

**COMPARATIVE GASIFICATION PROCESS STUDIES
FOR PROSOPIS (*P.JULIFLORA*) AND RICE HUSKS
(*ORYZA SP.*) INTO RENEWABLE ENERGY RESOURCES
IN KENYA**

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(Energy Technology)

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2018

**Comparative Gasification Process Studies for Prosopis (*P.Juliflora*) and
Rice Husks (*Oryza Sp.*) into Renewable Energy Resources in Kenya**

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**A thesis submitted in partial fulfillment for the Degree of Master of
Science in Energy Technology in the Jomo Kenyatta University of
Agriculture and Technology**

2018

DECLARATION

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

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DEDICATION

This work is dedicated to my lovely family; my wife Anzazi Nelly, my son Gewona Mshindi Kirigha and my daughter Amana Binti Kirigha for their patience, guidance and understanding during the process of carrying out the research.

ACKNOWLEDGEMENT

Special thanks go to my supervisors Professor Robert Kinyua and Dr. Paul Njogu for their timely support and guidance in this study. I would also like to thank my classmates for providing their positive criticism over the work and the Jomo Kenyatta University of Agriculture and Technology Institute of Energy and Environmental technology through the JICA project for allowing me to use their gasifier to conduct this research. Special thanks go to the laboratory technicians for their support from feedstock preparation to the actual gasification process.

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LIST OF ABBREVIATIONS

AD	Anaerobic digestion
BFB	Bubbling Fluid Bed
CHP	Combined Heat and Power
CFB	Circulating Fluid Bed
GCV	Gross Calorific Value
GC-TCD	Gas Chromatograph-Thermocouple Detector
HHV	Higher Heating Value
IAS	Invasive Alien Species
JKUAT	Jomo Kenyatta University of Agriculture and Technology
KEFRI	Kenya Forestry Research Institute
KIRDI	Kenya Industrial Development Institute
KLR	Kenya Law Report
LFG	Liquid Fuel Gas
MJ	Mega Joules

MW Mega Watts

USEPA United States Environmental Protection Agency

ABSTRACT

Management of Agricultural wastes especially rice husks and the invasive weed species *Prosopis juliflora* which has seen massive invasions in many areas in Kenya presents great challenges to the environment. Rice husks are a key byproduct of rice production that is not considered of economic value and since they do not biodegrade easily they pose a waste management issue in the rice growing regions. The invasion of *P. juliflora* in Kenya has resulted in a myriad of social and ecological concerns and has interfered with community livelihoods in several ways. The objective of the study was to carry out comparative studies on the potential for utilization of Rice husks and *P. juliflora* as renewable energy resources for syngas production. The study profiled optimal temperature and residence time for the gasification of *P. juliflora* and rice husks. Chemical composition of the Syngas was carried out at each cleaning device, as properties that require consideration with regard to investments in the bio energy. The analysis was carried out using Fourier Transform Gas Analyzer Matrix – MG from Bruker to determine the composition of the syngas. Co-firing of *P. juliflora* and rice husks was also assessed. Syngas from rice husks was found to be mainly composed of 17.05 ± 0.21 % CO, 15.7 ± 0.14 % CO₂, 4.3 ± 0.00 H₂, 7.35 ± 0.07 CH₄ and 28.1 ± 0.42 % N₂ while Syngas from *Prosopis* was found to be composed of 21.15 ± 0.91 % CO, 13.15 ± 0.50 % CO₂, 19.25 ± 0.07 H₂, 5.45 ± 0.07 CH₄ and 40.585 ± 0.19 % N₂. The development of the novel gasification technology that seeks to utilize Rice husks and *P. juliflora* as feedstock for bioenergy production is a breakthrough in clean energy development in Kenya.

CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Kenya's demand for energy has been growing steadily over time. According to the G.O.K, (2014), the peak demand for electricity was projected to grow from 1,354MW in 2013 to 3,400MW by 2015. US Power Africa, (2014) projects that power demand in Kenya will reach 2,600-3,600 MW by 2020. To meet this demand, an additional 5,000 MW of new generation is to be developed to bring total installed capacity to at least 6,600MW. The annual energy consumption was projected to increase from 8,087GWh in 2012/13 to 32,862GWh in 2016/17. It is projected that by 2030, peak demand will be 18,000MW against an installed capacity of 24,000MW. In Kenya electricity supply is predominantly sourced from hydro and fossil fuel (thermal) sources. The current generation energy mix comprises of about 52.1% from hydro, 32.5% from fossil fuels, 13.2% from geothermal, 1.8% from biogas cogeneration and 0.4% from wind, respectively (G.O.K, 2014). To meet this demand, Kenya's installed capacity should increase gradually to 19,200 MW by 2030. Mugo, (2010), noted that biomass energy provides 68% of Kenya's national energy requirements and it is expected to remain the main source of energy for long period into the future. In the year 2000, Kenya was reported to use about 34.3 million tonnes of biomass for fuel of which 15.1 million tonnes was in form of fuel wood while 16.5 million tonnes was wood for charcoal processed in kilns with only 10% efficiency (Muzee, 2012). Up to 43% of the national consumption was from sustainable supplies while 57% was from unsustainable supplies. Of Kenya's total land area of 57.6 million hectares, only 6% (3,456,000 hectares) is forest cover and is estimated to be decreasing at the rate of 52,000 hectares (0.09%) per year (Muzee, 2012) . In 1980, 94% of all the wood harvested in the country was used for wood fuel, 4% for poles and 2% for timber. By 1997, the proportions were estimated to

be 90% wood fuel, 5% for industrial feedstock and another 5% for poles and posts (Muzee, 2012).

1.1.1 Prosopis as an energy resource

Globally concerns have been raised concerning Invasive Alien Species (IAS) and their environmental effects, (Obiri, 2011). IAS threatens the survival of the native species in any particular habitat and have threatened many ecosystems and ultimately economic activities in any one region. It is worth noting that Kenya has had myriad of invasions of invasive alien species that have had negative impacts on biodiversity, agriculture, energy and human development activities. Mostly management strategies that are employed in the country have included quarantine measures for unintentional and intentional introductions, eradication, containment and control, monitoring and research, regional cooperation and public awareness. More research, cooperation, assistance and capacity building is required to effectively manage the problem of invasive species by using them as alternative sources of energy or how these contribute to household energy security.

In most cases, invasive species in the dry areas and mostly in the rangelands of East Africa have been introduced both intentionally and accidentally and are damaging the natural and man-made ecosystems affecting community livelihoods. According to Obiri (2011), he noted that in East Africa, and particularly Kenya, pastoralists have been adversely affected and disasters registered in many communities as a result of the invasive weed species. For instance, in 2006, following the heavy livestock losses caused by the invasive plant *P. Juliflora*, communities of Baringo, Kenya, instituted a constitutional case against the government of Kenya for introducing Prosopis in their environment (G.O.K, 2007). The communities pointed out a pack of disasters that befell them as a result of the prosopis weed (G.O.K, 2007). These include the lack of water around Lake Baringo due to the colonization of prosopis on the lake shores and human diseases such as asthma, lung inflammation and allergies”. These effects of the IAS have made them seem as if they are beyond control and cannot thus be put into other

useful uses. According to Mwangi, (2005) the effects of prosopis are distributed differently across the different categories of individuals within a society along gender lines, pastoralists and smallholder mixed farmers. It determines the factors that structure individual and group responses to the proliferation of *Prosopis juliflora*. It also establishes the kinds of interventions envisioned by the local communities for its control and management and what their specific role would be in such interventions. It is on this backdrop that the use of Prosopis a known prolific seeder with high growth and coppicing rate is being proposed as good alternative for use as an energy crop which does not require any input in its farming. This form of renewable energy can contribute tremendously to the provision of safe and sustainable energy and contribute to the development agenda (UNEP, 2016).

1.1.2 Rice husks as an energy resource

Rice husks have also posed several challenges for many rice millers. According to Njogu, (2015), Rice husks are a key byproduct of rice production that is not considered of economic value to millers. He further notes that the direct use of rice husks as an energy source is hampered by low density and low heat value. It is thus imperative to convert it into combustible gas. According to Rajvansh, (2013) Rice husks contain about 75% organic volatile matter and 25% ash. Rice husks can be converted thermally, biologically or chemically to other usable forms of energy like methane gas, liquid fuels (ethanol) and syngas/process gas. It is thus important to come up with innovative ways of sustainable utilization and management of such wastes. The current practice of open burning mostly leads to transfer of pollutants from land to the atmosphere

This study seeks to conduct a comparative study of the gasification process of prosopis, rice husks and co-firing process to determine the best conditions for which rice husks and *P. Juliflora* can be used as alternative sources of energy.

1.2 Statement of the problem

Great efforts and resources have been directed towards eradication of *P. Juliflora* in terrestrial ecosystems, though in most cases with commendable progress the reoccurrence nature of the plant and high coppicing rate continues to pose a great challenge in its eradication. The rate at which the species of plant has multiplied is so fast that it has overtaken native vegetation. Obiri, (2013) notes that *Prosopis* is a prolific seeder and has invasiveness behavior that results in a number of social, ecological and economic concerns to the local communities, and challenges to development partners. Likewise, the management of rice husks by the millers which is seen as of low economic value presents a huge challenge in its management since most of it is burned openly thus polluting the environment. Hence concerns over introduction of other sustainable control measures need to be explored. For effective management of rice husks as an agricultural waste and the invasive weed *P. Juliflora*, the most effective and efficient control is to use them as an alternative fuel to provide energy. There is thus a need to carry out studies on the gasification process concerning this weed and rice husks on the possibility of establishing a bioenergy industry within the country. The provision of bio energy can go a long way in boosting the energy security in the region as the country strives to industrialize.

1.3 Justification of the Study

The study is significant in the following ways; first, it will contribute to the existing knowledge and literature on the management of rice husks and *P. Juliflora* including any other invasive weed species and their contribution to Kenya's energy security. Secondly, its findings will be useful to policy makers, the local community and the researchers interested in exploring how rice husks and *P. Juliflora* can be converted into cheap sources of energy to serve community needs. With increasing need to manage rice husks and the menace emanating from the invasive weed *P. Juliflora* in Kenya, due to lack of proper control mechanisms, using the plant species to cater for energy needs is

an efficient and a lucrative option if we are to manage the species effectively and also to provide alternative sources of energy. There is a need to also examine how *P. Juliflora* and rice husks can contribute to energy security. In spite of considerable huge investments being mobilized to facilitate the control of *P. Juliflora* including mechanical removal there has been minimal success. Given its ability to grow and coppice rapidly, the considerable large amount of biomass it produces, experts are considering new control/management approaches that seeks to put an economic value to the weed as an incentive for its removal. This new technology seeks to make use of the weed and rice husks as feedstock for production of syngas for electricity production.

1.4 Hypothesis

The gasification process conditions such as the residence time, temperature and Pressure have no effect on the yield and composition of Syngas derived from rice husks and *Prosopis*.

1.5. Objectives

1.5.1 Main Objective

To study and optimize the gasification conversion processes of biomass via thermal gasification in the production of syngas for energy generation using *Prosopis* and Rice husks.

1.5.2 Specific Objectives

1. To determine syngas composition, calorific value and resident time for the gasification of *P. Juliflora* and rice husks as potential energy feedstock.
2. To determine the effects of co-firing *P. Juliflora* and rice husks on syngas composition, calorific value and resident time.
3. To determine the efficiency of the syngas cleaning devices.
4. To perform a techno-economic analysis of the gasification process.

1.6 Scope of the study

The study assessed the thermal gasification of *P. juliflora* and Rice husks. The study also assessed the potential for co-firing, efficiency of the process and finally techno economic analysis of the process.

1.7 Limitations of the study

The study had the following limitations;

1. Lack of analytical equipment within the research laboratories in JKUAT. The GC TCD did not have all the gas standards and it was hard to quantify Carbon monoxide from carbon dioxide. The quantification of the gas components had to be done outside the experiment area and the gas had to be transported using balloons to an external laboratory.
2. Analysis of the samples using the gas analyzer (Matrix MG) was very expensive and hence the focus on a few strategic samples was considered. The most important gases which contribute to the heat value were considered leaving out gases which could be toxic and hence would require some further analysis.

CHAPTER TWO

LITERATURE REVIEW

2.1 Invasive alien species (IAS)

Lowe (2000), defined invasive alien species as plants, animals, pathogens and other organisms that are non-native to an ecosystem, and which may cause economic or environmental harm or adversely affect human health are now being recognized as one of the leading threats to biodiversity and do impose enormous costs on agriculture, forestry, fisheries, and human livelihoods, as well as on human health. He further notes that the rapidly accelerating human trade, tourism, transport, and travel over the past century have dramatically enhanced the spread of invasive species, allowing them to surmount natural geographic barriers. It is noted that these species in most cases have proven difficult to eradicate especially *P. Juliflora* which has resisted mechanical and biological eradication means. He further notes that the ways in the invasive species affect native species and ecosystems are numerous and usually irreversible.

