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Pyrolysis of Sugarcane Bagasse

الانحلال الحراري لمخلفات قصب السكر

**A project Submitted in Partial Fulfillment for the Requirement of
the Degree of B.Eng. (HONOR) In Mechanical Engineering-(Power)**

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الآية

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

قال الله تعالى :

﴿قَالَ الَّذِي عِنْدَهُ عِلْمٌ مِّنَ الْكِتَابِ أَنَا آتِيكَ بِهِ قَبْلَ أَنْ يَرْتَدَّ إِلَيْكَ طَرْفُكَ فَلَمَّا رآه مُسْتَقِرًّا عِنْدَهُ قَالَ هَذَا مِنْ فَضْلِ رَبِّي لِيَبْلُوَنِي أَأَشْكُرُ أَمْ أَكْفُرُ وَمَنْ شَكَرَ فَإِنَّمَا يَشْكُرُ لِنَفْسِهِ وَمَنْ كَفَرَ فَإِنَّ رَبِّي غَنِيٌّ كَرِيمٌ﴾

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الإهداء

أهدي هذا المشروع الي والدي العزيز الذي قهر الصعاب حتى أصل الي ما أنا عليه الان, والي والدي
الحنونة التي سهرت الليالي في سبيل راحتي.

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ناصحي و بك أصبحت ما أنا عليه الان.

بالاضافة الي كل من علمني حرفاً, بروفاً ودكتوراً واستاذاً, أهدي إليك مشروع تخرجي, فقد كنت درياً ينيير
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Abstract

Energy is the economy back bone. Nowadays the demand for cheap and clean energy has become the major and most priority of every country looking to develop while maintaining its environment. Energy demand is increasing continuously due to rapid growth in population and industrialization development. The major energy demand is provided from fossil fuel sources. There are increasing environmental problems associated with the current use of fossil fuels. The potential for biomass to supply much larger amounts of useful energy with reduced environmental impacts compared to fossil fuels is the aim of this study. In this experimental study the slow pyrolysis of sugar cane bagasse process was discussed, two samples have been provided, first sample from Kenana bagasse, and the second sample from White Nile bagasse. One of the products from the slow pyrolysis process was bio-oil, it has been found from the laboratory analysis of the bio-oil that the calorific value is quite high with compare to the previous covered studies, which prove that bio-oil would be an environmentally friendly alternative that can be used for transportation and different industrial sectors.

ملخص الدراسة

الطاقة هي اساس الاقتصاد. في الوقت الحاضر أصبح الطلب على الطاقة الرخيصة والنظيفة من أولويات كل دولة تسعى الى التطور مع الحفاظ على بيئتها. استهلاك الطاقة يزداد بشكل متواصل بسبب النمو السكاني والتطور الصناعي. يتم استخدام الوقود الاحفوري لتلبية معظم احتياجات العالم من الطاقة. هناك مشاكل بيئية متزايدة متعلقة بالاستخدام الحالي للوقود الاحفوري. استخدام الكتلة الحيوية كمصدر للطاقة يقلل من الاثار البيئية الضارة التي يسببها الوقود الاحفوري.

في هذه الدراسة العملية نوقشت عملية الانحلال الحراري البطيء لمخلفات قصب السكر، اجريت العملية على عينتين من مخلفات قصب السكر تم توفيرهما من مصنعي سكر كنانة وسكر النيل الابيض. من اهم نواتج العملية سائل داكن اللون يعرف بالوقود الحيوي، التحليل المعلمي يظهر ارتفاع المحتوى الحراري لهذا السائل مقارنة بما تم التوصل اليه في الدراسات السابقة، مما يشير الى امكانية استخدام الوقود الحيوي في وسائل النقل والمجالات الصناعية المختلفة.

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Chapter one

Introduction

1.1 Background

Energy is the basis of human life. There is hardly any activity or moment that is independent of energy. Every moment of the day we are using energy. Earlier man used muscle power, then fire and animal power. Next, he learned to harness energy, convert it to useful form and put it to various uses [1]. There are mainly three energy sources: fossil, renewable, and fissile. The fossil energy sources are petroleum, coal and natural gas; the renewable energy sources covered are biomass, solar, wind, geothermal, and hydropower; and the fissile energy sources are uranium and thorium. Fossil fuels represent 78.3% of total energy supplies in the world today [2], Fossil fuels come from the decayed remains of prehistoric plants and animals, so their energy also comes, originally, from the sun. In some parts of the world new fossil fuels are being formed even today. But we are using fossil fuels at a far greater rate than they are being created, using up energy stored over hundreds of millions of years in a few hundred years [3]. Even if we had an unlimited supply of fossil fuels. Burning fossil fuels, however, sends greenhouse gases into the atmosphere, trapping the sun's heat and contributing to global warming, other pollutants are released into the air, soil, and water when fossil fuels are burned. These pollutants take a dramatic toll on the environment and on humans. Air pollution contributes to diseases like asthma. Acid rain from sulfur dioxide and nitrogen oxides harms plants and fish. Nitrogen oxides also contribute to smog [4]. For these reasons, is necessary to produce alternative fuels based on renewable sources to reduce GHG emissions and diversify the energy resources [5]. As the term suggests, renewable energy will not run out, unlike energy from fossil fuels [6]. There are several renewable energy sources that are in use today such as biomass, wind, solar, hydropower, and geothermal [7]. Among all of the renewable resources, biomass fuel is becoming ever more attractive as

suitable substitute for fossil fuels, due to the increasing demand for clean energy today, declining fuel reserves, and its contribution towards reducing dependence on crude oil. [8].Biomass can be converted to bio-fuel via different thermal, biological and physical processes. This research has focused on the pyrolysis of sugarcane bagasse. Pyrolysis of woody biomass and other organic solid wastes is among the thermo chemical processes with a promising future [9].

1.2 Problem statement

Energy supply is basic request of humankind, for cooking, heating, manufacturing, electricity generation and transportation. It's convenient to use coal, oil, and natural gas for meeting energy needs, but the world has a limited supply of these fuels, the high use of fossil energy nowadays causes global warming as a highly destructive mechanism of life. For these reasons biomass fuels as renewable energy sources have increasingly been considered as a suitable alternative to fossil fuels. Sugar cane bagasse is one of the most abundance biomasses in Sudan. Burn bagasse in boiler directly to generate power has low efficiency, beside the problem of bagasse spontaneously ignition during the storage, which represent hazard to the factory itself, and large losses of energy.

1.3 Objectives of the research

The objective of this research are

- To design and fabricate lab scale pyrolysis.
- To analyze syngas and bio-oil components.
- To reduce emissions from fuel combustion.

1.4 Scope of the research

This research is concerns to renewable energy in biomass field by using thermo chemical conversion especially pyrolysis in the section of slow pyrolysis. Also chemical and physical properties, gas flow and heat transfer by conduction, convection and heat exchanging.

1.5 Significant of the research

Reduce the CO₂ emissions to the climate by producing less carbon content fuels, solving the problems of these factories whose suffering from providing safe storing facilities for the excess quantity of bagasse, and also, solving their problem by converting the bagasse form solid state to liquid state and gaseous fuel which are easy to store and easy to transport, also use it as fuel to generate electricity more efficiently than burning bagasse directly. The remaining bio-char is very useful for soil so it can be used as fertilizer and reduce the air pollution by the fly ash.

Chapter two

Literature review

2.1 Introduction

Renewable energy sources are energy supplies that are refilled by natural processes at least as fast as we use them. All renewable energy comes, ultimately, from the sun. We can use the sun directly (as in solar heating systems) or indirectly (as in hydroelectric power, wind power, and power from biomass fuels) [7]. Renewable energy consumption represents 19.2% of the global energy consumption, biomass represents 14% of total energy consumption [10].

2.2 Types of Renewable Energy

2.2.1 Hydropower

Hydropower plants convert the energy of flowing water into electricity. This is primarily done by damming rivers to create large reservoirs and then releasing water through turbines to produce electricity.

Hydropower results in no emissions into the atmosphere but the process of damming a river can create significant ecological problems for water quality and for fish and wildlife habitat [7].

2.2.2 Geothermal

Geothermal power plants use high temperatures deep underground to produce steam, which then powers turbines that produce electricity. Geothermal power plants can draw from underground reservoirs of hot water or can heat water by pumping it into hot dry rock [7].

2.2.3 Wind Power

Wind power is produced by the energy of the wind turning aerodynamic blades mounted to a hub. The hub is connected to a shaft that turns a generator.

Large utility-scale wind turbines range in size from 50 kilowatts to over four megawatts. Smaller wind towers (under 50 kW) are suitable for residential and agricultural use [7].

