenges to withstand the global warming caused by fossil fuels. The weather pattern remain unpredictable coupled with weather related disasters. These disasters are destroying nature, crops and buildings and in most cases displacing humanity and wild animals. The results of this research have shown the quantities in terms of feedstocks required in order to replace gasoline with bioethanol.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

This chapter looked at overall outcome of the research and recommendations were made towards the areas where attention is needed.

6.1 Conclusion

1. The potential for bioethanol production in Zambia was established if only the country can go by scenario number two which is reflected in Table 5.21 which was 561,419,763.1 liters as at 2017 unlike Table 5.8 where bioethanol potential was 113,485,818.2 liters in 2017 under the first scenario of which results fell far below the national gasoline consumption of Table 5.1 which was 461,427,680 liters in 2017.
2. Established that sugarcane as a feedstock and existing sugar refineries in Zambia have the greatest potential considering the results obtained from molasses and the results of sugarcane yields under scenario two as consolidated in Table 5.18 giving 461,600,000 in 2017 summed from all the sugar companies' results.
3. Established that while modified vehicles are being manufactured and on the roads in countries like Brazil, in Zambia such cars have not penetrated due lack of promotions and availability of bioethanol as a fuel on the market.
4. Established that other feedstocks such as cassava yields were accurately accounted for in the country and cassava bioethanol potential was second to sugarcane and that efforts were in place to further enhance the production of this feedstock. The yields of sweet potato in Zambia were accounted for and converting it to bioethanol gave a reasonable result though the feedstock is only grown by peasant farmers. Sweet sorghum which is grown throughout the country was not accounted for by the Ministry of Agriculture because it is not categorized as a food commodity which made it difficult to establish the existing potential in the country for sweet sorghum.
5. The levelised cost of energy of each of the feedstock was calculated based on the cost of each feedstock. The levelised cost of energy for sugarcane based bioethanol was \$0.06786/liter while cassava was \$ 0.062/liter. Molasses levelised cost of energy was \$ 0.039/liter and sweet potato was \$ 0.304/liter. As can be seen, all the feedstocks above provided a competitive levelised cost of energy.

6.2 Recommendations

1. The potential established during this research needs to be enhanced so that the impending technological changes in this area do not affect the transport operations of the country.
2. The sugar refineries are leading the way in terms of commercializing the sugar plantations and in this vain, other sugarcane plantations can be conceived in Zambia to carter for bioethanol production.
3. Facilities to carter for modified vehicles in the country should be established and then promote the entry of such vehicles in the country for a given period with tax incentives.
4. Efforts should be made in the country to commercialize other feedstocks such as cassava, sweet potato and especially sweet sorghum which is not food stuff and its processing into bioethanol would not affect the food security of the country.
5. As can be seen from the levelised cost of energy results, efforts should be made towards enhancing sugarcane and cassava which showed that their conversion to bioethanol would provide the country the cheapest fuel energy source.

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APPENDICES

Appendix 1: Feedstocks used in this research.



Sweet potatoes [41]



Cassava roots [42]



Cassava plant [42]



Sugarcane [36]



Biofuel filling station [36]



Bioethanol car [36]

Appendix 2: Equations derived by the MATLAB

$E=4.175 \times 10^{-67} e^{0.0854 \text{yr}}$	1
$E=3.622 \times 10^{-97} e^{0.1191 \text{yr}}$	2
$E=1.207 \times 10^{-46} e^{0.06214 \text{yr}}$	3
$E=1.044 \times 10^{-67} e^{0.0854 \text{yr}}$	4
$E=1.54 \times 10^{-98} e^{0.1191 \text{yr}}$	5
$E=1.586 \times 10^{-47} e^{0.0620 \text{yr}}$	6
$E=1.788 \times 10^{-61} e^{0.0785 \text{yr}}$	7
$E=3.26 \times 10^{-13} e^{0.0206 \text{yr}}$	8
$E=2.801 \times 10^{-6} e^{0.3063 \text{yr}}$	9
$E=2.295 \times 10^{-94} e^{0.3063 \text{yr}}$	10
$E=1.13 \times 10^{-99} e^{0.1191 \text{yr}}$	11
$E=4.163 \times 10^{-49} e^{0.06214 \text{yr}}$	12
$E=2.828 \times 10^{-11} e^{0.02056 \text{yr}}$	13
$E=4.609 \times 10^{-73} e^{0.09234 \text{yr}}$	14
$E=1.836 \times 10^{-92} e^{0.1121 \text{yr}}$	15
$E=6.028 \times 10^{-67} e^{0.0854 \text{yr}}$	16
$E=4.801 \times 10^{-98} e^{0.1191 \text{yr}}$	17
$E=4.231 \times 10^{-47} e^{0.06214 \text{yr}}$	18
$E=1.569 \times 10^{-62} e^{0.0805 \text{yr}}$	19
$E=2.415 \times 10^{-89} e^{0.1111 \text{yr}}$	20