The impacts are sometimes massive but often subtle. Natural barriers such as oceans, mountains, rivers, and deserts that allowed the intricate co-evolution of species and the development of unique ecosystems have been breached over the past five centuries, and especially during the twentieth century, by rapidly accelerating human trade and travel. Planes, ships, and other forms of modern transport have allowed both deliberate and inadvertent movement of species between different parts of the globe, often resulting in unexpected and sometimes disastrous consequences in the case of Kenya as a country invasive alien species have been majorly been introduced by animal trade. Cattle which feed on the pods and seeds of *P. Juliflora* provide the most convenient means of dispersing the plant species over most parts of the coastal towns where animals are brought for sale. Plate 2.1 below shows the extent of *P. Juliflora* invasion in Turkana district



Plate 2.1: Prosopis invasion in a previously bare ground along the Turkwel River in Turkana district

(source; <https://www.wur.nl/en/show/Prosopis-upsurge-in-Kenya-Cause-and-effects.htm>)

Inter-governmental Panel on Climate Change (IPCC, 2005) report notes that Kenya has had several major invasions of alien species that have had negative impacts on biodiversity, agriculture and human development activities. From the studies, it is noted that Kenya has been invaded by thirty-four species (34): eleven arthropods, ten microorganisms, nine plant species and four vertebrates. In most cases the management

strategies have included quarantine measures for unintentional and intentional introductions, eradication, containment and control, monitoring and research, regional cooperation and public awareness. More cooperation, assistance and capacity building is required to effectively manage the problem of invasive species in the long run.

2.2 Effects of Invasive species on livelihoods

Obiri (2011) noted that like many areas globally, invasive species in the dry forests and rangelands of East Africa have been introduced both intentionally and accidentally and are damaging the natural and man-made ecosystems in many areas in Kenya, pastoralists have been adversely affected and disasters registered in many areas affecting the communities around. In 2006, following the heavy livestock losses caused by the invasive plant *P. Juliflora*, communities of Baringo, Kenya, instituted a constitutional case against the government of Kenya for introducing *Prosopis* in their environment (G.O.K, 2007). The communities pointed out a pack of disasters that befell them as a result of *prosopis* (G.O.K, 2007). These include the lack of water around Lake Baringo due to the colonization of *Prosopis* on the lake shores and human diseases such as asthma, lung inflammation and allergies” this shows the extent of which these IAS have affected the local people including the effect on their economic activities. Muturi (2009) noted that *Prosopis* had overall occurrence of 39% in in their study sites in 2007, in contrast to 0% in 1990 that was reported earlier. In these areas, *Acacia tortilis* occurrence dropped from 81% in 1990 to 43% in 2007, suggesting that *Prosopis* could be displacing it.

Invasive plant invasion is a man-made and slow onset disaster (SOD) that is least noticed and often forgotten. Several reasons are given as to why disasters caused by invasive plant species are often neglected. These include the fact that the disaster-impacts arising from invasive plants are often considered not high enough to attract the attention of the media and disaster managers. According to IPPC (2005), introduced species often consume or prey on native ones, overgrow them, infect or vector diseases

to them, compete with them, attack them, or hybridize with them. Invaders can change whole ecosystems by altering hydrology, fire regimes, nutrient cycling, and other ecosystem processes. Often the same species that threaten biodiversity also cause grave damage to various natural resource industries. The zebra mussel (*Dreissena polymorpha*), Lantana camara, kudzu (*Pueraria lobata*), Brazilian pepper (*Schinus terebinthifolius*), and rats (*Rattus spp.*) are all economic as well as ecological catastrophes. Invasive non-native species are taxonomically diverse, though certain groups (e.g., mammals, plants, and insects) have produced particularly large numbers of damaging invaders. Thousands of species have been extinguished or are at risk from invasive aliens, especially on islands but also on continents. Many native ecosystems have been irretrievably lost to invasion. Weeds cause agricultural production losses of at least 25% and also degrade catchment areas, near-shore marine systems, and freshwater ecosystems. Chemicals used to manage weeds can further degrade ecosystems. Ballast water carries invasive that clog water pipes, foul propellers, and damage fisheries. Imported pests of livestock and forests reduce yields drastically. Further, environmental destruction, including habitat fragmentation, and global climate change are extending the range of many invader”.

Lowe (2000) noted that the genes, species and ecosystems that make up the earth’s biological diversity are important because their loss and degradation diminishes nature. Species other than our own have a right to exist and to retain their place in the world. We do not know how to estimate which species are essential to ecosystem functioning, which are redundant, and which will be the next to flourish as the world changes. When we introduce a new species into an ecosystem, the full impact is often not immediately apparent. Invasion by species such as *Miconia calvescens* can change entire habitats, making them unsuitable for the original native community”.

2.3 Global Invasive Alien Species

Many of the species are either introduced accidentally or intentionally in many parts of the world. There are many examples where species have been introduced that have profound effects on the environment and the economies at large. Many examples exist that show how accidental introductions of species have affected habitats. A good example is on Caulerpa Seaweed (*Caulerpa taxifolia*) introduction in the Mediterranean. According to Lowe, (2000), Caulerpa was introduced to the Mediterranean around 1984, possibly as waste from the Monaco Aquarium. There is speculation that the species released into the Mediterranean was a hardier clone of the original tropical seaweed. It adapted well to colder waters and has spread throughout the northern Mediterranean where it is a serious threat to the native marine flora and fauna. New colonies are able to start from small segments of this plant and, being an opportunistic hitchhiker, it is a threat to the whole of the Mediterranean. Wherever it has established itself, it has smothered habitats such as the beds of native sea grass that serve as nurseries for many species. On 12th June 2000, divers in a lagoon near San Diego in the United States discovered a patch of Caulerpa measuring 20 metres by 10 metres. In this case too, it is thought that the infestation occurred after somebody emptied a fish tank into a storm-water drain”

Water hyacinth (*Ecchornia crasipess*) has also brought menace to many fresh water bodies in the world. According to Lowe, (2000), “This South American native is one of the worst aquatic weeds in the world. It’s beautiful, large purple and violet flowers make it a popular ornamental plant for ponds. It is now found in more than 50 countries on five continents. Water hyacinth is a very fast-growing plant, with populations known to double in as little as 12 days. Infestations of this weed block waterways, limiting boat traffic, swimming and fishing. Water hyacinth also prevents sunlight and oxygen from reaching the water column and submerged plants. Its shading and crowding of native aquatic plants dramatically reduces biological diversity in aquatic ecosystems”

Attempts have been made to list some of the worst invasive alien species in the world. According to Lowe (2000), he argues that amongst other species *Prosopis spp* is one of the worst species based on the criteria that they gave “Species were selected for the list using two criteria: their serious impact on biological diversity and/or human activities, and their illustration of important issues of biological invasion. To ensure a wide variety of examples, only one species from each genus was selected”

2.4 Invasive Alien Species in Kenya

In Kenya invasive alien species have been introduced in many areas especially in the agricultural sector. These could have been intentionally or accidentally reduced to either boost crop production or to control other species- biological control methods, which in some cases have done more harm than good to the ecosystems. For example, Nile perch introduction in Lake Victoria. According to Lowe, (2000), the Nile perch was introduced to Lake Victoria, Africa in 1954 to counteract the drastic drop in native fish stocks caused by over-fishing. It has contributed to the extinction of more than 200 endemic fish species through predation and competition for food. The flesh of Nile perch is oilier than that of the local fish, so more trees were felled to fuel fires to dry the catch. The subsequent erosion and runoff contributed to increased nutrient levels, opening the lake up to invasions by algae and water hyacinth (*Eichhornia crassipes*). These invasions in turn led to oxygen depletion in the lake, which resulted in the death of more fish. Commercial exploitation of the Nile perch has displaced local men and women from their traditional fishing and processing work. The far-reaching impacts of this introduction have been devastating for the environment as well as for communities that depend on the lake”.

According to Pasiiecznic (1999), “Concern about deforestation, desertification and fuel wood shortages in the late 1970s and early 1980s prompted a wave of projects that introduced *P. Juliflora* and other hardy tree species to new environments across the world. *P. Juliflora* has survived where other tree species have failed and, in many cases,

become a major nuisance. *P. Juliflora* has invaded, and continues to invade, millions of hectares of rangeland in South Africa, East Africa, Australia and coastal Asia”

The plate below shows the extent of *P. Juliflora* along a river bank in Turkana district.



Prosopis encroachment in an Acacia tortilis stand along the Turkwel river in Turkana District, Kenya

Plate 2.2: Prosopis encroachment in Turkana, Kenya

(Source; <https://www.wur.nl/en/show/Prosopis-upsurge-in-Kenya-Cause-and-effects.htm>)

2.5 Rice husks management in Kenya

According to Short, (2012) Rice is the third most important staple food in Kenya after maize and wheat. Historically, rice is a cash crop for rural producers. This is the main reason why rice husks present a huge management challenges is; Rice husks are difficult to ignite, and it does not burn easily with open flame unless air is blown through the

husk. It is highly resistant to moisture penetration and fungal decomposition. Husk therefore makes a good insulation material. Rice husk has a high silica (SiO_2) contents which means that it decomposes slowly when brought back to the field. It also makes it a poor fodder and also handling of rice husk is difficult because it is bulky and dusty. Rice husk has low bulk density of only 70-110 kg/m^3 , 145 kg/m^3 when vibrated or 180 kg/m^3 in form of briquettes or pellets (Short, 2012). It thus requires large volumes for storage and transport, which makes transport over long distances un-economical.

Short, (2012) further indicates that, when burned, the ash content is 17-26%, a lot higher than fuels (wood 0.2-2%, coal 12.2%). This means when used for energy generation large amounts of ash need to be handled. Rice husk has a high average calorific value of 3410 kcal/kg and therefore is a good, renewable energy source.

2.6 Biomass Gasification

Biomass gasification, which is the conversion of solid fuels like wood and agricultural residues into a combustible gas mixture, is a fairly new technology in East Africa with most of the projects either at planning or demonstration stages. The technology has been applied in electricity generation especially in rural areas allowing households to access their energy needs. The technology has also been applied in enterprise development in the peri-urban and rural areas where it has been used for running sawmills, power supply and milling of cereals. Muzee, (2012) notes that biomass gasification energy sub-sector is largely driven by the private sector and research institutions. Key representatives of research institutions include the Kenya Forestry Research Institute (KEFRI) and the Kenya Industrial Research and Development Institute (KIRDI). Others include Multimedia University, Moi University, Kenyatta University and Jomo Kenyatta University of Agriculture and Technology (JKUAT). There are also national and international non-governmental organizations such as Envirofit engaged in the sub-sector. The main drivers are the private sector with Tower Power Limited planning to generate a total of 23MW of electricity in Marigat and Mariakani, (Muzee, 2012).

2.7 Biomass to Energy Conversion Technologies

Biomass can be used in its solid form or gasified for heating applications or electricity generation, or it can be converted into liquid or gaseous fuels. According to United States Environment Protection Agency, (USEPA, 2007), Biomass conversion refers to the process of converting biomass feedstocks into energy that will then be used to generate electricity and/or heat.

According to USEPA, (2007) there are many potential advantages to using biomass instead of fossil fuels for meeting energy needs. Specific benefits depend upon the intended use and fuel source, but often include: greenhouse gas and other air pollutant reductions, energy cost savings, local economic development, waste reduction, and the security of a domestic fuel supply. In addition, biomass is more flexible (e.g., can generate both power and heat) and reliable (as a non-intermittent resource) as an energy option than many other sources of renewable energy. This research would attempt to look at gasification as energy conversion technology.

2.7.1 Biochemical conversion process

As biomass is a natural material, many highly efficient biochemical processes have developed in nature to break down the molecules of which biomass is composed, and many of these biochemical conversion processes can be harnessed. Biochemical conversion makes use of the enzymes of bacteria and other micro-organisms to break down biomass. In most cases micro-organisms are used to perform the conversion process.

2.7.2 Anaerobic Digestion

Anaerobic digestion (AD) is the process whereby bacteria break down organic material in the absence of air, yielding a biogas containing methane. The products of AD process are:

- Biogas (principally methane (CH₄) and carbon dioxide (CO₂))
- A solid residue (fiber or digestate) that is similar, but not identical, to compost
- A liquid liquor that can be used as a fertilizer

USEPA, (2007) Biogas fuel is generated from the anaerobic decomposition of organic material and is typically composed of about half methane, half CO₂, and small amounts of non-methane organic compounds and other contaminants. Like solid biomass, biogas fuel must be collected and treated for use in power generation. Some minimal amount of gas cleaning is required for almost any application using biogas.

2.7.3 Gasification

The importance of an efficient utilization of biomass as a renewable energy in terms of global warming and resource shortage are well known and documented. Biomass gasification is a promising CHP technology, due to its high electrical efficiency compared to other CHP systems in the lower and middle range of power. This power class has high potential with respect to heat demand, and hence, biomass gasification is predestined for decentralized energy systems.

USEPA, (2007) Notes that biomass *gasification* systems operate by heating biomass in an environment where the solid biomass breaks down to form a flammable gas. The gas produced—synthesis gas, or syngas—can be cleaned, filtered, and then burned in a gas turbine in simple or combined-cycle mode, comparable to LFG or biogas produced from an anaerobic digester in smaller systems, the syngas can be fired in reciprocating engines, micro turbines, Stirling engines, or fuel cells. Gasification technologies using

biomass byproducts are popular in the pulp and paper industry where they improve chemical recovery and generate process steam and electricity at higher efficiencies and with lower capital costs than conventional technologies. Pulp and paper industry byproducts that can be gasified include hogged wood, bark, and spent black liquor (Larson, 2006). So basically, biomass gasification, involves the conversion of solid fuels like wood and agricultural residues into a combustible gas mixture which could be used to provide heat or electricity.

Muzee, (2012), has studied some of the gasification technologies in East Africa and notes that different gasification reactor technologies exist in the market. The major ones include; down-draft fixed bed (also known as co-current fixed bed); up-draft fixed bed (also known as counter-current fixed bed); fluidized bed; entrained flow; slurry bed; supercritical water. Other minor technologies include Lurgi dry ash; blue tower; vertical vortex; screwing two-stage; and the plasma gasifier. The main technologies are as follows;

2.7.3.1 Down-Draft Fixed Bed Gasifier (DDFB)

According to Lettner, (2007), this type of gasifier consists of a fixed bed of carbon-rich fuel which the oxidizing medium flows through downwards. The gas produced is at a high temperature and the thermal efficiency is also relatively high. A significant advantage is that the formed tar levels are low.