2.2.4 Solar Energy

Solar energy comes directly from the power of the sun and is used to produce electricity, heat, and for lighting. Solar-electric power can be produced either by power plants using the sun's heat or by photovoltaic (PV) technology, which converts sunlight directly to electricity using solar cells [7]

2.2.5 Biomass

Biomass is the oldest fuel known to humans and could be considered another form of solar energy stored in plants through photosynthesis [5]. Biomass is the term used for all organic material originating from plants (including algae), trees and crops and is essentially the collection and storage of the sun's energy through photosynthesis. Biomass energy, or bioenergy, is the conversion of biomass into useful forms of energy such as heat, electricity and liquid fuels [11]. Biomass is a carbon neutral resource in its life cycle and the primary contributor of greenhouse effect. Biomass is the fourth largest source of energy in the world after coal, petroleum and natural gas, providing about 14% of the world's primary energy consumption [12]. Biomass appears to be an attractive feedstock for three main reasons. First, it is a renewable resource that could be sustainably developed in the future. Second, it appears to have formidably positive environmental properties by reducing Greenhouse emissions, possibly reducing NO_x and SO_x depending on the fossil fuels displaced. However, there are also negative impacts, such as the release of polycyclic aromatic hydrocarbons, dioxins, furans, volatile organic compounds, and heavy metals especially when combusted in traditional stoves. Third, it appears to have significant economic potential provided that fossil fuel prices increase in

the future [13]. Renewable biomass is being considered as an important energy resource all over the world. Biomass is used to meet a variety of energy needs, including generating electricity, fueling vehicles and providing process heat for industries. Among all the renewable sources of energy, biomass is unique as it effectively stores solar energy [14]. Biomass is a renewable energy source because its supplies are not limited. As long as we plant trees and crops we will have resources. Animal waste will always exist as long as the animals exist [15].

It is the only renewable source of carbon that can be converted into convenient solid, liquid and gaseous fuels through different conversion processes [14].

2.2.5.1 Biomass Formation

Botanical biomass is formed through conversion of carbon dioxide (CO_2) in the atmosphere into carbohydrate by the sun's energy in the presence of chlorophyll and water. Biological species grow by consuming botanical or other biological species. Plants absorb solar energy in a process called photosynthesis. In the presence of sunlight of particular wavelengths, green plants break down water to obtain electrons and protons and use them to turn CO_2 into glucose, releasing O_2 as a waste product [16].

2.2.5.2 Composition of Biomass

A plant can be considered as a structure that supports specialized organs. The structure consists of wood and the specialized organs include the leaves that perform photosynthesis and the roots that collect water and nutrients. Materials are transported from one site to another by sap. Fruits perform the function of sexual reproduction. Energy in a plant is stored in roots and tubers, in the sap and in the fruit. Structural parts of the plant also represent an accumulation of energy. Plant tissue consists of 50% to 95% water. Leaves are the plant's main photosynthetic organ. They contain, among other substances, proteins and much of the minerals

taken up. Good plantation management frequently involves returning leaves to the ground as mulch and fertilizer [17].

The basic structure of all wood and woody biomass consists of cellulose, hemicelluloses, lignin and extractives. Softwoods and hardwoods differ greatly in wood structure and composition. Hardwoods contain a greater fraction of vessels and parenchyma cells. Hardwoods have a higher proportion of cellulose, hemicelluloses and extractives than softwoods, but softwoods have a higher proportion of lignin. Hardwoods are denser than softwoods [13].

2.2.5.3 Types of Biomass

The six types of biomass are agricultural biomass, forest biomass, energy plantation, marine biomass, biomass from animal waste and municipal waste [12].

I. Agricultural biomass

Agricultural biomass which could be used for energy production is defined as biomass residues from field agricultural crops (stalks, branches, leaves, straw, waste from pruning, etc.) and biomass from the byproducts of the processing of agricultural products (residue from cotton ginning, olive pits, fruit pits, etc.) [12].

II. Biomass from animal waste

The potential biomass from animal waste includes primarily waste from intensive livestock operations, from poultry farms, pig farms, cattle farms and slaughterhouses. The animal waste is a rich source of fuel. The dung cakes prepared with animal wastes can be used for meeting cooking energy requirement in rural and semi-urban areas [12].

III. Forest biomass

Forest biomass, which is used or can be used for energy purposes consists of firewood, forestry residues, material cleared from forests to protect them from forest fires, as well as byproducts from wood industries [12].

IV. Municipal waste

The municipal waste consists of solid wastes as human excreta, garbage, city wastes and commercial wastes. It also includes liquid form domestic sewage and effluent from community institutional activities. There are a number of ways these wastes can be recycled and resources recovered in terms of fuel gas, manure and liquid fuel, etc. [12]

V. Energy plantation

Energy plantation means growing selected species of trees and shrubs which are harvestable in a comparatively shorter time and are specific means for fuel. The sources of energy plantation depend on the availability of land and water and careful management of the plants. The fuel wood may be used either directly into wood burning stoves and boilers or processed into methanol, ethanol and producer gas. There are many species suitable for energy plantation. Few of them are: *Acacia nilotica*, *Acacia auriculiformis*. [12]

VI. Marine biomass

Floating water plants (e.g., water hyacinths) are pest plants in many rivers, lakes and ponds in tropical and semitropical areas of the world. The growth rate of water hyacinths is very high and it is nutrient rich with net productivity of up to 25 tons of dry product per acre per year [12].

2.2.5.4 Energy Content of Biomass

Biomass refers to all forms of plant-derived material that can be used for energy such as: wood, herbaceous plants, crop and forest residues, animal wastes, etc. Because biomass is a solid fuel it can be compared to coal. On a dry-weight basis, heating values range from 17.5 GJ per ton for various herbaceous crops like wheat straw, sugarcane bagasse to about 20 GJ per ton for wood. The corresponding values for bituminous coal and lignite are 30 GJ per ton and 20 GJ

per ton respectively. At the time of its harvest biomass contains considerable amount of moisture, ranging from 8 to 20 per cent for wheat straw, to 30 to 60 per cent for woods, to 75 to 90 per cent for animal manure, and 90 to 95 per cent for water hyacinth. In contrast the moisture content of the most bituminous coals ranges from 2 to 12 per cent. Thus the energy densities for the biomass at the point of production are lower than those for coal. On the other side chemical attributes make it superior in many ways. The ash content of biomass is much lower than for coals, and the ash is generally free of the toxic metals and other contaminants and can be used as soil fertilizer. Biomass is generally regarded as a low-status fuel, and in many countries rarely finds its way into statistics. It offers considerable flexibility of fuel supply due to the range and diversity of fuels which can be produced. Biomass energy can be used to generate heat and electricity through direct combustion in modern devices, ranging from very-small-scale domestic boilers to multi-megawatt size power plants electricity (e.g., via steam turbines), or liquid fuels for motor vehicles such as ethanol, or other alcohol fuels. Biomass-energy systems can increase economic development without contributing to the greenhouse effect since biomass is not a net emitter of CO₂ to the atmosphere when it is produced and used sustainably. It also has other benign environmental attributes such as lower Sulphur and NO_x emissions and can help rehabilitate degraded lands. There is a growing recognition that the use of biomass in larger commercial systems based on sustainable, already accumulated resources and residues can help in improving natural resource management [12].

2.2.5.5 Biomass as Fuel

Biomass fuels have negligible sulfur content and therefore, do not contribute to sulfur dioxide emissions that cause acid rain, there are numerous ways to use biomass as fuel:

- Biomass can be burned as harvested. Wood, saw dust, corn cobs, rice husks, and other agricultural residue can be burned directly in appropriate furnaces. The heat of combustion of most dry biomass lies in the 15 to 19 MJ/kg range.
- The utility of wood as a fuel can, traditionally, be improved by transforming it into charcoal.
- Wood can be gasified to drive vehicles and fuel industries.
- Methanol can be made from wood.
- Palm oil can be used in Diesel engines.
- The sap of some plants is so rich in hydrocarbons that it also can be used directly as Diesel fuel.
- Sugars and starches can be fermented into ethanol.
- Biomass residues can be digested into a methane-rich biogas [16]

2.3 Sugarcane bagasse

Sugarcane bagasse is a residue widely generated in high proportions in the agro-industry. It is a fibrous residue of cane stalks left over after the crushing and extraction of juice from the sugarcane. Bagasse is generally gray-yellow to pale green in colour. It is bulky and quite non uniform in particle size. The sugar cane residue bagasse is an underutilized, renewable agricultural material that consist of two distinct cellular constituents. The first is a thick walled, relatively long, fibrous fraction derived from the rind and fibro-vascular bundles dispersed throughout the interior of the stalk. The second is a pith fraction derived from the thin walled cells of the ground tissue [18].For every 1 (wet) ton of sugarcane approximately 100 kg of sugar is produced, 35 kg molasses, and 270 kg wet bagasse [19,20].

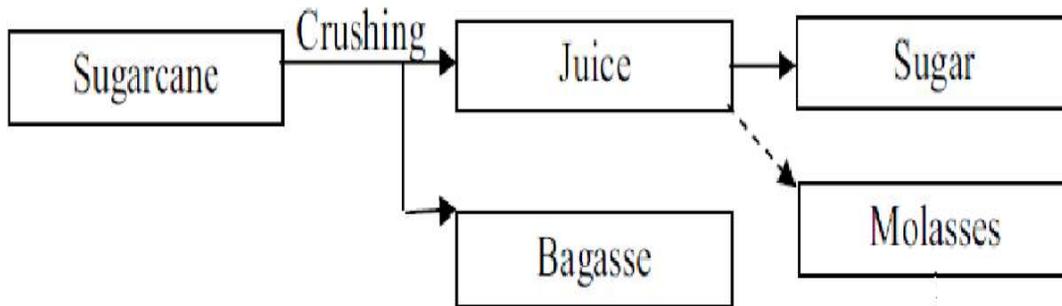


Figure (2.1) sugar cane products [20]

2.3.1 Composition of sugarcane bagasse

Sugarcane bagasse is a lignocellulose, lignocellulose is the major part of biomass, so this type is described in some detail. Lignocellulosic material is the non-starch, fibrous part of plant materials. Cellulose, hemicellulose, and lignin are its three major constituents [16].