2.7.3.2 Up-Draft Fixed Bed Gasifier (UDFB)

This gasifier is similar to the down-draft type except that air, oxygen or steam flow through the bed upwards. The throughput of this method is relatively low, but the thermal efficiency is similar to the down-draft type. The volume percentage of methane in the produced gas is significant, which facilitates methanation for Synthetic Natural Gas production. Tar production is also high at normal operation temperatures implying additional costs in cleaning (Lettner, 2007).

2.7.3.3 Fluidized Bed Gasifier (FB)

A fluidized bed can be bubbling (BFB) or circulating (CFB). Fluidized beds are very common for combustion of coal, biomass and waste in medium to large heat and power plants (>5 MW). In the fluidized bed, the fuel is fluidized by the oxidizing agent. The operational temperature is lower, meaning that the fuel needs to be reactive. Fluidized beds generally require careful feedstock preparation, considering moisture content and size of the solid fuel particles (Lettner, 2007).

2.7.3.4 Entrained Flow Gasifier (EF)

In this technology, the solid or liquid fuel fed to the entrained flow gasifier is gasified with oxygen. Reaction occurs in a dense cloud of aerosol at high temperatures and usually high pressures. A high throughput can be achieved, but the thermal efficiency is reduced as the high-temperature syngas must be cooled significantly before cleaning (Lettner, 2007). Low methane and tar production but high oxygen requirements are other features of the EF-gasifier, which make it most suitable for H₂ -rich gas production (Olofsson, 2005). EF-gasifiers are the only attractive option for extremely large (>1,000 MW thermal) bio-refinery systems.

2.7.4 Pyrolysis

According to McKendry,(2001), pyrolysis is the conversion of biomass to liquid (termed bio-oil or bio-crude), solid and gaseous fractions by heating the biomass in the absence of air to around 500° C. The main products of pyrolysis are charcoal, fuel gas and bio-oil. He further notes that pyrolysis can be used to produce predominantly bio-oil if flash pyrolysis is used, enabling the conversion of biomass to bio-crude with an efficiency of up to 80%. Aston, (1996) notes that the bio-oil can be used in engines and turbines and its use as a feedstock for refineries is also being considered. Problems with the conversion process and subsequent use of the oil such as its poor thermal stability and its corrosivity still need to be overcome. Upgrading bio-oils by lowering the oxygen content

and removing alkalis by means of hydrogenation and catalytic cracking of the oil may be required for certain applications.

In pyrolysis, large hydrocarbon molecules (cellulose, hemicelluloses and part of the lignin) break down into smaller and lighter molecules. Unlike combustion and gasification, pyrolysis occurs in total absence of oxygen. Basu, (2010), Concludes that Pyrolysis process conditions have significant influence on the composition of the produced oils. Pyrolysis oils typically suffer from poor thermal stability and cause corrosion to engines. Generally, bio-oil is a difficult product to be used or upgraded directly (Soltes, 1998) and (McKendry, 2002).

Pyrolysis oils can primarily be phenolic; therefore, hydro treating is necessary to remove oxygen. Single ring phenolics and cyclic ketones present in the oils can be upgraded through deoxygenation to hydrocarbon fuels. Heavier, higher molecular weight products such as the polycyclic aromatics need also to be hydrocracked. Several catalysts have been tested. Initially, typical petroleum hydro treating or hydrocracking catalysts at high pressures have been used but more recently acidic zeolites at lower pressures have gained interest (Soltes, 1998).

2.8 Cost Benefit Analysis (CBA)

A CBA of setting up a gasification plant is a crucial step for the success of such a project. A CBA is usually accomplished by first describing quantifiable and unquantifiable energy, environment and economic costs and benefits of the biomass gasifier system (Larson, 2006). The costs may include capital investment like design, fabrication and acquisition of the gasification system; as well as installation of electricity feed into the system. The maintenance and operation of the biomass gasification system form the other kind of costs to be incurred. Operational costs may involve gas clean-up and compressional costs. The costs of consumption of electricity and/or LPG during installation of the facility should also be considered (NREL, 2011). Maintenance of electricity feed into the grid connection also adds up to the total quantifiable costs in the

establishment of the biomass gasification system. Another cost to be considered would be wood preservation and drying which may involve some energy input (Craig, 1996). On the other hand, the benefits of establishing a biomass gasification system would include the savings to be gained by avoiding the consumption of grid electricity and/or LPG. Revenues to be obtained by selling the generated electricity to the grid also counts as a major quantifiable benefit. Such an initiative could also attract grants from development agencies that focus on promoting renewable energy initiatives which would be beneficial to the gasification project. Sale of the biomass byproducts or left overs to possible and ready users could also count as a benefit.

Cost benefit analysis is evaluated using parameters such as the net present value (NPV), cost benefit ratio (CBR) and the internal rate of return (Craig, 1996). Mukhopadhyay, (2003), found that gasifier technologies improved the economic activities and quality of life of a village in India. The benefit cost ratio (BCR) of this biomass gasifier system in India was found to be 1.68. The internal rate of return was found to be 19 %, which was more than the cost of capital at 8% thus the gasifier project was economically viable.

2.9 Analytical Techniques for Gas Analysis

2.9.1 Gas Chromatography-TCD

Gas Chromatography coupled to a thermocouple detector system (GC-TCD) can be used to determine the kind of gases that form part of syngas (Willard, 1986). From previous studies, the main gases include methane, carbon monoxide, carbon dioxide, hydrogen, oxygen and nitrogen. The gases with important calorific values include methane, carbon monoxide and hydrogen. GC-TCD works by first separating the gas components in the gas sample depending on their chemical and physical properties, before detecting them using the TCD. The GC section consists of a coiled and packed glass or stainless-steel column housed in an oven. The packing material or stationary phase usually consists of diatomaceous earth. Samples travel through the column with the aid of carrier gas/mobile phase, usually helium. The sample is injected into the column and the different

inorganic gases separate as they travel through the column at different velocities. The TCD depends on the fact that different gases have unique thermal conductivities. Changes in thermal conductivity in electrically heated wires in the detector due to the different gas components are sensed as electrical resistance are measurable. Through calibration standards, both qualitative and quantitative analysis is possible. GC-TCD is thus instrumental in quantifying syngas components (Harvey, 2000).

2.9.2 Fourier Transform - Infra Red Gas Analyzers

These analyzers work on the principle that different gas molecules undergo unique forms of molecular bond vibrations, stretching and twisting depending on the different functional groups within their chemical structures when they absorb energy (Willard, 1986). The gas sample is let into a gas cell, and infra-red radiation is passed through. The different gas components absorb the radiation and transmit a percentage of the incident radiation. A spectrum for each gas component is obtained and identification is done by comparing the obtained spectrum to a library of spectra contained in the equipment's computer software. Modern FT-IR gas analyzers have the capability of identification and quantification without the need of a calibration measurement. This is made possible by specialized software that can evaluate the measured spectra in real-time. This technique is robust and faster than traditional methods of gas analysis.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

Experimental design was used to study the relationship resulting from the different residence time, gas composition and calorific value during the gasification process

3.2 Study area.

The study was carried out at JKUAT research laboratories. Samples of *Prosopis* were collected from Baringo area Kenya, where the tree shrub is highly prolific and Rice husks were collected from the rice growing regions (specifically in Mwea Rice Irrigation scheme in Kirinyaga, Kenya), where management of the rice husks poses a great agricultural waste management problem.

Figure 3.1 below shows the Mwea Rice irrigation scheme while figure 3.2 shows some of the areas in Kenya that are infested by *prosopis juliflora*



Figure 3.1: Map of Kenya showing Mwea Irrigation Scheme (Imbenzi, 2015)

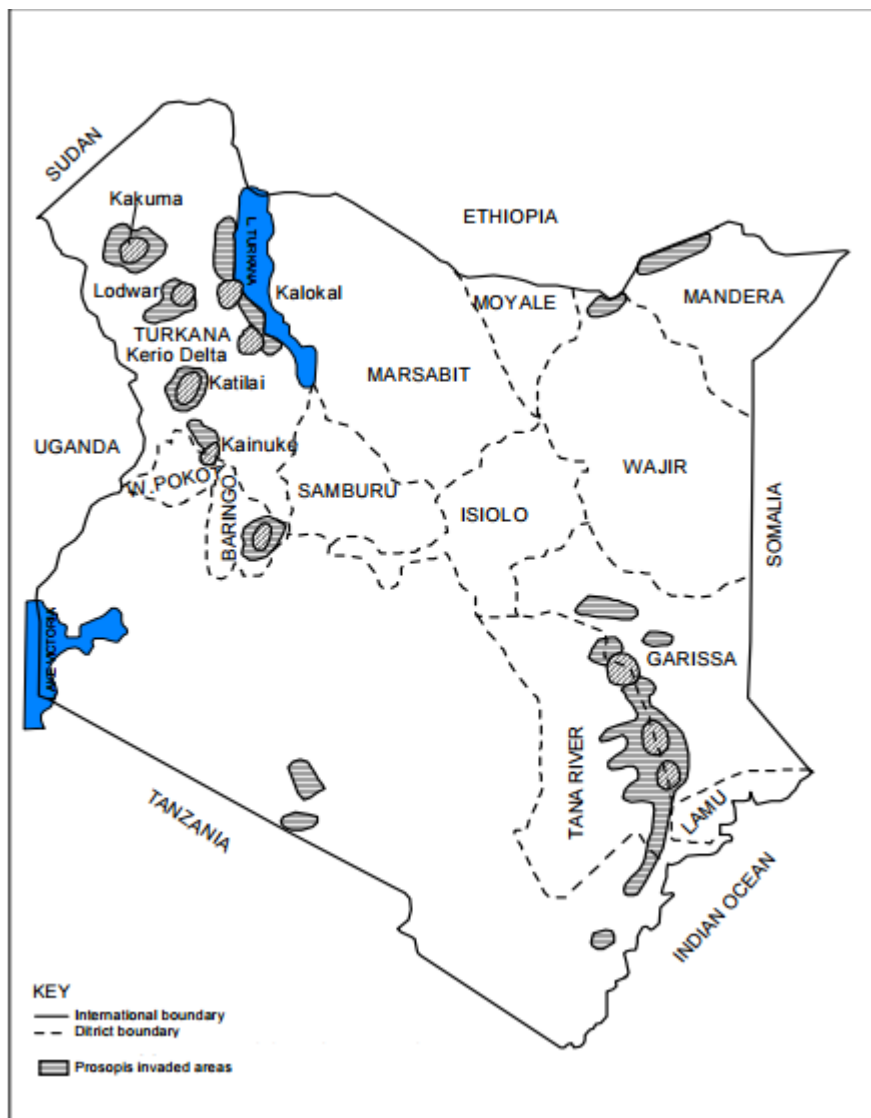


Figure 3.2: Location of Prosopis invasions in Kenya (Choge, 2004)

3.3 Research Design

An experimental design to study the relationship that exists from the different residence time, gas composition and calorific value during the gasification process was used. To meet study objectives, the study was divided into four broad areas as follows;

3.3.1 Determination of syngas composition, calorific value and resident time for the gasification of *P.Juliflora* and rice husks as potential energy feedstock.

The activities under this objective entailed determining gas composition, calorific value and residence time of *P.Juliflora* biomass and rice husks. The parameters of the two biomass types were then be compared

3.3.2 Determination of the effects of co-firing *P.Juliflora* and rice husks on syngas composition, calorific value and resident time.

This entailed determining the benefits of co-firing using the two types of biomass. This involved mixing the various proportions of the two types of biomass under study and compared the results obtained on the various parameters

3.3.3 Determination of the efficiency of the syngas cleaning devices.

In this area gas samples were collected at each gas cleaning device and a gas analysis carried out to determine the gas composition and calculate the efficiencies of the gas cleaning devices

3.3.4 Techno-economic analysis of the gasification process

In this study area the economic analysis of the plant was carried out. It entailed performing an economic analysis by calculating the cost-benefit analysis of the project. Two methods were used; (a) Determination of the Net Present Value and (b) determination of the Internal Rate of Return of the project.

3.4 Sampling methods and sample preparation

3.4.1 Sample Collection

Samples were taken from the stems of *P. Juliflora* Stands in Baringo district in Kenya using manual methods. Initially only 700 kg of samples were collected. The rice husks

were collected from the rice growing areas in Mwea region in Kirinyaga, Kenya. Samples were collected, and sun dried to around 10% for Prosopis and 9% for the rice husks. The Moisture content for the samples were determined using an oven by using the following procedure (a) One gram of the biomass was weighed into a crucible and placed in an oven set at 105 ° C for 24 hours. (b) The sample was dried to constant weight. The sample was then weighed, and the mass difference calculated. (c) This above value was used to determine the moisture content.

Figure 3.3 below shows some of the steps used to obtain the feedstock for the gasification experiment.

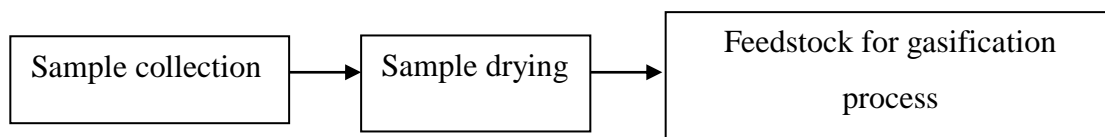


Figure 3.3: Sample preparation flow chart

3.4.2 Sample Treatment

For the gasification process the feedstock were well dried under natural conditions in the sun and in the case of *prosopis* they had to be pelletized into uniform size (about 10 cm long and 4 cm wide) and all had a uniform moisture content. Moisture content for rice husks was 9%) while for Prosopis was 10%.

3.4.3 The gasification process

An updraft Gasifier as shown in figure 3.4 and plate 3.1 was used to obtain syngas from the biomass materials under study.

Figure 3.4 below shows the various stages in the gasification process

3.4.4 Process Studies and optimization

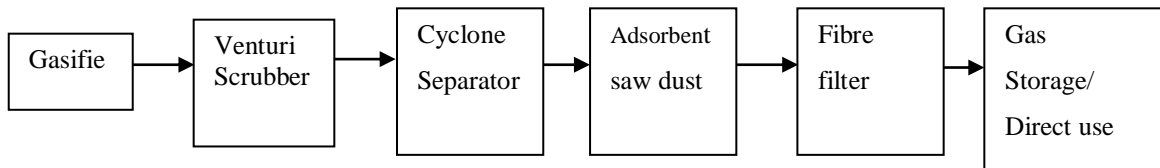


Figure 3.4: Gasification process of generating syngas from biomass

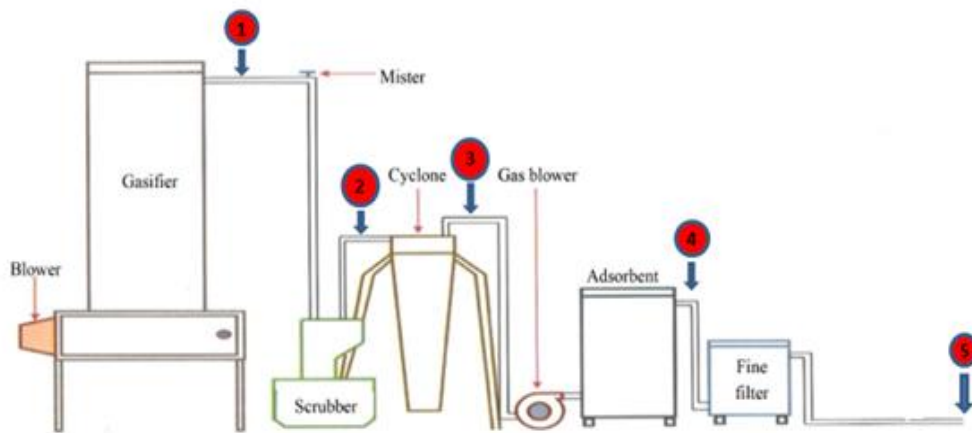


Figure 3.5: A schematic of the gasification plant at JKUAT, Kenya (Source; Njogu et al., 2015)



Plate 3.1: Up-draft gasification plant at JKUAT

Here thermal degradation of biomass occurred under limited oxygen condition to produce raw syngas which contains other pollutants. The hot syngas moves through a venturi scrubber (see figure 3.5 above) to be cooled and dissolve some gases in water e.g. Carbon dioxide (CO_2). The syngas passed through a cyclone separator where tars and suspended particles (fly ash) were removed. Tar was collected at the bottom of the Cyclone Separator. The syngas was then flown through adsorbent saw dust to remove moisture; from the adsorbent saw dust the was then passed via the fibre filter to remove any suspended fine particles in the syngas.

3.5 Determination of residence time, gas composition and calorific value of syngas from *P. Juliflora* and rice husks

3.5.1 Determination of the biomass residence time

The pelletized and dried feedstock was introduced into the gasification chamber which was connected to a temperature and pressure probes which were used to provide data. Residence time was determined using a stop watch.

3.5.2 Determination of the Calorific Value of Syngas

The calorific value was calculated using the following standard formula from (Zoran, 2008) who noted that if there are no experimental data for GCV value can be easily calculated by using the following formulae for gaseous fuels

$$\text{GCV} = (12.77 \cdot \text{H}_2 + 12.644 \cdot \text{CO} + 39.858 \cdot \text{CH}_4 \dots) / 100 \dots \dots \dots (3.1)$$

Where C, H, O and are mass fractions of carbon, hydrogen, oxygen and Sulphur in the gas

3.5.3 Determination of the Chemical composition of syngas

Gas samples obtained from the gasification process were collected and transported to a laboratory (Fletcher Ltd in Kitengela) for analysis using gas balloons. The gas compositional analyzes were done using a gas Analyzer Matrix – MG from Bruker coupled with a comprehensive software package **OPUS GA (Gas Analysis)**. Using this software, the target gas was measured in a gas cell for high sensitivity compound analysis based on FT-IR spectroscopy. From the obtained spectra the gas concentrations were retrieved automatically by a nonlinear fitting procedure within the comprehensive software package, without the need for gas calibrations. The influences of interfering gases as well as of varying gas temperatures and pressures were taken into account by the analysis routine. Equipped with a gas cell featuring an optical path length 5 m

(MG5) the MATRIX-MG (see figure 3.6 and plate 3.2) can detect and quantify gas components that occur in concentrations from only a few parts per billion (ppb) up to one hundred percent. The MATRIX-MG spectrometers measure up to 5 spectra per second at high spectral resolution of 0.5 cm^{-1} and up to 30 spectra per second at 4 cm^{-1} spectral resolution. The gas analyzer uses a non-linear fitting algorithm with proven reliability for the rapid identification and quantification of gas compounds with remote sensing spectrometers.

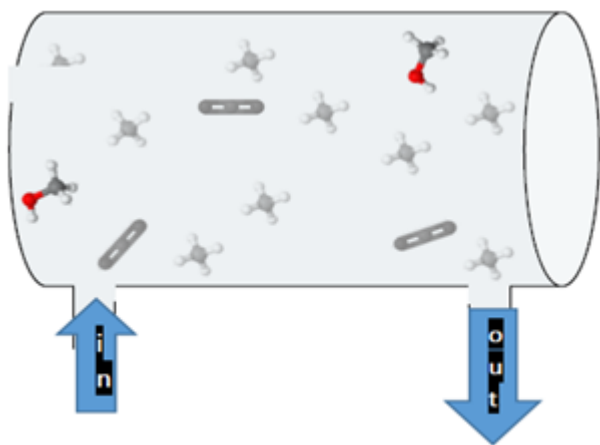


Figure 3.6: Gas inlet and outlet in a Matrix MG gas cell.

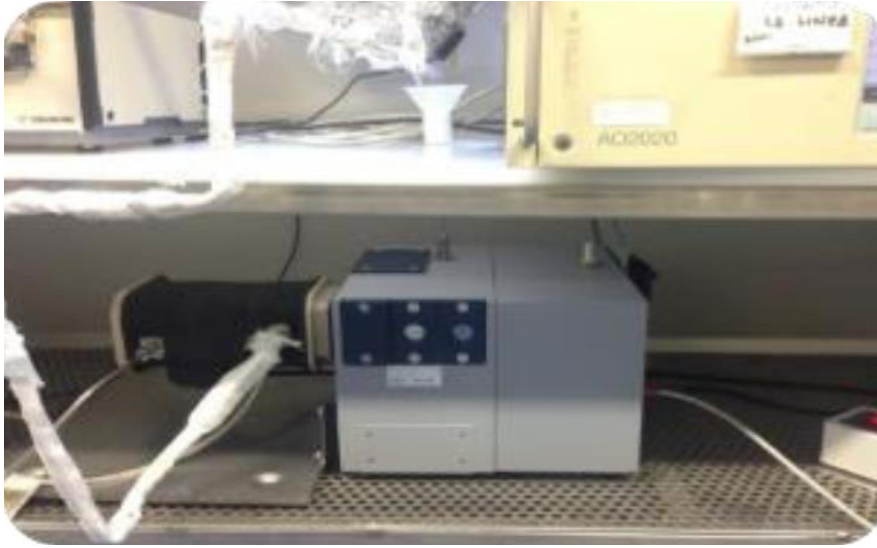


Plate 3.2: Matrix MG at Fletcher Ltd Laboratories, Kitengela

The analyzer has software (OPUS GA) that allows the quantification of more than 400 compounds without the need to perform gas calibrations.

The MATRIX-MG Series is perfectly suited for a very broad range of applications, such as the monitoring of process gases in production lines or exhaust gases, the analysis of motor vehicle exhausts and biogases, the determination of gas impurities in high purity gases, as well as for scientific research.

The target gas was analyzed inside a gas cell with optical path of 5m multi-reflection specially optimized for fast gas exchange, which allows analysis in dynamic processes.

The Syngas was subjected to chemical composition analysis at each of the gas cleaning stage. (See figure 3.5 on the sampling points)

3.5.4 Determination of the effects of Co-firing.

Proportion of *P. Juliflora* and rice husks in the ration of (1:1) were co-fired in the gasifier. The parameters analyzed were chemical composition as per the procedure described in section 3.5.3 Gas calorific value was determined as per the procedure as described in section equation (3.1) above and the various parameters compared.

3.5.5 Determination of the efficiency of the gas cleaning devices.

Samples were collected after each stage of the gas cleaning process and subjected to chemical analysis as described in section 3.4.3.2. The percentage of gas removal was compared to the inputs at each of the cleaning stages to obtain the results where an analysis showing the various percentages of the mixture components in the analyte were obtained.

3.5.6 Techno-economic analysis of syngas for energy production.

Figure 3.7 below shows the pathways for conversion of biomass into a useful product. Before setting up an energy project costs associated with the intended use and the end products need to be considered.

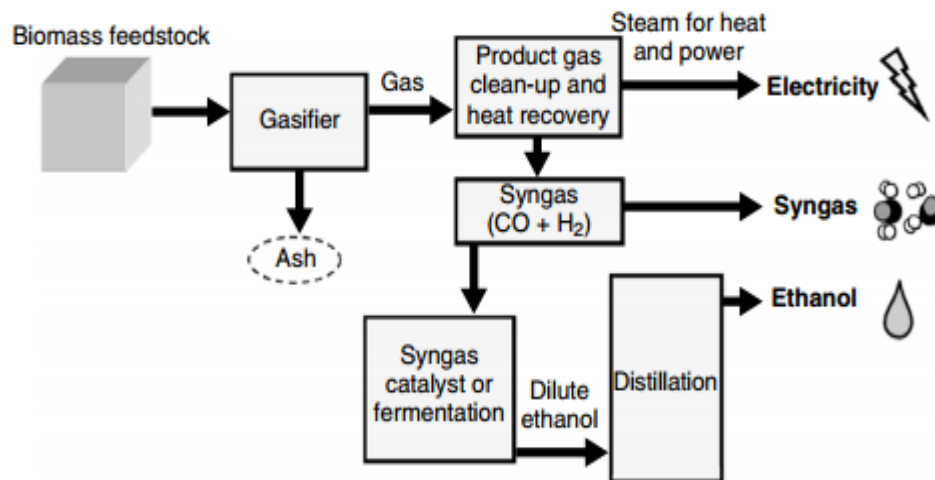


Figure 3.7: Thermochemical route for production of energy, gas, and ethanol (Basu, 2010)

The purpose of the Techno economic analysis or cost benefit analysis (CBA) is to help make informed choices on the viability of the project and to compare one project investment with other competing projects by use of a particular feedstock in order to determine which is more feasible. Several factors were considered in the operation of the facility, various variables were analyzed as to whether this will be used to generate electricity or for direct use. The current cost of energy in Kw/h was compared against the cost of producing syngas for either direct use or for electricity production;

Issues that were considered especially in operation and maintenance of this plant included;

(1) Capital (i.e., equipment) costs include: Design and engineering and administration, permits and fees, Site preparation and installation of utilities, equipment, equipment housing, and installation, startup costs and working capital

(2) Operation and maintenance cost elements include; Parts and materials, labor, utilities, financing costs, taxes, administration

Two types of Cost benefit analysis were applied; NPV (Net Present Value) and IRR (Internal Rate of Return)

3.5.6.1 Determination of the Net Present Value (NPV)

NPV is the value in the present of a sum of money, in contrast to some future value it will have when it has been invested at compound interest, (Craig, K. (1996)

$$NPV = \sum_{t=1}^n \frac{(R_t - C_t)}{(1+i)^t} - I_0 \dots\dots\dots (2)$$

Where;

R_t = Revenue in year t

C_t = Costs in year t

I_0 = Initial Investment

3.5.6.2 Determination of the IRR (Internal Rate of Return)

Internal rate of return (IRR) is the interest rate at which the net present value of all the cash flows (both positive and negative) from a project or investment equal zero. Internal rate of return is used to evaluate the attractiveness of a project or investment

As the NPV calculation is dependent on the choice of the discount rate, an alternative measure attempts to find the discount rate for which NPV is zero (or costs equal benefits). This is the IRR mathematically expressed as; (Craig, 1996).

$$NPV = \sum_{t=1}^n \frac{(R_t - C_t)}{(1+i)^t} - I_0 \dots\dots\dots$$

.... (3)

3.6 Research instruments

Updraft Gasifier – This is what was used to gasify the feed stock

Matrix – MG Gas analyzer – This instrument was used to analyze the concentration of the various gas components in syngas

Pressure and temperature probe - These were used to monitor temperature in the gasification chamber and the syngas pressure at the outlet

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Determination of residence time, gas composition and calorific value of syngas from *P. Juliflora* and rice husks

Table 4.1 below shows the operational parameters during the gasification experiment;

Table 4.1: Operational parameters for the gasification experiment

Parameter (N=3)	Type of feed stock		
	Rice husks	Prosopis	Co-firing Prosopis/ Rice husks (Ratio: 1:1)
Total Operation time (min)	60 ± 5.0	130 ± 10.50	180 ± 6.03
Moisture Content (%)	9 ± 0.36	10 ± 0.76	9 ± 0.20
Weight of feedstock (kg)	30 ± 2.00	38 ± 2.0	34 ± 1.0
Average Reduction Zone temperature (°C) at the bottom	510 ± 5.00	710 ± 2.08	650 ± 2.65
Average drying zone temperature (at the top) (°C)	220 ± 2.65	320 ± 3.06	280 ± 12.17
Average Calorific Value (MJ/M ³)	5.53	7.21	7.73

Using a stop watch it was found out that complete gasification of rice husks took approximately one hour (60 ± 5.0 minutes); prosopis combined with rice husks took three hours (180 ± 6.0277 minutes) while prosopis alone took approximately two hours and 10 minutes (130 ± 10.5040 minutes) before gas production could stop. The rice husks took shorter time to gasify because of their light weight by volume and have a larger surface area to volume ratio compared to prosopis which is more compact and had less surface area to volume ratio which took longer time to completely gasify them. Figure 4.1 below shows the biomass weighing process

4.1.1 Gas Composition of *P. juliflora* and Rice husks

Gas analysis was carried out using a gas analyzer “Matrix MG “from Bruker completed with a gas analysis software called “OPUS GA”.