2.3.1.1 Cellulose

Cellulose is a complex carbohydrate which consists of unbranched chains of linked glucose units. Cellulose is found to be a major component of the plant cell walls. It is a glucose-based polysaccharide and the repeating unit of the cellulose polymer consists of two glucose anhydride units, called as cellobiose unit. Cellulose is a strong substance because the straight-chain molecule hydrogen bonds, forming a pseudo crystalline structure which gives rigidity to the structure. [21].

2.3.1.2 Hemicellulose

Hemicellulose is a mixture of polysaccharides, composed almost entirely of sugars such as glucose, mannose, and xylose. In contrast to cellulose, hemicellulose is a heterogeneous branched polysaccharide that binds tightly, but non-covalently, to the surface of each cellulose micro fibril. Hemicellulose differs from cellulose, in consisting primarily of xylose and other five-carbon monosaccharides [22].

2.3.1.3 Lignin

As a major cell wall component, lignin provides rigidity, internal transport of water and nutrients and protection against attack by microorganisms. Lignin is an amorphous polymer consisting of phenyl propane units, and their precursor' are three aromatic alcohols namely p-coumaryl, coniferyl and sinapyl alcohols [21].

Sugarcane bagasse is composed of approximately 50% cellulose, 25% hemicellulose and 25% lignin. The high cellulose content makes sugarcane bagasse ideal as a composite reinforcement. Different researchers have recorded different chemical compositions for bagasse and some are listed in Table (2.1). Elemental analysis of bagasse shows that it is composed of 45.5 wt% C, 5.6 wt% H, 45.2 wt% O and 0.3 wt% N [19].

Table (2.1)chemical compositions for bagasse [19].

Cellulose	Hemicellulose	Lignin	Protein	Fat and waxes	Ash	Saccharose	Silica	Glucose	References
50	25	25							Huang <i>et al.</i> 2012, Xu <i>et al.</i> 2010
40	24.4	15	1.8	0.6	5	14		1.4	Vazquez <i>et al.</i> 1999
40-43	28-30	9-11	8-9	2-2.5	5-6				Ramaraj 2007
46	24.5	19.5		3.5	2.4		2		Mulinari <i>et al.</i> 2009a
69.4	21.1	4.4		5.5	0.6				Habibi <i>et al.</i> 2008
41.8	28	21.8							Bilba <i>et al.</i> 2003
55.2	16.8	25.3			1.1				Trindade <i>et al.</i> 2005
56	6	29			7				Maldas and Kokta 1991
36.32	24.7	18.14							Vilay <i>et al.</i> 2008

2.3.2 Calorific value of bagasse

The calorific value (CV) of a material is an expression of the energy content, or heat value released when burnt in air. The CV is usually measured in terms of the energy content per unit mass, or volume; hence MJ/kg for solids, MJ/l for liquids, or MJ/Nm³ for gases. The CV of a fuel can be expressed in two forms, the gross calorific value (GCV), or higher heating value (HHV) and the net calorific value (NCV), or lower heating value (LHV).

The HHV is the total energy content released when the fuel is burnt in air, including the latent heat contained in the water vapour and therefore represents the maximum amount of energy potentially recoverable from a given biomass source. The actual amount of energy recovered will vary with the conversion technology, the LHV is the appropriate value to use for the energy available for subsequent use [22].

The high calorific value and low calorific value of bagasse are calculated by using mathematical formulae based on the percentage of major contents like moisture, ash and brix. It was observed that both HHV and LHV of bagasse are much influenced by the content of moisture in it [23].

2.3.3 Applications of sugarcane bagasse

Traditionally, Bagasse is burnt for its fuel value to produce steam and renewable electricity in most sugar mills around the world, such as Kenana factory in Sudan. When excess electricity is generated it is sold to the electricity grid. This process is called 'co-generation'. And used in smaller quantities for produce paper pulp, chemical reactants, or animal feed additives. Implementing thermo-chemical processing of bagasse will extend its uses to high-density energy products (char and bio oil) as well as activated carbon and high quality fertilizer (from char). Bagasse is a by-product from the sugar industry and is therefore a second-

generation biofuel, which implies that it does not compete with food crop production. Sacrificing agricultural land for fuel production may in the future become viable if fuel prices increase significantly [19, 20, 24].

2.3.4 Drying of bagasse

Efficiency in the sugar industry was never an issue in the past two decades, as the bagasse generated in the sugar season, was sufficient for the steam and power requirements of the plant. In recent days, sugar mills have recognized the potential for the profitable generation of excess power, using cogeneration. The availability of surplus bagasse, or other fuels, is a major issue when considering year-round cogeneration with power export to the grid. Bagasse drying is one of the strategies which help to generate additional power in the plant. As the mill run bagasse maintains a high moisture content, its heating value is improved by reducing the moisture level of the product. Bagasse drying also improves boiler efficiency. A reduction of moisture content by 5%, results in approximately 13 % increase in the calorific value of the fuel and 3% increase in boiler efficiency [25].

2.3.4.1 Drying concepts

Drying is generally used to remove moisture or liquid from a wet solid by bringing this moisture into a gaseous state. In most drying operations, water is the liquid evaporated and air is the normally employed purge gas. In general, the main goal of drying is to decrease the moisture content of solid materials to below a certain limit, which results in quality enhancement, and ease of handling and further processing. A drying process is fundamentally a simultaneous heat and mass transfer operation and is widely used in a variety of thermal energy applications. Generally, the heat supplied is transported by convection from the surroundings to the particle surfaces and from there by conduction further into the particle throughout the drying process [25].

There are several ways to drying bagasse, here in Sudan the sugar factories open sun drying is used. For example in kenana sugar factory the sugar cane bagasse coming out of the sugar extraction process is automatically transported by conveyer belts to the factory's back yard and left it there for 8 to 10 days under the sun heat to reduce the moisture content from 51% to (10-15) %. Figure (2.2) shows the drying process at Kenana factory.

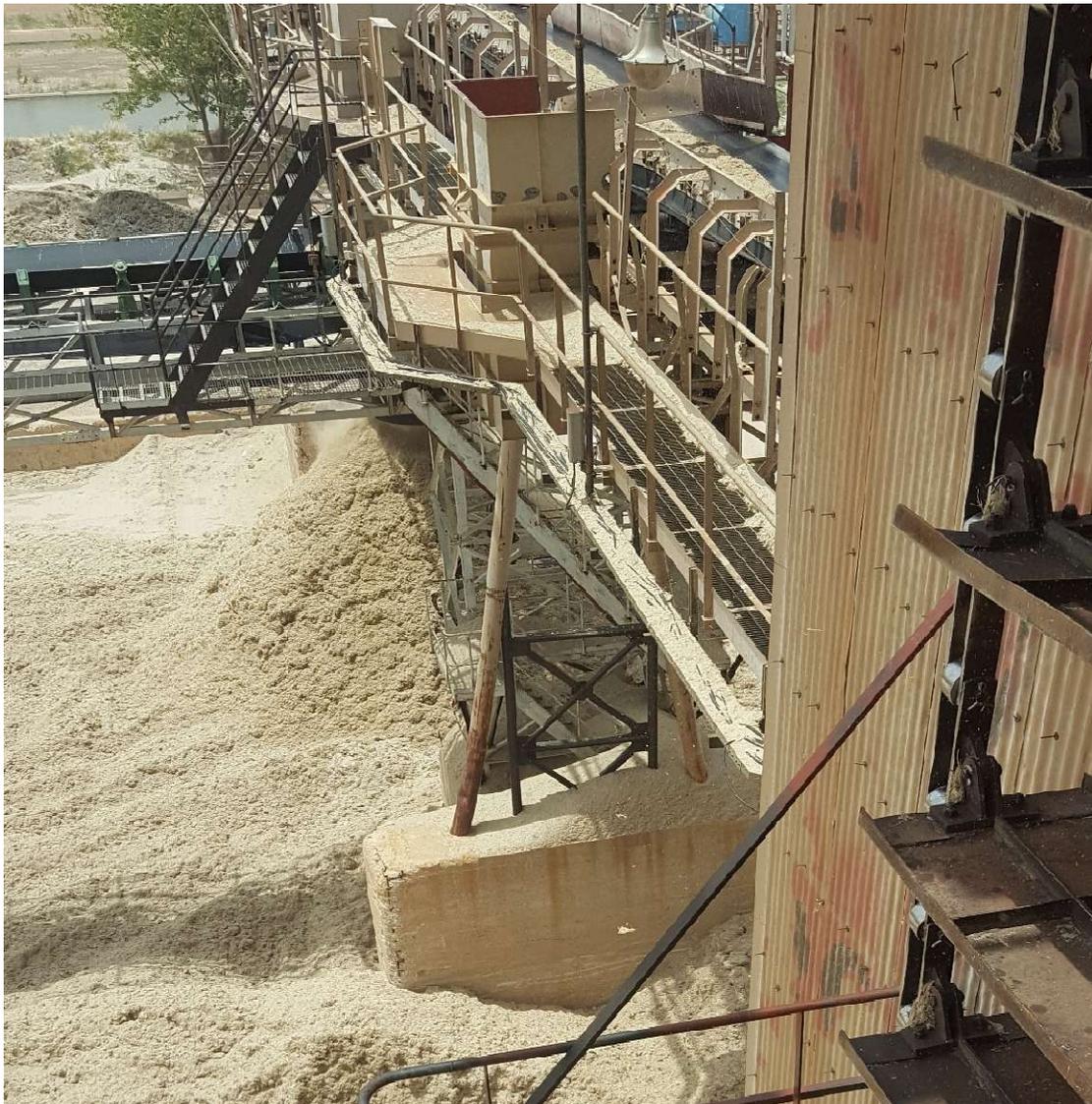


Figure (2.2) Kenana factory drying yard

2.4 Conversion of biomass

The term “conversion technology” encompasses a broad range of technologies used to convert solid waste into useful products, chemicals and fuels [26]. Biomass can be converted into useful forms of energy using a number of different processes.