The results for the gas composition are presented in table 4.2 below for the two biomasses in question (a) rice husks (RH), (b) Prosopis (MT). The discussion mainly focused on the flammable gases H₂, C_O and CH₄ (%).

Table 4.2: Percentage Mean \pm SD for Syngas components for Rice Husks and Prosopis

Component	% Mean \pm SD for each of the Syngas components for Rice Husks (RH) and <i>Prosopis</i> (MT)	
	Rice Husks	Prosopis
H ₂	4.3 \pm 0.00	19.25 \pm 0.07
CO	17.05 \pm 0.21	21.15 \pm 0.91
CO ₂	15.7 \pm 0.14	13.15 \pm 0.50
O ₂	0.1 \pm 0.01	0.165 \pm 0.02
CH ₄	7.35 \pm 0.07	5.45 \pm 0.07
N ₂	28.1 \pm 0.42	40.585 \pm 0.19
Others	27.4 \pm 0.83	0.25 \pm 0.35

N=3

4.1.2 Determination of the effects of Co-firing

Table 4.3 compares the % Mean \pm standard deviation for gas composition of the different biomasses under test, Rice Husks, Prosopis and co-firing results in the ratio 1:1; for purposes of this research only the flammable gaseous components were considered as they are the ones that would be used to calculate the heat value of the syngas.

Table 4.3: Percentage Mean \pm SD for each of the Syngas components for the three biomasses

	% Mean \pm SD for each of the Syngas components for the three biomasses		
	Rice husks	Prosopis	Co-firing (Rice husks/ Prosopis)
H₂	4.3 \pm 0.00	19.25 \pm 0.07	15.4 \pm 0.3
CO	17.05 \pm 0.21	21.15 \pm 0.91	18.37 \pm 0.45
CO₂	15.7 \pm 0.14	13.15 \pm 0.50	12.77 \pm 0.21
O₂	0.1 \pm 0.01	0.165 \pm 0.02	0.203 \pm 0.03
CH₄	7.35 \pm 0.07	5.45 \pm 0.07	8.87 \pm 0.35
N₂	28.1 \pm 0.42	40.585 \pm 0.19	32.6 \pm 0.56
Others	27.4 \pm 0.83	0.25 \pm 0.35	11.79 \pm 0.54

N=3

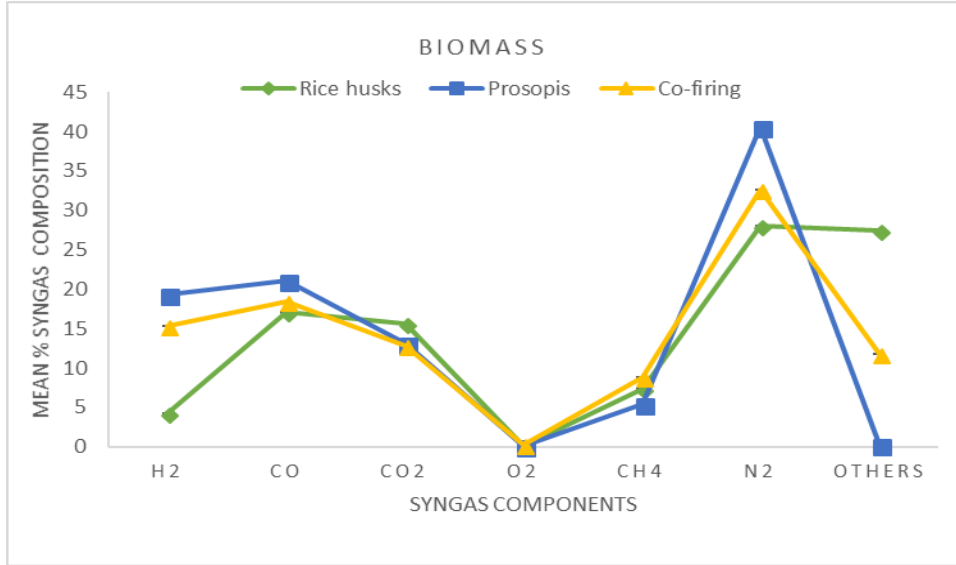


Figure 4.1: Trends of the mean % composition of various gaseous components.

From figure 4.1 above, it depicts that from the study Prosopis had the highest concentration of Hydrogen gas at 19.25 ± 0.07 % compared to Rice husks 4.3 ± 0.00 %. When these two feed stocks were co-fired it was found out that hydrogen production was improved compared to using rice husks alone to around 15.4 ± 0.30 %. The same applies to carbon monoxide gas where prosopis had the highest concentration of 21.15 ± 0.91 % compared to rice husks which had 17.05 ± 0.21 % but when we co-fire them we obtain an average of 18.37 ± 0.45 %. Most interesting results were for Methane gas whereby Prosopis had the lowest at 5.45 ± 0.07 % compared to rice husks at 7.35 ± 0.07 % but when co-fired, the methane gas percentage went up to 8.87 ± 0.35 %. This work relates to what was done by Njogu. *et al.* (2015) where they found out that syngas from rice husks was composed of 16.5% - 17.55% CO, 14.5% - 16.1% CO₂, 4.1% - 4.5% H₂, 6.8% - 7.2% CH₄ and 17.9% - 45.7% N₂ among others. The findings also relate to the work of (Sridhar, 2008) who found out that syngas from *prosopis juliflora* had ; 19 ± 1 % - H₂; 19 ± 1 % - CO; 1.5 % -CH₄; 12 ± 1 % CO₂; 2 ± 0.5 % H₂O and the rest, N₂

Multiple Comparisons using Analysis of Variance (ANOVA) at 95% Confidence Level (significance at the 0.05 Level).

Table 4.4: Multiple comparisons of syngas components using ANOVA

(Biomass)		Significance at the 0.05 confidence level			
		H₂	CH₄	CO	CO₂
Prosopis	Prosopis/Rice husks	0	0	0.013	0.416
	Rice husks	0	0.004	0.004	0.002
Prosopis/Rice husks	Prosopis	0	0	0.013	0.416
	Rice husks	0	0.006	0.132	0.001

Results from table 4.4 above show that there was an increase in the % composition of H₂ in both Prosopis and Prosopis/Rice husks as compared to Rice husks alone. The % composition of H₂ in the syngas was highest in Prosopis, followed by Co-firing Prosopis/Rice husks and lastly rice husks alone. All three biomasses showed a significant difference in the % composition of H₂ in the syngas composition amongst each other. The high concentration of H₂ in Prosopis can be attributed to high cellulose content in the woody biomass compared to the rice husks.

The % composition of CH₄ in the syngas was highest in Co-firing Prosopis/Rice husks (8.87 ± 0.35), followed by Rice husks (7.35 ± 0.07). Prosopis showed the least % composition of CH₄ in the syngas. There was a significant difference in the % composition of CH₄ in the syngas for all the three biomasses.

The % composition of CO in the syngas was highest in Prosopis (21.15 ± 0.91), followed by co-firing Prosopis/Rice husks (18.37 ± 0.45). Rice husks had the least % composition of CO in the syngas (17.05 ± 0.21). However, there was no significant difference in the % composition of CO in the syngas for rice husks and co-firing prosopis/rice husks.

There was a decrease in the % composition of CO₂ in the syngas from rice husks (15.7 ± 0.14), prosopis (13.15 ± 0.50) to co-firing prosopis/rice husks (12.77 ± 0.21) in that order. However, there was no significant difference in the % composition of CO₂ in the syngas for prosopis and co-firing prosopis/rice husks.

The % composition of N₂ in the syngas was highest for each of the three biomasses. All the three biomasses showed a significant difference in the % composition N₂ in the syngas.

The % composition of other gases in the syngas reduced significantly from rice husks to the other two biomasses. prosopis showed the least % composition of other gases in the syngas while rice husks had the highest. There was a significant difference in the % composition of other gases in the syngas for all the three biomasses.

4.1.3 Estimation of the Energy derived from the gasification of Rice husks, Prosopis and Co-firing

According to Morvay (2011), “The Gross Calorific Value (GCV) is used to designate energy transferred as heat to the surroundings per unit quantity of fuel when burned at constant volume (for solid and liquid fuels) or at constant pressure (for gaseous fuels)

with the H₂O product of combustion in the liquid phase. Gross Calorific Value (GCV) is sometimes called the Higher Calorific Value or Higher Heating Value”. For gaseous fuels it is calculated as follows;

$$\text{GCV/HHV} = (12.22 \cdot \text{H}_2 + 12.644 \cdot \text{CO} + 39.858 \cdot \text{CH}_4 / 100) \text{ MJ/M}^3 \dots\dots\dots (4.1)$$

According to equation 4.1 then;

i. Energy content for the rice husks

The energy content GCV of rice husks was calculated using equation 4.1 above;

$$\text{GCV/HHV} = (12.22 \cdot 4.1 + 12.644 \cdot 16.26 + 39.858 \cdot 7.03 / 100) = 5.35 \text{ MJ/m}^3 \dots\dots\dots (4.2)$$

ii. Energy content for Prosopis;

$$\text{GCV/HHV} = (12.22 \cdot 19.25 + 12.644 \cdot 21.25 + 39.858 \cdot 5.45 / 100) = 7.21 \text{ MJ/M}^3 \dots\dots\dots (4.3)$$

iii. Energy content from co-firing of rice husks and prosopis

$$\text{GCV/HHV} = (12.22 \cdot 15.40 + 12.644 \cdot 18.37 + 39.858 \cdot 8.87 / 100) = 7.73 \text{ MJ/M}^3 \dots\dots\dots (4.4)$$

From the results, it was evident that the energy content of co-firing prosopis and rice husks was higher (7.73 MJ/M³) compared to gasifying rice husks (5.35 MJ/M³) and prosopis alone (7.21 MJ/M³). Co-firing thus increases the energy content of the syngas.

Another important observation made is that co-firing rice husks alone took 60 ± 5.0 minutes while Prosopis alone took 130 ± 10.50 Minutes. Co-firing the two feedstocks took 180 ± 6.02 minutes while continuously producing syngas. The longer residence time for co-firing ensured that higher volume of syngas was obtained. From the experiment the gasification of rice husks was about 30 ± 2.0 kg/ hr. This relates to studies by, Njogu *et al.* (2015) who found out that gasification of rice husks took 25 – 32 kg/hr.

4.3 Determination of the efficiency of the gas cleaning devices for system improvements

Syngas was sampled at various sampling points along the gas cleaning system currently in place. For this analysis only one feed stock was used, in this case being rice husks. There were five sampling points each labelled as follows (see figure 3.5 above);

(1) - This is after the gasifier (raw gas), here the syngas has not been cleaned and would be conveyed to the various cleaning devices in the system as follows;

(2) - This is after the water scrubber, where in this stage the syngas passes through a water column where carbon dioxide is dissolved in the water thus reducing its concentration from the syngas.

(3) - This is after the cyclone separator. At this stage the gas enters the cyclone separator at an angle and this angular motion separates the heavy components of syngas like tar and char which are then deposited at the bottom of the cyclone separator

(4) – This is after the fiber filter. The fiber filter is used to remove very fine particles suspended in the syngas like fly ash and other micro particles

(5) – This is after the saw dust filter. The saw dust filter contains adsorbent materials which help to remove moisture in the gas.

A gas pump was used to collect the gas samples which were put in balloons for further analysis see plate 4.1 below. The samples were taken in triplicate for repeated analysis and to obtain the required averages.



Plate 4.1: gas collection balloons used to transport the gas to the laboratory

Table 4.5: Concentrations of the rice husks derived syngas at the various sampling points

Sampling point	(1)	(2)	(3)	(4)	(5)
H₂	3.55	4.00	4.40	4.25	4.30
CO	16.00	15.75	16.35	16.15	17.05
CO₂	13.75	14.00	14.60	15.65	15.70
O₂	0.145	0.14	0.10	0.13	0.10
CH₄	6.80	6.95	6.85	7.20	7.35
N₂	25.45	25.40	24.70	27.10	28.10
Others	34.30	33.76	33.00	29.52	27.40

N=3

Table 4.6: Mean \pm Stdev of the % Concentrations of the syngas mixture at the various sampling points for Rice husks

	H ₂	CO	CO ₂	O ₂	CH ₄	N ₂	Others
%	4.1 \pm	16.26 \pm	14.75 \pm	0.123 \pm	7.03 \pm	26.15 \pm	31.597 \pm
Conc	0.340	0.49	0.90	0.02	0.23	1.40	2.99
Rang e	3.55–4.40 %	15.75–17.05 %	13.75–15.70 %	0.1–0.15 %	6.80–7.35 %	24.7–28.10 %	27.40 – 34.30 %

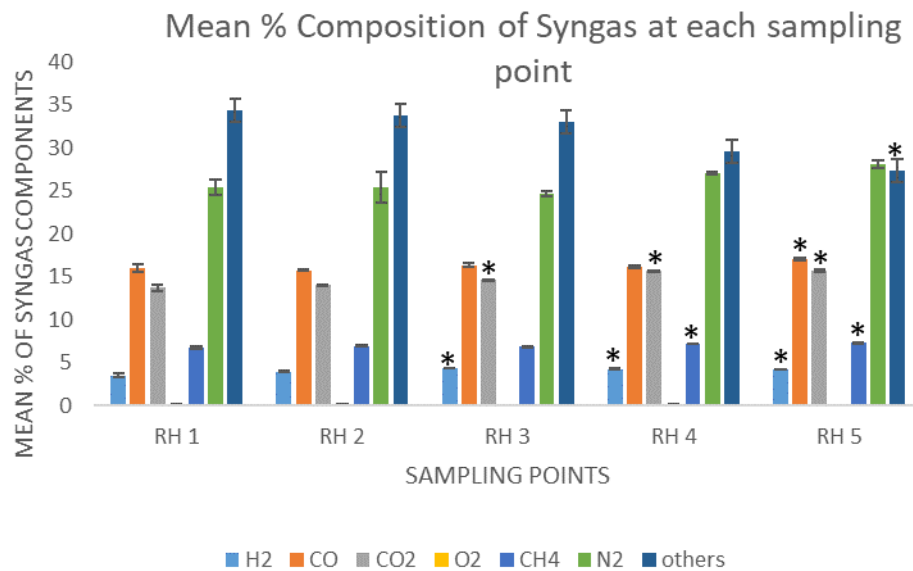


Figure 4.2: A bar graph representing percentage mean gas composition of the various gas components at the various sampling points.

SYNGAS COMPONENTS

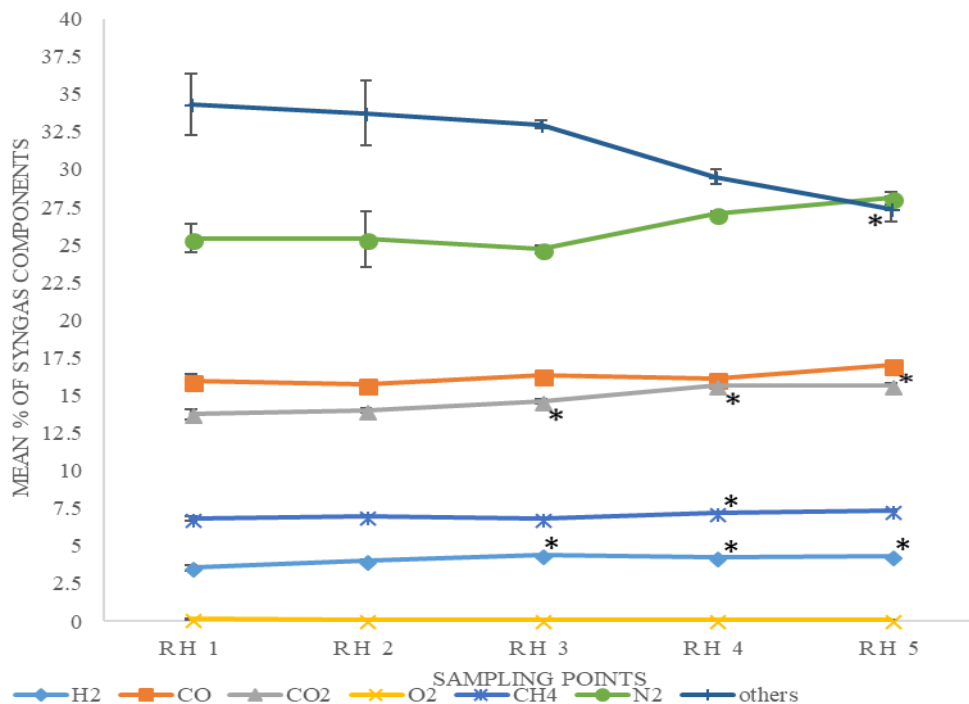


Figure 4.3: Trends of the % mean gas composition of the various gas components at the various sampling points

Table 4.7: Multiple comparisons of syngas components using ANOVA

		Significance at the 0.05 level			
		H2	CH4	CO	CO2
(1)	(2)	0.061	0.464	0.851	0.712
	(3)	0.004	0.970	0.661	0.036
	(4)	0.010	0.025	0.970	0.001
	(5)	0.008	0.006	0.044	0.001

From figure 4.3 above, it was observed that there was an increase in the % composition of H₂ in the syngas from rice husks from sampling point (1) to (3). This could have happened due to dissipation of H₂ from the scrubbing water. The % of H₂ at sampling point 4 was lower than at point (3). There was thus a significant difference in the % composition of H₂ in the syngas at sampling points (3), (4) and (5) as compared to sampling point number (1).

From figure 4.5 it was further observed that there was an increase in the % composition of CH₄ in the rice husks derived syngas from sampling point (3) to (4) and (5). This could be attributed to some enrichment within the system as these tests were conducted without purging the system. There was thus a significance difference in the % composition of CH₄ in the syngas at sampling points (4) and (5) as compared to sampling point (1).

From figure 4.2 and 4.3, there was a significant difference in the % composition of CO in the syngas at sampling point (5) as compared to sampling points (1) and (2). It was observed that there was an increase in % composition of CO₂ in the syngas from sampling point (1) to (5). This also could be attributed to formation of CO to CO₂ within the system as there are traces of air in the system and purging did not occur initially before obtaining the gas samples. Moreover, there was a significant difference in the % composition of CO₂ in the syngas at sampling points (5), (4) and (3) as compared to sampling point (1).

From figure 4.3 it was observed that there was no significant difference in the % composition of N₂ in the syngas from sampling point (1) to (5). There was a decrease in the % composition of other gases in the syngas from sampling point (1) to (5). There was a significant difference in the % composition of other gases at sampling point (5) as compared to points (1), (2) and (3).

There was no significant difference in the % composition of O₂ in the syngas for all sampling points as there was limited supply of oxygen in the gasification process.

To calculate efficiency of the cleaning of the cleaning gases only the gases that were to be cleaned were considered in this case being CO₂, N₂ and Other gases;

$$\text{Efficiency (E)} = \text{output/input} \times 100$$

For cleaning other gases;

$$\text{Output} = 34.40 - 27.40 = 6.9$$

$$E = 6.9 / 34.30 \times 100 = 20\%$$

For Cleaning CO₂;

$$\text{Output} = 13.75 - 15.70$$

$E = -1.95 / 13.75 \times 100 = -14\%$ this means that carbon dioxide gas could not be cleaned by the system

For Cleaning N₂

$$\text{Output} = 25.45 - 28.10 = -2.65$$

$E = -2.65 / 25.45 \times 100 = -10.41$. This means the system cannot efficiently clean N₂ gas

Oxygen Levels were negligible and were thus not considered in this calculation.

4.4 Techno-economic analysis of the gasification process

Total energy production was recorded as follows;

While using rice husks the average volume of gas generated was 55M³/hr. (from equation 4.2).

This is equivalent to $55\text{M}^3 \times 5.35\text{MJ/M}^3 = 294.25 \text{ Joules}$

If the plant operates for 12 hours, it will produce $12 \times 55\text{M}^3 = 669\text{M}^3$ of Syngas

$$= 669\text{M}^3 \times 5.35\text{MJ}/\text{m}^3 = 3,579.2 \text{ MJ}$$

While using prosopis the average volume of syngas generated was 90m^3 in about two hours (130 Minutes) from equation 4.3;

$$\text{This is equivalent to } 90\text{m}^3 \times 7.21\text{MJ}/\text{M}^3 = 504.7 \text{ MJ}$$

If the plant operates on average for 12 hours, it will produce $(12 \times 60 / 130) \times 90 = 498.4\text{m}^3$

$$\text{This is equivalent to } 498.4\text{m}^3 \times 7.21\text{MJ}/\text{M}^3 = 3,593.9\text{MJ}$$

When the two feed stocks were Co-fired (MT/RH) the average volume of the gas generated was 124m^3 from equation 4.4;

$$\text{This is equivalent to } 124\text{m}^3 \times 7.73\text{MJ}/\text{m}^3 = 958.52 \text{ Mega Joules}$$

If the plant operates for 12 hours, it will produce $(12 \times 60 / 180) \times 124\text{m}^3 = 496 \text{ m}^3$

$$\text{This is equivalent to } 496 \text{ M}^3 \times 7.73\text{MJ}/\text{m}^3 = 3,834.08 \text{ MJ}$$

The Energy could be used directly or be used to generate electricity;

If the energy is to be used to generate electricity

Then assuming 50% Thermal efficiency of the engine, then the output energy for the engine is;

$$3,579.2\text{MJ} \times 50\% = 1789.6 \text{ MJ} - \text{For rice husks}$$

$$3,593.9\text{MJ} \times 50\% = 1796.95 \text{ MJ} - \text{For prosopis}$$

$$3,834.08 \times 50\% = 1917.04 \text{ MJ} - \text{For Co-firing Rice husks and prosopis}$$

This would be the mechanical input fed into the generator, Assuming the generator and the drive train operate at 35% efficiency bearing in mind that Kwh electricity output = 3.6 MJ, then

$$1,789.6 / 3.6 \times 35\% = 173.9 \text{Kwh} - \text{from rice husks}$$

$$1,796.95 / 3.6 \times 35\% = 174.7 \text{Kwh} - \text{from prosopis}$$

$$1,917.04 / 3.6 \times 35\% = 186.4 \text{ Kwh} - \text{from co-firing the two feed stocks}$$

The results show that if these weeds and agricultural wastes are gasified they contain lots of energy potential especially if efficiencies are improved with regards to the gasifier and the generator.

4.3.1 Net Present Value (NPV) and the Internal Rate of Return (IRR)

The gasifier system in JKUAT was installed at total cost of 800,000 Kshs and about Ksh 120,000 Kshs annual maintenance cost.

The current cost of electricity per unit is 15Ksh (including tax levy and other fees)

Annual electricity production (assuming the plant is running for 12hours);
While using rice husks = $173.9 \text{kWh} \times 365 \times 15 \text{ksh/kw} = 952,102.5 \text{ ksh}$

The Net Present Value and IRR figures for Rice husks, Prosopis and co-firing the two feed stocks for the 10-year period are as tabulated in tables 4.8 through 4.10. followed by relevant discussion.

Table 4.8: NPV and IRR results while using syngas from rice husks

Annual Income (Rice husks)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Annual Income	952,103	952,103	952,103	952,103	952,103	952,103	952,103	952,103	952,103	952,103
Initial Capital Outlay	(838,500)	-	-	-	-	-	-	-	-	-
Annual cost										
Rice husks (1 ton)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)
Storage	-	-	-	-	-	-	-	-	-	-
Labour	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)
Annual Maintenance costs	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)
Net Cash flow	(600,598)	237,903	237,903	237,903	237,903	237,903	237,903	237,903	237,903	237,903
Rate (%)	10									
NPV (Kshs)	358,561									
IRR (%)	37									

From the results in table in table 4.8 above, NPV and IRR are both positive meaning that rice husks can be a viable option if used solely as a feed stock to obtain syngas for energy production.

Table 4.9: NPV and IRR results while using syngas from Prosopis

Annual Income (Prosopis)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Annual Income	956,483	956,483	956,483	956,483	956,483	956,483	956,483	956,483	956,483	956,483
Initial Capital Outlay	(838,500)	-	-	-	-	-	-	-	-	-
Annual cost										
Prosopis (1 ton)	-	-	-	-	-	-	-	-	-	-
Storage	-	-	-	-	-	-	-	-	-	-
Labour (includes pelletization)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)
Annual Maintenance costs	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)
Net Cashflow	(202,018)	636,483	636,483	636,483	636,483	636,483	636,483	636,483	636,483	636,483
Rate (%)	10									
NPV (Kshs)	2,149,814									
IRR (%)	315									

From the results in table in table 4.9 above, NPV and IRR are both positive meaning that prosopis can be a viable option if used solely as a feed stock to obtain syngas for energy production.

Table 4.10: NPV and IRR results while co-firing rice husks and syngas

Annual Income (Co-firing)	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Annual Income	1,020,540	1,020,540	1,020,540	1,020,540	1,020,540	1,020,540	1,020,540	1,020,540	1,020,540	1,020,540
Initial Capital Outlay	(838,500)	-	-	-	-	-	-	-	-	-
Annual cost										
Prosopis (1 ton)	-	-	-	-	-	-	-	-	-	-
Transport Baringo/Marigat to KJUAT	(2,013,857)	(2,013,857)	(2,013,857)	(2,013,857)	(2,013,857)	(2,013,857)	(2,013,857)	(2,013,857)	(2,013,857)	(2,013,857)
Rice husks (1 ton)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)	(394,200)
Transport - Mwea to JKUAT	(630,720)	(630,720)	(630,720)	(630,720)	(630,720)	(630,720)	(630,720)	(630,720)	(630,720)	(630,720)
Storage	-	-	-	-	-	-	-	-	-	-
Labour (includes pelletization)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)	(240,000)
Annual Maintenance costs	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)	(80,000)
Net Cashflow	(3,176,737)	(2,338,237)	(2,338,237)	(2,338,237)	(2,338,237)	(2,338,237)	(2,338,237)	(2,338,237)	(2,338,237)	(2,338,237)
Rate (%)	10									
NPV (Kshs)	(11,218,830.35)					No IRR since cash flows are negative				

From the results in table in table 4.10 above, NPV is negative and hence no IRR since the cash flows are negative. This means that co-firing may not be a viable option for energy production. This is basically due to high transportation costs of the raw materials from one point to the other. It is best to gasify on site to eliminate the transport component.