Factors that influence the choice of conversion process are: the type and quantity of biomass feedstock, the desired form of the energy requirements, environmental standards, economic conditions, and project specific factors. In many situations the form in which the energy is required determines the process route followed by the available types and quantities of biomass. The conversion technologies to utilize biomass can be classified into three basic categories as shown in Figure (2.3) [27, 28].

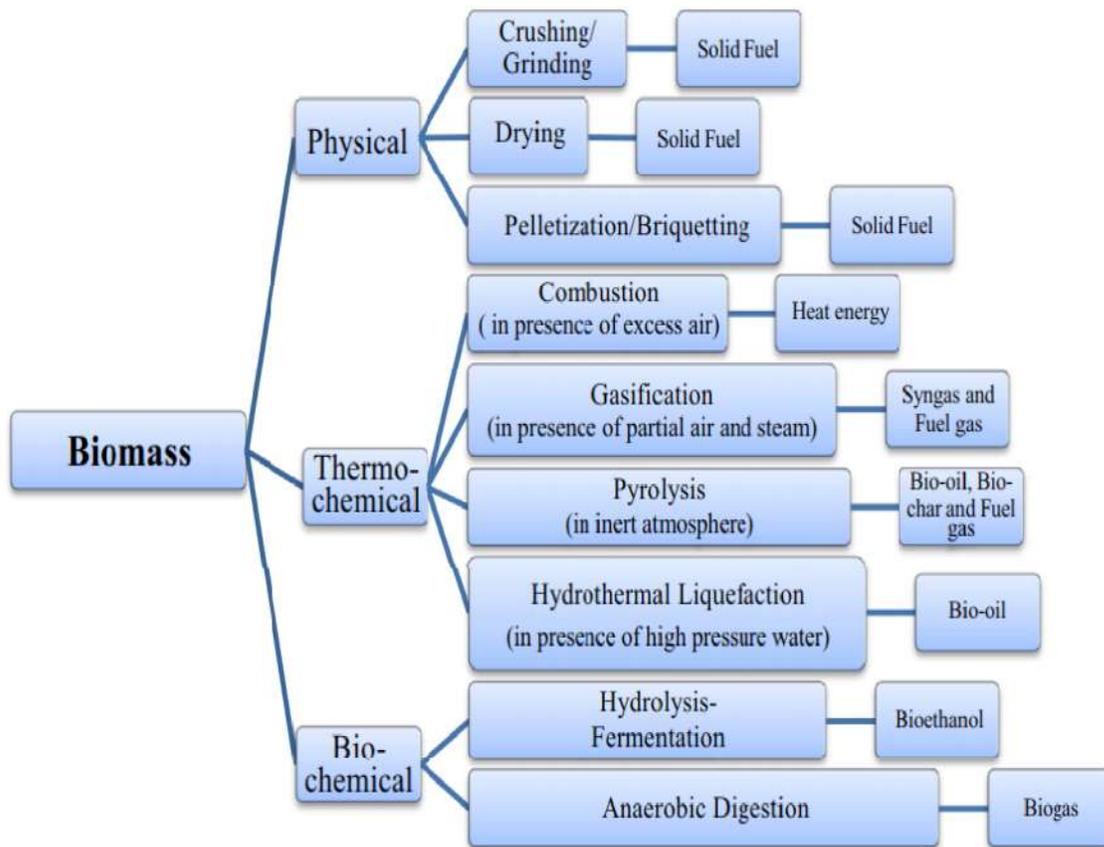


Figure (2.3) Biomass conversion pathways [28].

2.4.1 Physical conversion

Physical conversion of biomass uses densification techniques including crushing, heat, and pressure, mainly for the purpose of converting biomass into solid fuels [28].

2.4.2 Biochemical conversion

Biochemical conversion processes include anaerobic digestion (which occurs in controlled reactors or digesters and also in a less controlled environment in landfills), and anaerobic fermentation (for example, the conversion of sugars from cellulose to ethanol.) Biochemical conversion proceeds at lower temperatures and lower reaction rates than other conversion processes. Higher moisture feedstocks are generally good candidates for biochemical processes. The lignin fraction of biomass cannot be converted by anaerobic biochemical means and only very slowly through aerobic decomposition. As a consequence, a significant fraction of woody and some other fibrous feedstocks exits biochemical conversion as a residue. This residue called digestate, may or may not have market value, although it can be composted [26].

2.4.3 Thermochemical conversion

Thermochemical conversion is a major method for production of second generation liquid biofuels from non-food biomass. As the term implies, thermochemical conversion involves the use of heat to change biomass from solid to other forms. The process has several advantages over biological processes, including greater feedstock flexibility, conversion of both carbohydrate and lignin into products, faster reaction rates, and feasible to transport it. At the same time, biomass feedstock involves interactions with catalyst reactants to transform basic molecular structures into those more similar to useable fuels. The four main thermochemical paths for conversion of biomass are direct combustion for heat,

electricity, and power generation, pyrolysis and gasification for fuel and chemicals, and liquefaction for production of liquid oily fuel from wet substrates. [29] Among these four thermochemical conversion processes, pyrolysis is estimated to be a well-established and promising method for biomass treatment due to its technical characteristic and variety of products. [28]

2.4.3.1 Combustion

Biomass combustion supplies about 11% of the world's total primary energy, there are several broad categories of combustion applications, the most common application of biomass energy in developing countries is its use as a source of heat for cooking, sometimes called traditional biomass use. Industrial use of biomass combustion takes place in a combustor or furnace with the heat being used to in a manufacturing process, or to raise steam in a boiler which can expand through a steam turbine to generate shaft power, the produced shaft power or electricity can be used directly to drive a mill or other machine. Combustion of biomass is a process in which the biomass is burnt with the oxygen from the air to release the stored chemical energy as heat in burners, boilers, internal combustion engines and turbines. The scale of combustion devices encompasses a few kW of thermal input such as a single gas ring for cooking, to huge coal fired combustion boilers with inputs of 3 - 5 GW in a single unit serving the electrical needs [30]. Combustion of biomass produces hot gases at temperatures around 800 –1000 °C. It is possible to burn any type of biomass but in practice combustion is feasible only for biomass with moisture content lower than 50%, unless the biomass is pre-dried. High moisture content biomass is better suited in the case of biological conversion processes [27].

2.4.3.2 Gasification

Biomass gasification is generally a complex thermochemical process in which a solid fuel reacts with an oxidizing agent such as air, oxygen, steam, carbon dioxide and hydrogen or a mixture of these at temperatures in general above 700 °C, being converted into a gas mixture which contains carbon monoxide, carbon dioxide, hydrogen, methane and trace amounts of higher hydrocarbons such as ethane and ethene, water, nitrogen (if air is used as the oxidizing agent) and undesired impurities, such as tars, ammonia, sulfur-containing compounds, acidic species, and metals, depending on the biomass composition. As a renewable carbon source, biomass can be used as an alternative to fossil fuels for the production of “synthesis gas” (or syngas) a mix of mainly CO and H₂ with some CO₂, methane and higher carbon compounds by gasification with oxygen, CO₂ and/or steam. The gaseous products composition is influenced by many factors such as the feed composition, water content, reaction temperature, and the extent of oxidation of the pyrolysis products. The gases generated are cleaned by removing the tars, and then filtered and the clean gas collected ready for use. Each syngas component (CO, CO₂, CH₄, H₂ etc.) could be recovered, separated and utilized [31]. Generally, gas can be divided into low calorie gas (4-12 MJ/m³), medium calorie gas (12-28 MJ/m³) and high calorie gas (above 28 MJ/m³). For the most part, direct gasification of biomass yields low calorie gas [32]. The overall efficiency of conversion of biomass to energy using gasification and pyrolysis is estimated as 75–80% [33].

2.4.3.3 Liquefaction

Liquefaction is a promising technology among the thermochemical routes to convert biomass to liquid valuable products via complex chemical and physical reactions. Bio-oils, bio-crudes or polyols obtained via liquefaction of biomass can

be upgraded to gasoline and diesel like fuels and various polymeric materials. A significant majority of these products could be obtained from liquefied biomass particularly biomass based wastes in the near future. For this reasons biomass liquefaction has a great potential. Approaches and techniques of biomass liquefaction have to be understand and it has to been emphasized the importance of the subject very well. Liquefaction can be divided in two categories, direct liquefaction and indirect liquefaction. Direct liquefaction refers to pyrolysis, solvolysis liquefaction and high pressure hydrothermal liquefaction to produce liquid tars and oils and/or condensable organic vapours. On the other hand indirect liquefaction is a sort of condensing procedure of a gas mixture ($\text{CO}+\text{H}_2$) to produce liquid products in the present of catalysts. In fact indirect liquefaction is the other name of the classic gasification process. In the indirect liquefaction process firstly, biomass is gasified to syngas in the presence of partial O_2 /air at very high temperature more than $1000\text{ }^\circ\text{C}$ and then this gas mixture undergoes a catalytic reaction. In this reaction, Fe-, Co-, Ru- and Ni-based catalysts are mostly used at high temperature around $340\text{ }^\circ\text{C}$ or low temperature around $230\text{ }^\circ\text{C}$ to produce olefins and gasoline or diesel and linear waxes respectively [34].

2.5 Pyrolysis

Pyrolysis is defined as a thermochemical decomposition of biomass, either in total absence or limited supply of oxidizing agent that does not permit gasification. In other words, it allows the conversion of a biomass sample through the agency of thermal energy alone. It is worth noting that pyrolysis is not only a thermal conversion technology by itself, but also the first stage of both combustion and gasification. During pyrolytic process, long chains of carbon, hydrogen, and oxygen in the complex biomass macromolecules are broken down into smaller and simpler molecules, providing the three main products: gas, condensable vapors

(tars or oils), and char (solid residue). The proportion of these three products can vary depending on pyrolysis process and conditions. The main objective is obtaining products with better properties compared to the initial biomass. This is why especially the production of liquid bio-oil from fast pyrolysis in the last decades has attracted large attention [28].

Pyrolysis Process Types

Depending on the operating condition, pyrolysis can be classified into three main categories:

Slow, fast and flash pyrolysis. These differ in process temperature, heating rate, solid residence time, biomass particle size, *etc.* However, relative distribution of products is dependent on pyrolysis type and pyrolysis operating parameters as shown in Table (2.2) [35].

Table (2.2) Pyrolysis types [35]

Pyrolysis Process	Solid Residence Time (s)	Heating Rate (K/s)	Particle Size (mm)	Temp. (K)	Product Yield (%)		
					Oil	Char	Gas
Slow	450–550	0.1–1	5–50	550–950	30	35	35
Fast	0.5–10	10–200	<1	850–1250	50	20	30
Flash	<0.5	>1000	<0.2	1050–1300	75	12	13

2.5.1 Fast pyrolysis

Fast pyrolysis is a process in which very high heat flux are imposed to biomass particles, leading to very high heating rates, in the absence of oxygen. Biomass decomposes to generate vapours, aerosol and char. After cooling and condensation of the vapours and aerosol, a dark brown mobile liquid is formed which has a heating value of about half of the conventional fuel oil. Fast pyrolysis process produces 60-75wt% of liquid bio-oil, 15-25wt% of solid char and 10-20-wt% of non-condensable gas, depending on the feedstock used. No waste is

generated because the bio-oil and solid char can each be used as a fuel and the gas can be recycled back in the process. Fast pyrolysis uses much higher heating rates than slow pyrolysis. While slow pyrolysis is related to the traditional pyrolysis processes for making charcoal, fast pyrolysis is an advanced process, which is carefully controlled to give high yields of liquid. Research has shown that maximum liquid yields are obtained with high heating rates, at reaction temperatures around 500°C and with short vapour residence times to minimize secondary reactions. Very short residence times result in incomplete depolymerisation of the lignin due to random bond cleavage and inter-reaction of the lignin macromolecule resulting in a less homogenous liquid product, while longer residence times can cause secondary cracking of the primary products, reducing yield and adversely affecting bio-oil properties [36]. A fast pyrolysis process includes drying the feed to typically less than 10% water in order to minimise the water in the product liquid oil (although up to 15% can be acceptable), grinding the feed (to around 2 mm in the case of fluid bed reactors) to give sufficiently small particles to ensure rapid reaction, pyrolysis reaction, separation of solids (char), quenching and collection of the liquid product (bio-oil). Virtually any form of biomass can be considered for fast pyrolysis [30].

The essential features of fast pyrolysis process are:

- Very high heating and heat transfer rates, which usually requires a finely ground biomass feed: <1mm;
- Carefully controlled pyrolysis reaction temperature of around 500°C in the vapour phase, with short vapour residence times of typically less than 2 second;
- Rapid cooling of the pyrolysis vapours to give the bio-oil product [36].

2.5.2 Flash Pyrolysis of Biomass

Generally, flash pyrolysis is used to maximize high-grade bio-oil production from biomass. The flash pyrolysis process has been the subject of intense research since many years ago. The process is still under development and from the commercialization process point of view, the first step of the development of the flash pyrolysis process is to provide a liquid fuel that can replace fossil fuel oil in any static heating/combustion or electricity generation application such as boilers and turbines. The flash pyrolysis is an irreversible thermo-chemical process in which organic material is rapidly heated in the absence of oxygen, whereby the material is decomposed and can be separated into distinct fractions of liquid, char and gas. Ash is largely retained in the char, whereas the liquid fraction is a homogeneous mixture of organics and water commonly referred as bio-oil. The flash pyrolysis process typically applies operation conditions at a high heating rate (> 200 K/s up to 10^4 K/s), moderate temperatures (400-600 °C), and a short gas residence time (< 1 s) which allow the process to produce about 50-75 wt. % of liquid bio-oil, 15-25 wt. % of solid char and 10-20 wt. % of non-condensable gases from a wood feedstock. The water content of the bio-oil is usually limited to about 15-35 wt. %. Besides, a small particle size of the applied biomass and an efficient char removal before rapid condensation of the vapours (bio-oil) are required in order to maximize bio-oil production and reduce cracking [37].

2.5.3 Slow pyrolysis

Slow pyrolysis (conventional pyrolysis) has been used for thousands of years and is a thermal decomposition of biomass in the absence of oxygen or much less oxygen than is required for combustion [5]. To optimize the yield and quality of char, the following parameters are required:

- A reaction temperature in the region of 400-500°C for most biomasses;

- A slow heating rate (1-50°C/min) with large particle sizes typically < 5cm;
- A long vapour residence time: 5 - 30 minutes char contact time to promote secondary reactions.

The longer residence time causes the vapours to continue to react and allows secondary cracking of vapours (Vapors do not escape as rapidly as they do in fast pyrolysis). This reduces the organic liquid yield and increases the char and gas production. The slow heating rate, and large biomass particle size causes a temperature gradient which effectively lowers the pyrolysis temperature inside the particle. Dehydration and secondary reactions therefore become the dominant reactions thereby increasing the char yield. As the char zone becomes thicker during carbonisation, the thermal conductivity decreases and the resistance to heat transfer increases. The temperature gradient appears and gradually increases and the inner zone is more difficult to heat. A typical slow pyrolysis product distribution yields 35 wt% char, 30 wt% liquid, 35 wt% gas [20, 39].

2.5.4 Pyrolysis Products

Pyrolysis oil, solid char and non-condensable gases are the primary products of biomass pyrolysis, the fraction of each product can vary, depending on the operating conditions and types of biomass used [37].

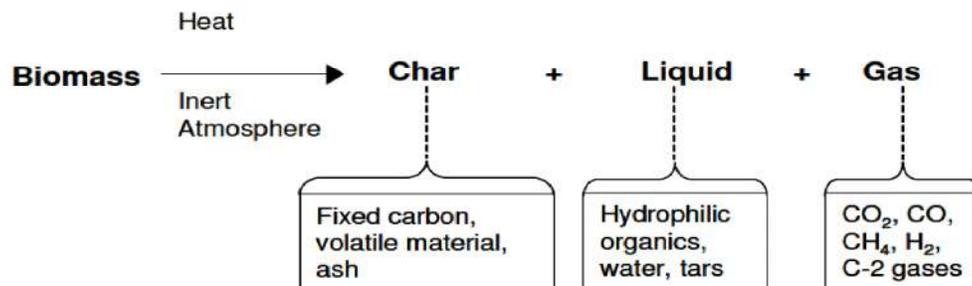


Figure (2.4) Pyrolysis products [50]

2.5.4.1 Bio-oil

Bio-oils are dark brown, free-flowing organic liquids that are comprised of highly oxygenated compounds and is immiscible with other hydro-carbonaceous fuels. The synonyms for bio-oil include pyrolysis oils, pyrolysis liquids, bio-crude oil (BCO), and wood liquids [38]. Because of the high oxygen and water content the heating value is significantly less than that of conventional fossil fuels. During combustion the water is evaporated which absorbs a significant portion of energy. Bio-oil is a complex mixture of different types and sizes of molecules derived from depolymerised lignocellulosic compounds [20]. Bio-oil yield increased with increasing pyrolysis temperature, higher heating rates caused an increase in the yield of liquid products because of reduced heat and mass transfer limitations, resulting in maximum oil yields .Bio-oil contains less amounts of oxygen content than that of the original feedstock. The decrease in oxygen content of the oil compared to the original feedstock is important, because the high oxygen content is not attractive for the production of transport fuels. The high oxygen content is indicative of the presence of many highly polar groups leading to high viscosities and boiling points as well as relatively poor chemical stability. Some ash remains in the bio-oil which can cause corrosion and increase instability due to catalytic effects [40].

Therefore the ash content should preferably be less than 0.1 wt% for use in engines .Hot gas filtration can be used to reduce the ash content to less than 0.01 wt% [20].