CHAPTER FIVE:

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The research has shown that residence time has no effect on the overall gas composition and the gas calorific value irrespective of whether gasification took longer or shorter time. It was also noted that higher temperatures lowered the gasification time, this means that optimal temperatures gave out the best results. It was further noted that co-firing also helped improve the syngas calorific value.

From the results, it is proven that *Prosopis Juliflora* and rice husks are very promising biofuel feed stocks which is readily available at a very low cost and can produce high quality gas which could be used for a myriad of energy applications. The net present value (NPV) and the internal rate of return (IRR) have demonstrated viability for the study especially if gasification is done on site to avoid high transport charges.

Gasification of agricultural wastes and the invasive weeds thus is a better option of managing them. Through the gasification process, it can provide employment to the local communities and cheap energy which can readily be fed into the electricity grid to improve the community's livelihoods

5.2 Recommendations

The research recommends the use of *Prosopis* and rice husks as cheap raw materials to obtain green energy and gasification (for energy recovery) is the best management approach for both the invasive weeds and agricultural wastes. The research provides a viable solution to invasive weeds management and agricultural wastes management problem especially in Kenyan rural set-ups which also provides alternative means of cheap and readily available energy to the local communities.

Areas recommended for further research include research to ascertain the toxicity levels of the syngas produced to determine its impact to the environment if the

technology was to be implemented on large scale for commercial purposes. Secondly the quantification of *Prosopis sp.* available for gasification should be done to assess the sustainability of the plant if the project was to be implemented on large scale.

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APPENDICES

Appendix 1: Gas Analysis

The identification and quantification of the gas compounds was performed by the *MATRIX-MG* from Bruker coupled with a comprehensive software package OPUSGA (Gas Analysis).

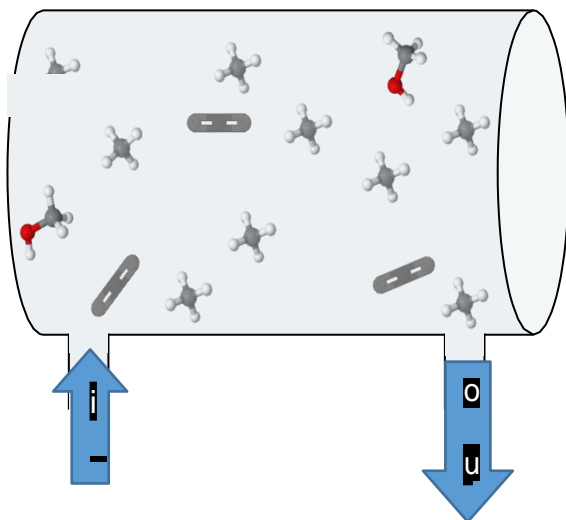
It uses a non-linear fitting algorithm with proven reliability for the rapid identification and quantification of gas compounds with remote sensing spectrometers.

OPUSGA allows the quantification of more than 400 compounds without the need to perform gas calibrations.

The *MATRIX-MG* Series is perfectly suited for a very broad range of applications, such as the monitoring of process gases in production lines or exhaust gases, the analysis of motor vehicle exhausts and biogases, the determination of gas impurities in high purity gases, as well as for scientific research.

The target gas was analysed inside a gas cell with an optical path of 5 m multi-reflection specially optimized for fast gas exchange, which allows analysis in dynamic processes.

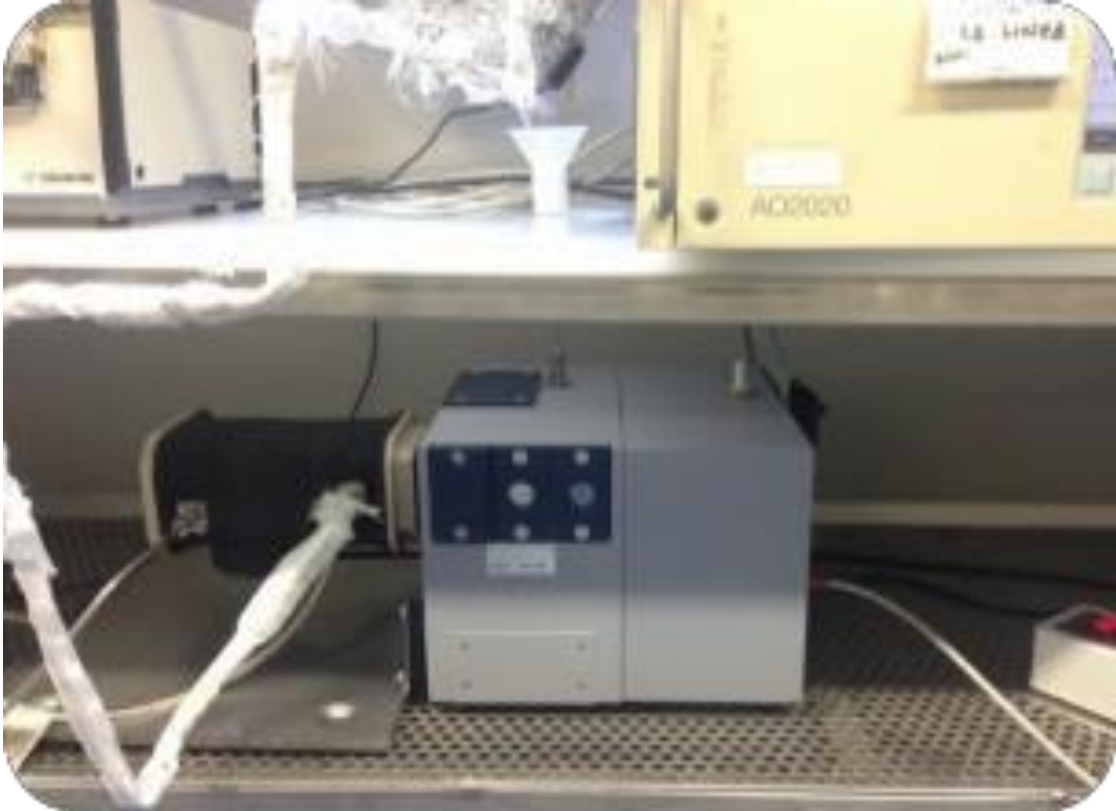
An illustration is given below for the flow of gas and a pictorial of the instrument.



Appendix 2: Results

SAMPLE ID / PARAMETER	H ₂	CO	CO ₂	O ₂	CH ₄	N ₂	H ₂ S
	RH-1	3.4	15.7	13.5	0.15	6.7	24.8
RH-1 (After gasification)	3.7	16.3	14.0	0.14	6.9	26.1	ND
RH-2	4.1	15.8	14.1	0.14	6.9	26.7	ND
RH-2 (After gasification)	3.9	15.7	13.9	0.14	7.0	24.1	ND
RH-3	4.4	16.5	14.5	0.09	6.8	24.9	ND
RH-3 (After Cyclone/SP)	4.4	16.2	14.7	0.11	6.9	24.5	ND
RH-4	4.3	16.3	15.7	0.12	7.2	27.2	ND
RH-4	4.2	16.0	15.6	0.14	7.2	27.0	ND
RH-5	4.3	17.2	15.8	0.09	7.4	28.4	ND
RH-5	4.3	16.9	15.6	0.11	7.3	27.8	ND
MT-1	19.3	21.8	12.8	0.15	5.50	40.45	ND
MT-2	19.2	20.5	13.5	0.18	5.40	40.72	ND
MT/RH (1)	15.4	18.8	12.6	0.23	8.9	32.1	ND
MT/RH (2)	15.7	17.9	13.0	0.17	8.5	32.5	ND
MT/RH (3)	15.1	18.4	12.7	0.21	9.2	33.2	ND

Appendix 3: Photo of the MATRIX





.....MATRIX-MG Series

.....Automated High-Performance Gas Analyzers.....Section

Innovation with Integrity

→ FT-IR →



..... Section Break (Continuous)

The MATRIX-MG Series comprises three high-performance FT-IR gas analyzers in a compact and rugged housing. They are designed for the automated, high-precision and real-time monitoring of gas concentrations in many different applications. ¶

..... Column Break

¶ **Key-Features:**

- Fast, continuous and fully-automated identification and quantification of gas compositions
- Its outstanding sensitivity allows to detect concentrations from a few parts per billion up to one hundred percent
- No calibration to the target gas necessary. Easy operation and maintenance
- Compensation of atmospheric gases and ~~water~~ humidity. Embedded in a compact and rugged housing
- Based on the RockSolid™ Interferometer for permanently aligned optics and insensitivity to vibrations
- Temperature-controlled gas cell (up to 191 °C)
- Accounts for variable pressure and temperature of the gas by included sensors inside the gas cell
- Output of measurement results to industrial communication interfaces

MATRIX-MG-Series

Section Break (Continuous)



Column Break

Fully-Automated-Identification-and-Quantification

The target gas is measured in a gas cell for high sensitivity compound analysis. From the obtained spectra the gas concentrations are retrieved automatically by a nonlinear fitting procedure within the comprehensive software package, without the need for gas calibrations. The influence of interfering gases as well as of varying gas temperature and pressure are taken into account by the analysis routine.

High-Dynamic-Range

Equipped with a gas cell featuring an optical path length of 0.5 m (MG01), 2 m (MG2) or 5 m (MG3) the MATRIX-MG-Series can detect gas components that occur in concentrations from only a few parts per billion (ppb) up to one hundred percent.

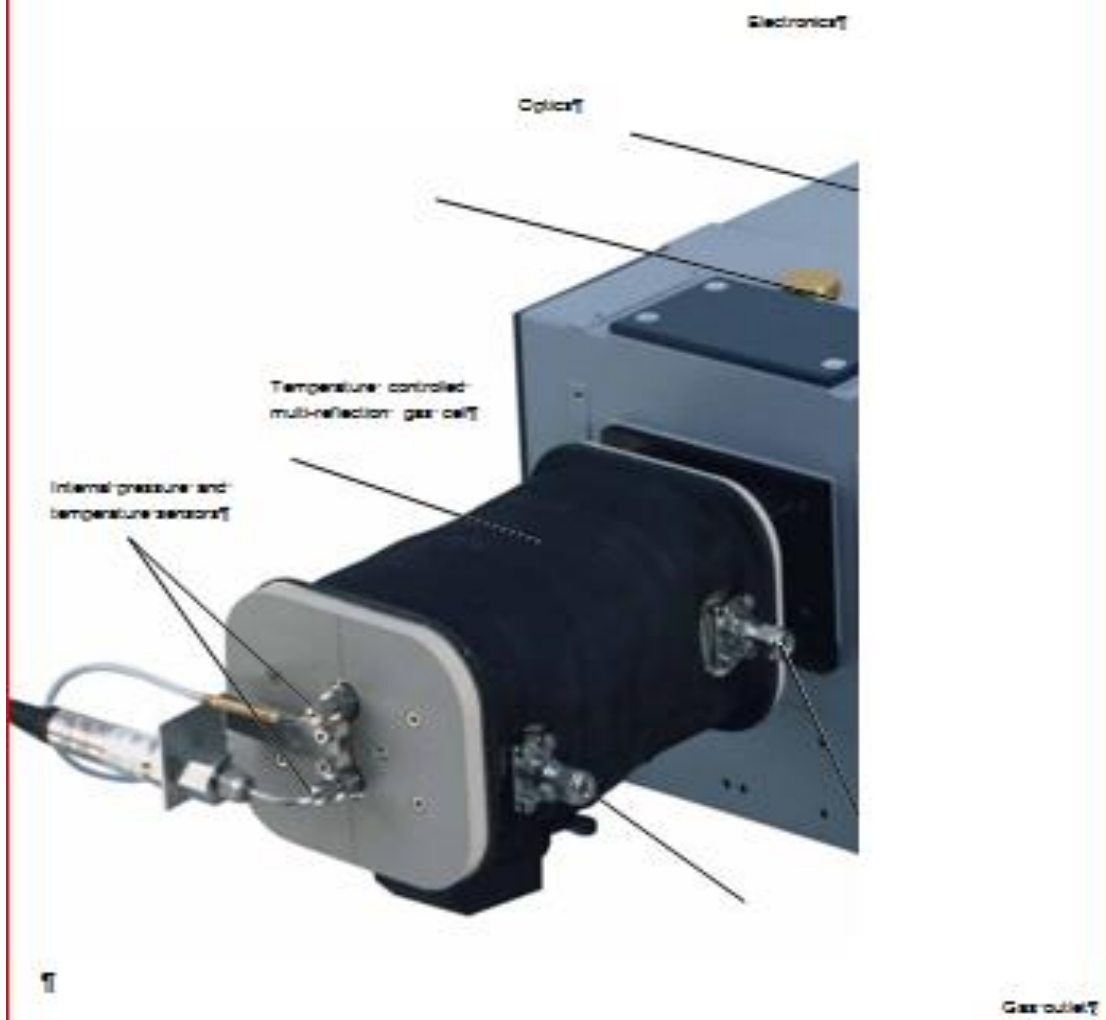
Fast-and-Continuous-Quantification

The MATRIX-MG spectrometers measure up to 5 spectra per second at high spectral resolution of 0.5 cm⁻¹ and up to 20 spectra per second at 4 cm⁻¹ spectral resolution.

An innovative gas cell design enables a fast gas exchange to measure dynamic processes. Standard fittings enable the easy connection of the gas analyzer to external piping.