I. Fuel Applications of Bio-oils

Over the last two decades there has been a growing interest in using biomass-derived fuels. Initially this interest was driven by concerns for potential shortages of crude oil, but in recent years the ecological advantages of biomass fuels have become an even more important factor. Biomass fuels can be considered

essentially CO₂neutral and have a very low sulfur content compared to many fossil fuels. In addition, being a liquid, bio-oil can be easily transported and stored. However, the properties of bio-oil also result in several significant problems during its use as fuel in standard equipment such as boilers, engines, and gas turbines constructed for combustion petroleum-derived fuels. Poor volatility, high viscosity and corrosiveness are probably the most challenging and have so far limited the range of bio-oil applications. In addition, bio oil is not yet a commercial product and it lacks the quality standards necessary for commercial application. The variability of its composition due to different feedstocks, reactor configurations, and recovery systems that results in differences in physical and chemical properties as well as combustion behavior makes largescale applications even more difficult. However, compared to traditional biomass fuels such as black liquor or hog fuel, bio-oil presents a much better opportunity for high-efficiency energy production, and significant effort has been spent on research and development directed to the application of bio-oil for the generation of heat and power and for use as a transport fuel [40]. Commercial pyrolysis bio-oil should maintain its chemical and physical properties such as stability and viscosity. This can be achieved if the oil exhibits high inhomogeneity, processing lower molecular weight compounds. High molecular weight derived compounds present in pyrolysis oil come from the lignin monomers present in the biomass. Therefore biomass with less lignin content is desirable to reduce the heavier molecular weight compounds present in pyrolysis oil and produce a more homogenous liquid. Table (2.3) shows the comparison of fuel properties and composition between standard diesel oil and pyrolysis bio-oil for different feed stocks [35].

Table (2.3) properties of standard diesel oil and pyrolysis bio-oil for different feed stocks [35].

	C (wt%)	H (wt%)	N (wt%)	S (wt%)	O (wt%)
Diesel	86	11.1	1	0.80	0
Wood	55–58	5.5–7	0–0.2	0	35–40
Willow	43.17	7.15	0.10	0.10	49.49
Straw	28.2	8.78	0.10	0.10	62.83
Sweet grass	38.3	7.42	0.10	0.10	54.08
<i>Dactylis glomerata</i>	36.75	8.82	1.88	0.10	52.46
<i>Festuca arundiance</i>	32.05	9.76	1.41	0.10	56.69
<i>Lonium perenne</i>	30.64	9.63	0.77	0.10	58.86
Reed canary grass	38.42	7.89	0.10	0.10	53.49
Sesame stalk	61.69	7.96	29.37	0.98	-
Rapeseed	74.04	10.29	11.70	3.97	-
Miscanthus	48.1	5.4	42.2	0.5	.01
Cherry stone	46.9	7.9	45.1	0.1	-
Sunflower oil cake	66.5	9.2	4.5	19.8	-
Sugar cane bagasse	46.27	6.55	46.9	-	0.1–0.15

Bio-oil can be used as a substitute for fossil fuels to generate heat, power and chemicals. Short-term applications are boilers and furnaces somewhat longer term [35].

II. Furnaces and Boilers

Furnaces and boilers are commonly used for heat and power generation. Technologically they produce less efficient combustion compared to turbines and engines. On the other hand, furnaces and boilers can operate with a great variety of fuels ranging from natural gas and petroleum distillates to sawdust and coal/water slurries. Therefore bio-oil seems to be more suitable for boiler applications as long as it meets acceptable emission levels, economic viability and consistent quality characteristics.

Several studies have been conducted using pyrolysis bio-oil in boiler applications to replace heavy fuel oil. The important findings of these studies could be summarized as follows:

- Pyrolysis bio-oils have significantly different combustion characteristics compared to fossil fuels;

- Bio-oils with high viscosity and high solids and water content exhibit worse combustion performances in boilers;
- Different pyrolysis bio-oils differ in combustion behaviour and exhaust gas emissions;
- The flame from bio-oil combustion is longer compared to that of standard fossil oil;
- Harmful gas emissions from pyrolysis bio-oil in boiler applications are lower than from burning heavy fuel oils except for particulate levels;
- Some modifications of the burners and boilers are required for proper utilization of pyrolysis bio-oil in heat and power generation [35].

III. Applications of Bio-oil for Producing Chemicals

For many centuries wood pyrolysis liquids were a major source of chemicals such as methanol, acetic acid, turpentine, tars, etc. At present, most of these compounds can be produced at a lower cost from other feedstocks derived from natural gas, crude oil or coal. Though over 300 compounds have been identified in wood fast pyrolysis oil, their amounts are small and isolation of specific single compounds is seldom practical or economic as it usually requires complex separation techniques. Therefore, the development of technologies for producing products from the whole bio-oil or from its major, relatively easy separable fractions is the most advanced [40].

2.5.4.2 Syngas

Similar to char, about 10% to 35% of bio-gas is produced in slow pyrolysis processes. However, a higher syngas yield is possible in flash pyrolysis with high temperatures. The increase in reactor temperature increased the syngas flow rate which lasts for a shorter period of time and then reduces dramatically.

Moisture content influences the heat transfer process in pyrolysis, having an unfavourable effect on syngas production. High moisture content contributes to the extraction of water-soluble components from the gaseous phase, hence causing a significant decrease in gaseous products. Syngas mainly consists of hydrogen (H_2) and carbon monoxide (CO). It also contains small amount of carbon dioxide (CO_2), water, nitrogen (N_2), hydrocarbons such as CH_4 , C_2H_4 , C_2H_6 , tar, ash, *etc.*, depending on biomass feedstock and pyrolysis conditions. These components are obtained during several endothermic reactions at high pyrolysis temperatures. H_2 is produced from the cracking of hydrocarbons at higher temperatures. CO and CO_2 are the indicators of the presence of oxygen in the biomass. Those components mainly originate from the cracking of partially oxygenated organic compounds. However, the composition of syngas is clearly affected by the reactor temperature as shown in Figure (2.5). H_2 increases sharply and CO increases slowly with the increase of the temperature while other components show an opposite tendency [35]. The gas heating value from slow pyrolysis is around 10 – 15 MJ/Nm³ and varies in dependence on temperature and heating rate. Fast pyrolysis of biomass produces gas with a heating value around 14 MJ/Nm³ [41].

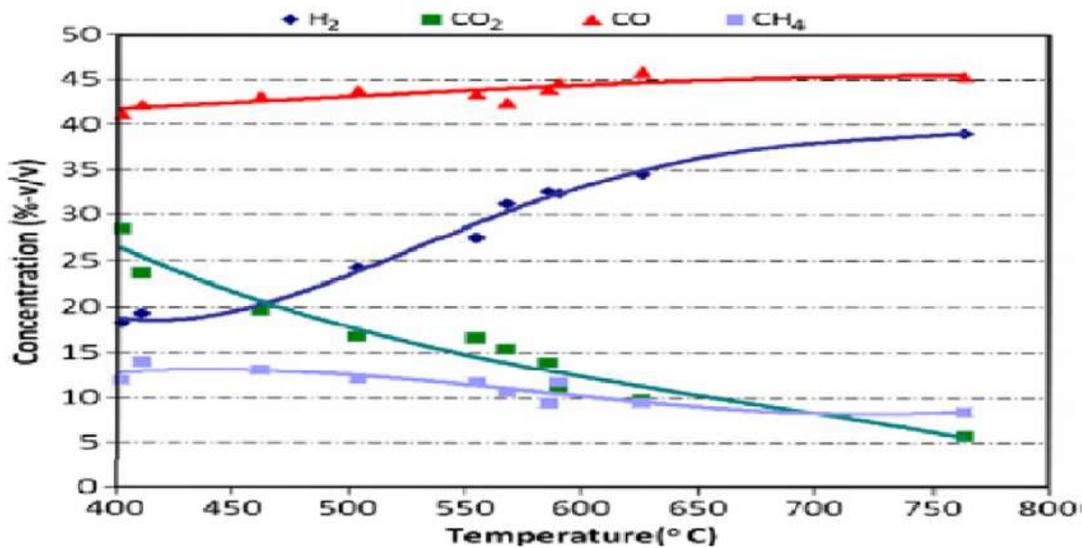


Figure (2.5) Gas composition of pyrolysis versus pyrolysis temperature [35]

Syngas from biomass pyrolysis could be a renewable alternative fuel for internal combustion (IC) engines and industrial combustion processes. Commercial petrol and diesel engines can be easily converted to use gaseous fuel for the use of power generation, transportation and other applications [35].

2.5.4.3 Biochar

Biochar (also called charcoal) is the major solid product, which contains unconverted organic solids and carbonaceous residues produced from the partial or complete decomposition of biomass components, as well as a mineral fraction. The physical, chemical, and mechanical properties of chars depend on the feedstock type and pyrolysis operating conditions. Slow pyrolysis (typical product yields: bio-oil 30 wt%, biochar 35 wt%, and gas 35 wt%) at pyrolysis temperatures ranging from 300 to 700 °C favours the production of biochar by reducing the yields of bio-oil [43]. The heating value of char obtained from pyrolysis of sugarcane bagasse is approximately 36 MJ/kg [41]. Depending upon composition and physical properties, bio-char can be utilised in various industrial processes such as: solid fuel in boilers, producing activated carbon, making carbon nanotubes, producing hydrogen rich gas, etc. [35]

Production of biochar, in combination with its storage in soils, has been suggested as one possible means of reducing the atmospheric CO₂ concentration. Biochar's climate-mitigation potential stems primarily from its highly recalcitrant nature. Which slows the rate at which photosynthetically fixed carbon (C) is returned to the atmosphere. In addition, biochar yields several potential co-benefits. It is a source of renewable bioenergy; it can improve agricultural productivity, particularly in low-fertility and degraded soils where it can be especially useful to the world's poorest farmers; it reduces the losses of nutrients and agricultural chemicals in run-off; it can improve the water-holding capacity of soils; and it is

producible from biomass waste. Of the possible strategies to remove CO₂ from the atmosphere, biochar is notable, if not unique, in this regard [43]. Preliminary results indicate that biochar bio-energy not only leads to a net sequestration of CO₂, but that the presence of biochar in soil may decrease emissions of two even more potent greenhouse gases, nitrous oxide (NO_x) and methane. The reason for the reductions in methane and NO_x emissions is not currently known. Lower nitrification is one potential mechanism, possibly due to lower mineralization resulting from a higher C: N ratio or lower carbon quality [44]. Figure illustrates the manipulated carbon cycle due to biochar carbon sequestration. Biochar is recalcitrant against decomposition and remains in the soil for centuries or millennia. Thus pyrolysis can transfer 50% of the carbon stored in plant tissue from the active to an inactive carbon pool. The remaining 50% of carbon can be used to produce energy and fuels. This enables carbon negative energy generation if re-growing resources are used. (I.e. with each unit of energy produced CO₂ is removed from the atmosphere) [45].

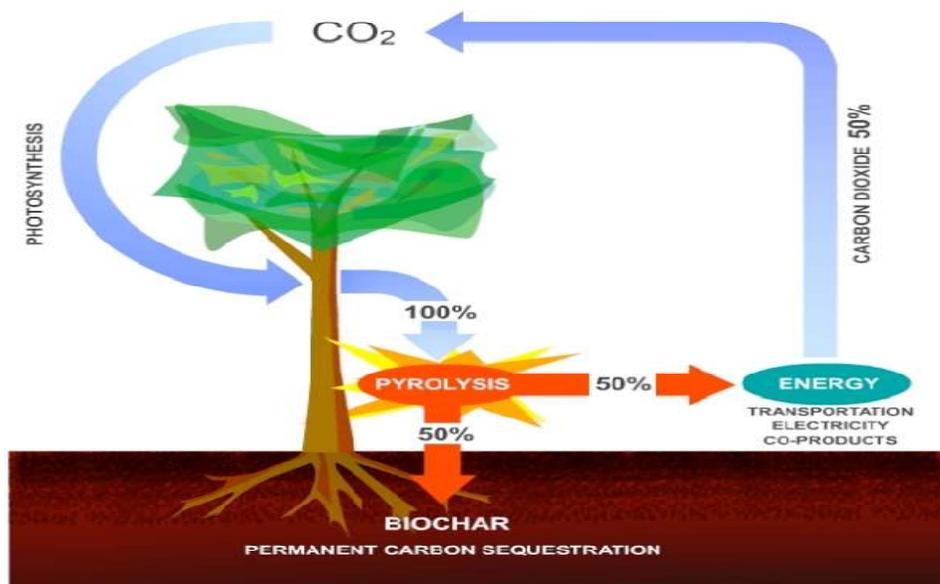


Figure (2.6) Biochar carbon cycle [45].

2.5.5 Factors Influencing Biomass Pyrolysis Products and technology requirements

Many studies have been carried out to determine the operating parameters that influence the distribution of pyrolysis products as well its composition. Temperature, biomass initial moisture content, ash content, particle size, heating rate, and type of biomass are variables that can affect the yield of the products [37].

2.5.5.1 Temperature

Temperature is the most influential process variable because it determines the final yield of the pyrolysis products. An increase in pyrolysis temperature increases the yield of gaseous and decreases char production. The maximum yield of liquid oil is usually achieved at a temperature in the range of 450 to 600°C and then drops with further increases in temperature. More hydrocarbons and olefins are produced in the gas at relatively high temperatures (> 650°C), suggesting that thermal cracking of higher hydrocarbons takes place at high temperature. Char yields decreases gradually with temperature to an almost constant value above 650 °C when the de-volatilization is almost completed [37]. Figure (2.7) shows the effect of temperature on pyrolysis products yield [20].

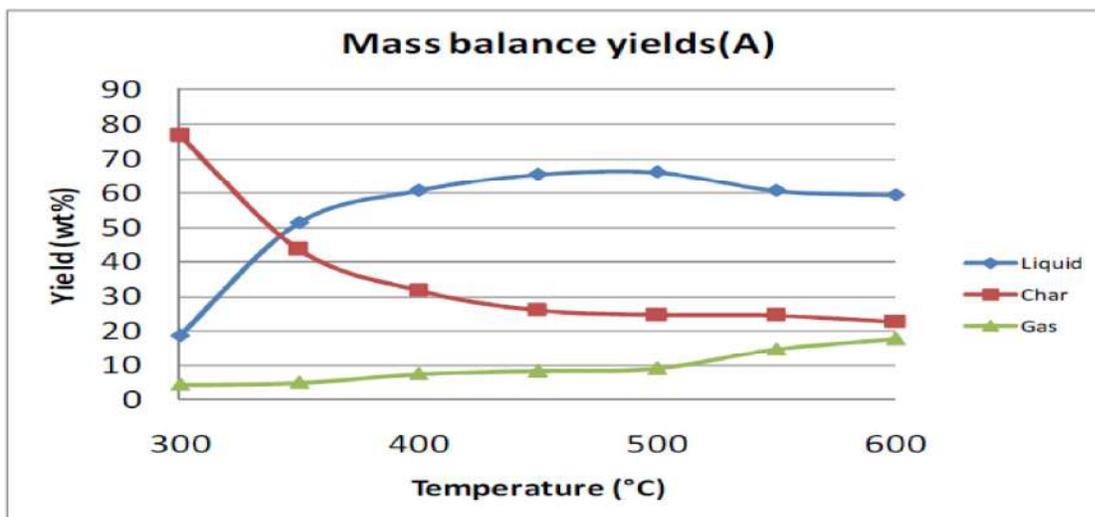


Figure (2.7) the effect of temperature on pyrolysis products yield [20].

2.5.5.2 Heating rate

Heating rate is a fundamental parameter that defines the type of biomass pyrolysis, i.e., flash, fast, and slow pyrolysis [42]. High heating rates caused a sharp increase in the yield of the liquid products due to heat and mass transfer limitations. Char yield decreased from 34.3 to 27.1% when heating rate increased from 5 to 700 °C/min [46].

2.5.5.3 Initial Moisture Content

The presence of moisture in wood waste (Woodex) material increased the char yield by as much as 5 wt% within the temperature range of 390 - 460 °C. The moisture also decreased the tar yield from ash-free Woodex by as much as 10 wt%. They proposed that the decrease in the tar yield and the increase in the char yield are probably due to the free-radical reactions between tar and moisture such as depolymerization and trapping. The formation of gases, however, was not affected by the presence of moisture [37].

2.5.5.4 Type of Biomass and Feedstock Ash content

The effects of different type of biomass on the pyrolysis products have been studied. Biomass is in general considered more reactive than coal upon pyrolysis. The wide variability of chemical and physical properties among different types of biomass, however, reflects in different reactivity. In addition to the biomass principal components, i.e., cellulose, hemicellulose and lignin, minor component such as ash also plays an important role in the pyrolysis process. The presence of mineral matters either as additives or natural ash content strongly affects the pyrolysis of biomass. Ash in biomass consists typically of K, Na, Mg, Ca, Si and minor amount of P, S, Fe, Al and MN. Of all the metals present in biomass, potassium has a pronounced catalytic effect on the pyrolysis reactions promoting

the char and gas formation at the expense of the tar yield with an enhancement in the activity of dehydration, decarboxylation and charring reactions [37].

2.5.5.5 Particle size

It is generally assumed that an increase in particle size causes greater temperature gradients inside the particle. Due to the temperature gradient, at a given time the temperature of the core is lower than the surface temperature. The cores of larger particles become carbonized, but cannot be decomposed completely, which results in an increase in char yield but a decrease in liquids and gases. Smaller particles provide a greater reaction surface and a high heating rate, which allows a quicker decomposition of the biomass. The highest char yield was obtained at the highest particle size ($D_p > 1.8$ mm) from slow pyrolysis of sunflower bagasse at 500°C, but there was no significant effect on the liquids yield[46].

2.5.5.6 Pressure

Pyrolysis pressure influences the size and shape of the char due to changes in the void fraction in the char. High pressure increases the rate of decomposition reactions and prolongs the residence time for vapour-particle interaction. Figure (2.8) shows the effect of pressure on char yield from slow pyrolysis of cellulose [46].

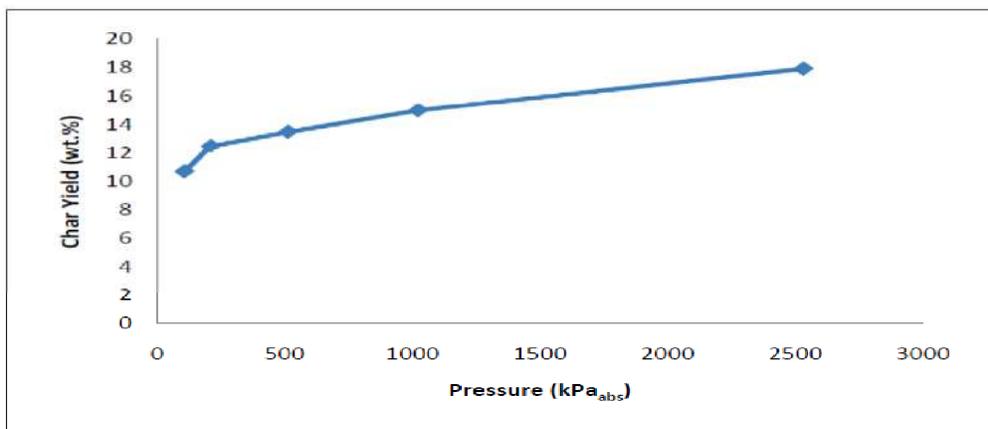


Figure (2.8). The effect of pressure on char yield of slow pyrolysis [47].