Its design makes the Matrix-MG-Series ideally suited for the automated, fast, precise and continuous quantification even of fast fluctuating gas compositions. Due to the vast range of detectable gas components (>400 compounds available) the MATRIX-MG-Series provides a very large detection range for proper applications. The comprehensive accessories allow to measure gases in a broad pressure- and temperature range.

• **MATRIX-MG5**





The industrial-grade MATRIX-IR Cube with its proven RockSolid™ design is the basic fundamental of the MATRIX-IR Series gas analyzers.

The newly designed 5 m multi-reflection gas cell of the MATRIX-IR5 allows for a high optical throughput (high sensitivity) and an optimized gas flow for a fast gas exchange. Its nickel-plated inner surface and gold mirrors allow to measure even corrosive gases.

Internal pressure and temperature sensors enable online, in-situ measurements of the gas temperature and pressure for high-precision quantification results.

The compact and rugged design allows for an easy integration in many industrial, scientific and even mobile applications.

OPUS-GA

The comprehensive software package OPUS-GA (OPUS-Gas Analysis) automatically evaluates the measured spectra in real-time in order to identify and quantify the gas compounds.

The quantification is based on a non-linear fitting algorithm that fits the corresponding library spectrum to the measurement. In this fitting procedure also the absorptions of interfering gases are included.

More than 400 compounds can be identified and quantified without the need of a calibration measurement.

Optionally, individual reference spectra can be measured by the user.

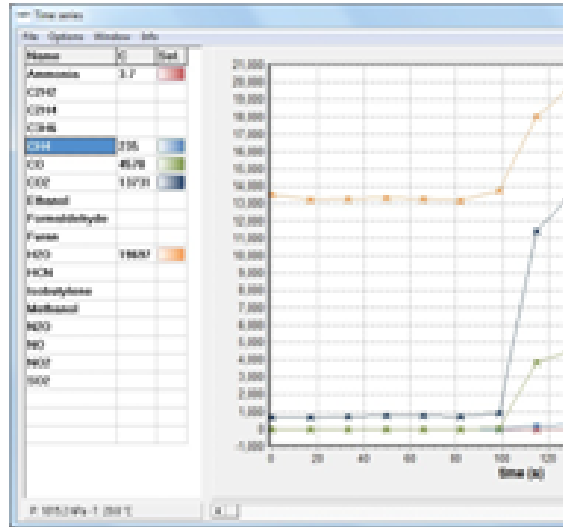


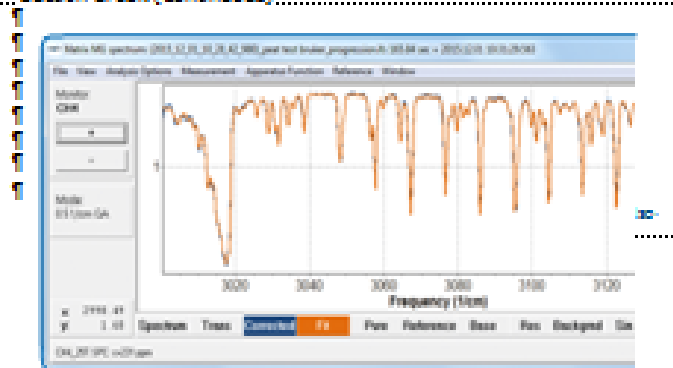
Figure 1: Screenshot of the OPUS-GA software interface showing the measured spectra and the corresponding fit for the gas compounds.

In detailed analysis, the measured spectra and the corresponding fit can be further investigated within OPUS-GA.

Section Break (Continuous)

The picture on the left shows the measured spectrum (blue) and the fit (orange) to quantify the methane (CH₄) concentration of the measured gas. In this spectral range also water shows significant absorption bands. In the picture on the right only the contribution to the fit that is originating from the methane in the gas is displayed. The additional absorption bands in the measurement are arising due to water vapor.

..... Column Break



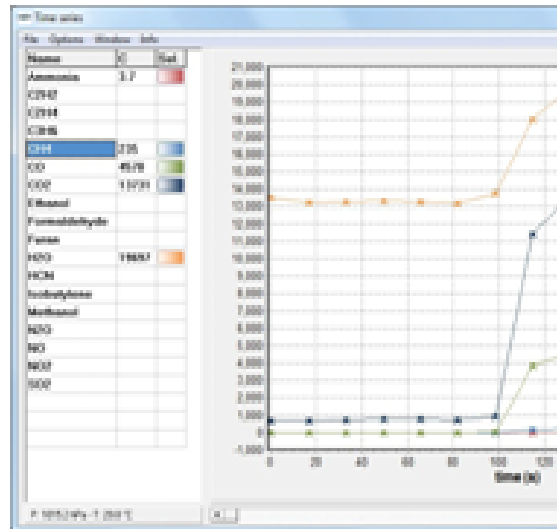
OPUS-GA

The comprehensive software package OPUS-GA (OPUS-Gas Analysis) automatically evaluates the measured spectra in real-time in order to identify and quantify the gas compounds.†

The quantification is based on a non-linear fitting algorithm that fits the corresponding library spectrum to the measurement. In this fitting procedure also the absorptions of interfering gases are included.†

More than 400 compounds can be identified and quantified without the need of a calibration measurement.†

Additionally, individual reference spectra can be measured by the user.†



Additionally, individual reference spectra can be measured by the user.†

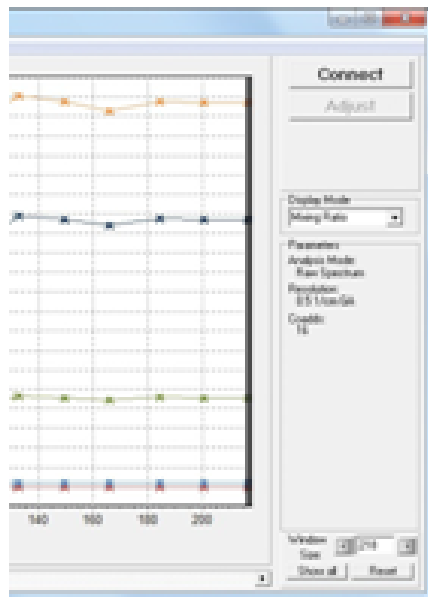
In detailed analysis, the measured spectra and the corresponding fits can be further investigated with OPUS-GA.†

Section Break (Continuous)

The picture on the left shows the measured spectrum (blue) and the fit (orange) to quantify the methane (CH₄) concentration of the measured gas. In this spectral range also water shows significant absorption bands. In the picture on the right, only the contribution to the fit that is originating from the methane in the gas is displayed. The additional absorption bands in the measurement are arising due to water vapor.†

Column Break

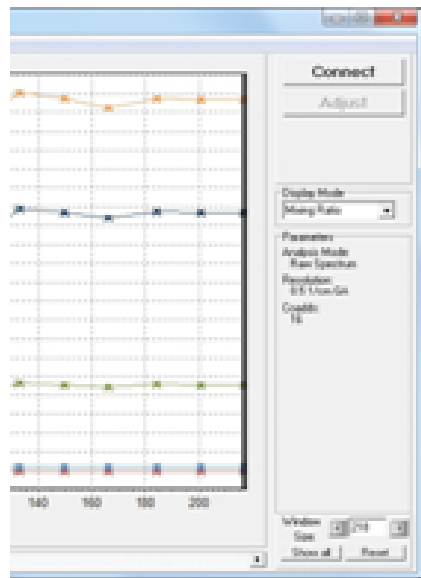




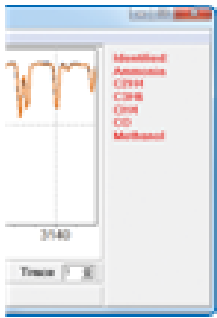
- Automatic identification and quantification of the target gas
- Automatic composition of (ppm/pppt) compounds
- No calibration to target gas (optional)
- More than 400 compounds available
- Transmission of measurement values to industrial interfaces possible



Comparison of the measured spectrum (blue) with the fit. The additional absorption bands in the measurement (blue) are obviously water vapor in the target gas. Section Break (Next Page)



- Automatic identification and quantification of the target gas
- Automatic composition of (ppm/ppb) compounds
- No calibration to target gas necessary
- More than 400 compounds available
- Transmission of measurement values to industrial interface possible



Comparison of the fit (red) and the raw measurement (blue) in the region of the **Section Break (Next Page)**

• Applications

Due to the vast range of detectable gas components (1400+ compounds are available without the need to perform calibration measurements), the MATRIX-MS can be used in a very broad field of applications.

Among these are for example:



Industrial applications like process surveillance in production lines



Monitoring of the exhaust gas of smokestacks



Motor vehicle exhaust analysis



Biogas analysis



Determination of gas impurities



Scientific research..... Section Break (Next Page).....



• Options

To meet the specific requirements for a very broad range of applications, we offer several different options for the MATRIX-NG Series:

• Option for Fast-Gas-Exchange

This option features a gas cell and external tubing to enable a very fast gas exchange to analyse dynamic processes, such as car engine exhaust gas.

• High-Resolution-Option

This option allows to measure with a resolution of better than 0.5 cm⁻¹ (standard: better than 1 cm⁻¹) and enables the identification and quantification of gas mixtures even with heavily overlapping absorptions.

• High-Pressure-Option

The high-pressure option allows to measure gases at a pressure of up to 20 bar (at 20 °C, standard: 2 bar) and extends the detection limits even further. It is especially suited to detect very low gas concentrations, such as impurities in **gas**.



MATRIX-NG with Opt. gas exchange

A variety of accessories is available for easier integration into dedicated applications and processes, such as pumps, heated filters, sample probes and transfer lines.

Section Break (Continuous)



To protect the user against hot surfaces (the MATRIX-NG gas analysers are supplied with a protective housing around the gas cell).

For lowest detection limits and trace gas analysis a 25-m multi-reflection gas cell is available upon request.



Specifications

	MG201	→	MG2	→	MG201
Optical path length (applicable)	0.1m	→	2m	→	5m
Maximum gas flow rate (L/min)	10 L/min	→	10 L/min	→	10 L/min
Dimensions	~447 x 320 x 240 mm ³	→	~640 x 450 x 250 mm ³	→	~640 x 450 x 250 mm ³ without protective housing ~1000 x 600 x 300 mm ³ with protective housing
Weight	~25kg	→	~27kg	→	~25kg
Transmission/Measurement interface	such as 4-20 mA analog, PROFIBUS, Modbus (available)				

Performance

Wavenumber range	→	650 ~ 5000 cm ⁻¹ (wavenumber range optional)
Detector	→	Liquid nitrogen cooled MCT, other detectors optional, e.g. DTG44
Interferometer	→	Rotating, gas phase (optional)
Resolution	→	Up to 30 spectra/s at 4 cm ⁻¹ resolution Up to 5 spectra/s at 0.5 cm ⁻¹ resolution
Resolution	→	Better than 1 cm ⁻¹ (optional) (Option: better than 0.5 cm ⁻¹)
Wavenumber accuracy	→	Better than 0.05 cm ⁻¹ @ 3000 cm ⁻¹
Wavenumber accuracy	→	Better than 0.1%



..... Section Break (Continuous)

Know-How-meets-Service

Q&U Optical is the leading manufacturer and worldwide supplier of Fourier Transform Infrared, Near Infrared and Raman spectrometers for various industries and applications. For years, we set new standards on the market when it comes to precision and efficiency, ergonomics and ease of operation, consulting and services.

Highest-Quality-from-a-Renowned-Company: Always-more-than-you-suspect

We are never satisfied with the common market standards. This is where our own research and development departments play a major role: here new ideas are turned into innovative products - in more precision, advanced user comfort and unrivalled quality. For us, it is obvious that these highest demands are also valid for our production processes and test routines ensure the quality that is common to all Q&U Optical spectrometers. No matter which new products we design, we place the very highest demands on quality.

..... Column Break

Worldwide-on-site-We-are-there-where-you-need-us

Q&U Optical's on-site service specialists are scientists and engineers who know their way around the world. They are available all over Europe, North and South America, Asia and Oceania: an efficient global technical support is guaranteed. This includes professional training and consulting services for our customers.



Plenty of time for personal consultation and customer service guarantee a sustainable and efficient solution.

Bruker

Our success stems from our commitment and dedication to provide you the proper analytical tool you require to solve demanding research problems in a timely, quality controlled procedure.

Related Bruker Optics Instrumentation



BR-37 Remote Sensing FT-IR

The BR-37 is a rugged, dual-beam sensing system providing high performance Spectroscopy in the field. The BR-37 can easily be deployed in the field for various air monitoring applications. Emissions from smoke stacks, waste disposal and hazardous emissions from chemical plants can be observed with an operating range typically several kilometers.

OPS - Open-Path Air Monitoring System

The open-path air monitoring system allows identification and quantification of airborne pollutants and atmospheric gases. Infrared radiation is modulated by an interferometer and transmitted as an array of optical fibers positioned as a distance of kilometers or hundreds of meters. Typical applications include monitoring of air quality, industrial, construction or municipal sites and high precision quantification of atmospheric gases.



SIGIS-2 Scanning Imaging Remote Sensing System

SIGIS-2 is a scanning imaging remote sensing system that allows rapid identification, quantification and visualization of gas clouds from long distances. The system maps a predefined area and results of the analysis are visualized by a video image overlaid by a chemical image. SIGIS systems are applied in environmental applications, atmospheric research, and industrial facility surveillance and are part of the equipment of emergency response forces around the world.

HI90 - Hyperspectral Imaging System

The HI90 is a high performance imaging Fourier transform spectrometer based on a focal plane array detector that allows for real-time identification and visualization of gas clouds from long distances. Each pixel of the array records an image from the corresponding field of view. Its spectrum is obtained by Fourier transformation and contains the infrared signature of the scene.



Section Break (Continuous)

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