2.5.5.7 Char removal

Char acts as a vapour cracking catalyst so rapid and effective separation from the pyrolysis product vapours is essential. Cyclones are the usual method of char removal, however, some fines always pass through the cyclones and collect in the liquid product exacerbating the instability of the oil [48].

I. Cyclone separator

The gas cyclones belong to the type of centrifugal separators. A gas cyclone is a stationary mechanical device that utilizes centrifugal force to separate solid or liquid particles from a carrier gas. The flow enters near the top through the tangential inlet, which gives rise to an axially descending spiral of gas and a centrifugal force field that causes the incoming particles to concentrate along, and spiral down, the inner walls of the cyclone separator. The collected particulates are allowed to exit out an under flow pipe while the gas phase reverses its axial direction of flow and exits out through the vortex finder (gas outlet tube). Figure (2.9) shows a typical cyclone separator [49].

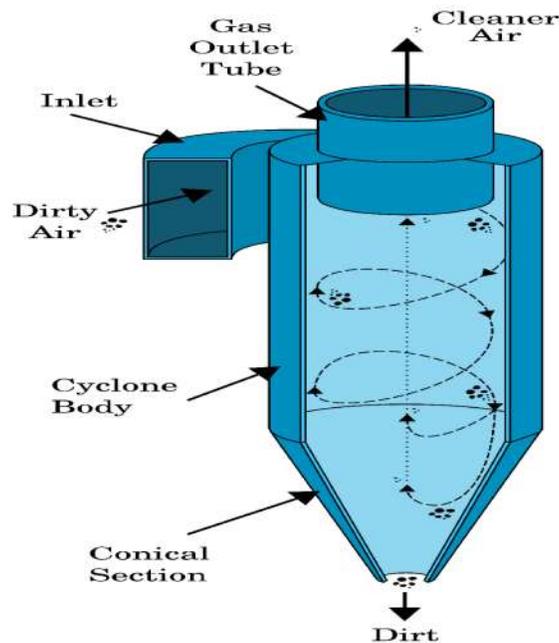


Figure (2.9) cyclone separator [49].

2.5.5.8 Liquids Collection

Vapour, aerosols and non-condensable gases are mainly available in pyrolysis gaseous products. These require rapid cooling to minimize secondary reactions and to condense the true vapours, while the aerosols require coalescence or agglomeration. The commonly used methods of this purpose are cooling with a simple heat exchanger [35].

2.6 Carbon and Energy Flows on Pyrolysis

To determine how pyrolysis processes and biochar systems may benefit climate change, through their effect on emissions of greenhouse gases, an understanding of carbon and energy flows is required.

Carbon is drawn from the atmosphere as carbon dioxide by growing plants through photosynthesis and assimilated into biomass. Under natural processes of death and decomposition the carbon is released as carbon dioxide back to the atmosphere in a fairly short timescale. Biomass has an energy value roughly related to its carbon content (together with contributions from other elements and factors). This energy can be released through combustion and used for purposes such as electricity generation or heating. The carbon is thermo-chemically oxidised to carbon dioxide and returns to the atmosphere. In this manner the energy available from biomass is considered renewable and carbon neutral. If the usable energy so produced substitutes energy that would otherwise be obtained by burning fossil fuels, then the carbon dioxide emission associated with the fossil fuel combustion is avoided.

If biomass is pyrolysed, the carbon and the energy value are split between the three product streams: char, liquid and gas. The total mass of the products will be equal to the mass of the starting material, if properly accounted, and the total carbon content of the products will also equal that of the biomass. However, some energy is inevitably lost as heat from the process meaning the total energy value in the

products is less than the starting material. Some energy is also required to run the pyrolysis process: to dry the feed, to heat to temperature, to drive equipment. In theory, all this can be supplied by recycle from the products, once the process has been started-up, with the effect that the product quantities available for use downstream of the pyrolysis process are reduced [50].

Current Studies on slow pyrolysis of sugar cane bagasse

In South Africa, Direct contact heat exchange performed well. A single phase bio-oil instead of fractionated product was obtained. The maximum amount of bio-oil was produced at a heating rate of 15 °C min⁻¹ for processes. The optimum temperatures were 500 and 450 °C for SP (slow pyrolysis), SP (slow pyrolysis) produced char with the highest HHV (28 MJ/kg) at a temperature range of 450-600°C.

- [PYROLYSIS OF SUGARCANE BAGASSE *by* Thomas Johannes Hugo]

The study of pyrolysis experiments of grape bagasse were carried out in a fixed-bed reactor in order to investigate the effects of pyrolysis temperature, and heating rate, the maximum oil yield was obtained at a final pyrolysis temperature of 550°C, a heating rate of 50 °C /min.

The bio-oil was identified and presented as a bio-fuel candidate. The bio-oil may be used as a source of low grade fuel directly, or it may be upgraded to higher quality liquid fuels by the application of various processes (such as cracking and hydrogenation), this study was conducted in Turkey.

- [Bioresource Technology 102 (2011) 3946–3951, _I. Demiral, E.A. Ayan / Bioresource Technology 102 (2011) 3946–3951]

In China, the study of pyrolysis of sugarcane bagasse was carried out in affixed-bed reactor. The bio-oil got the highest yield of 56.12 wt% and the high heating value of the bio-oil was 26.4 MJ/kg, The analysis of bio-oil compositions showed that the Bio oil from pyrolysis of the blends could be a potential source of renewable fuel with lower content of acid, ketone, aldehyde, phenolic compounds and higher content of hydrocarbon, alcohol, ester compounds.

- [Energy Conversion and Management 120 (2016) 238–246, M.-Y. Hua, B.-X. Li / Energy Conversion and Management 120 (2016) 238–246].

The temperature and bed material played an important role in the yields of pyrolysis products. The gas yields increased with temperature for all combinations of the variables. The liquid yield reached its maximum value at 500°C for almost all combinations of variables, this study was conducted in Brazil.

- [Journal of Analytical and Applied Pyrolysis xxx (2016) xxx–xxx, F.L. Mendes et al. / Journal of Analytical and Applied Pyrolysis xxx (2016) xxx–xxx]

In India, the yield of bio-oil was found to be increased upon increasing the temperature from 400 °C to 500 °C, whereas further increment of temperature, (e.g. above 500 °C) reduce the yield of bio-oil. At higher temperature, reduction in bio-oil occurs due to formation of gaseous fraction at the expense of liquid fraction.

Sugarcane trash was obtained from local sugarcane farm located near Bardoli, Gujarat, India. It was freed of physical impurities, dried for 24 hours at 110°C, Its density, heating value, moisture and carbon content was 340 kg/m³, 18.5 MJ/kg, 5% and 50.4 %, respectively.

- [Pyrolysis of Sugarcane Trash for the Production of Bio-Oil, Y. C. Rotliwala Head Chemical Engineering Department S. N. Patel Institute of Technology Bardoli-394 345, India, P. K. B ebara Scientist C Central Pollution Control Board Delhi-110 032, India].

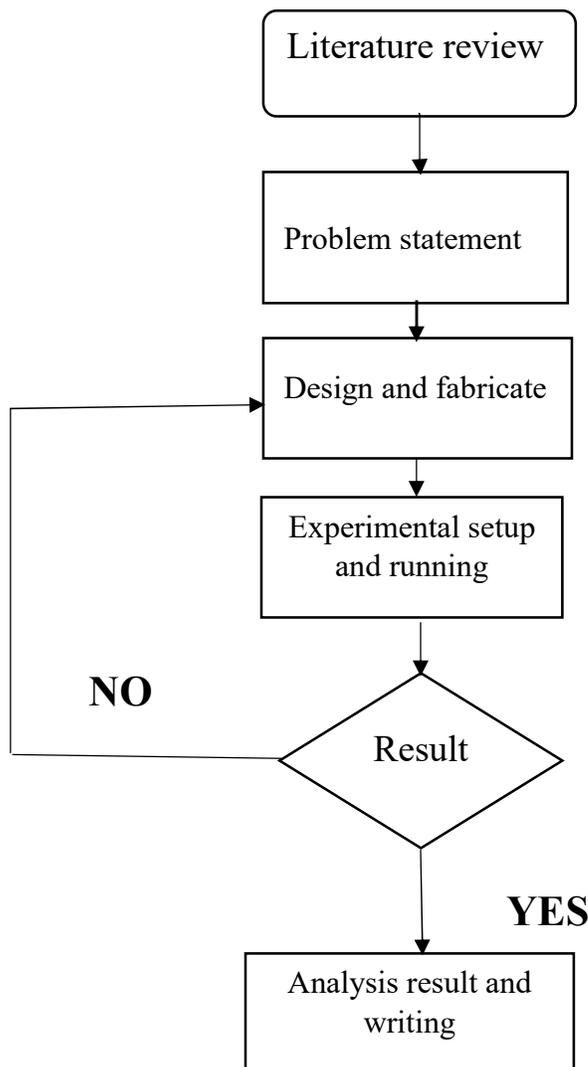
Chapter three

Methodology of the project

3.1 Introduction

Pyrolysis and other thermochemical conversion processes offer an important opportunity for the utilization of the biomass from agricultural and forestry residues. However, the pyrolysis process is regarded as a promising process for the biomass utilization. Pyrolysis of biomass can be described as the direct thermal decomposition of the material in the absence of oxygen to obtain a collection of solid, liquid and gas products.

3.2 Flow chart



3.3 Design of testing rig

The device used in this study (pyrolysis system) is shown in figures (3.1)

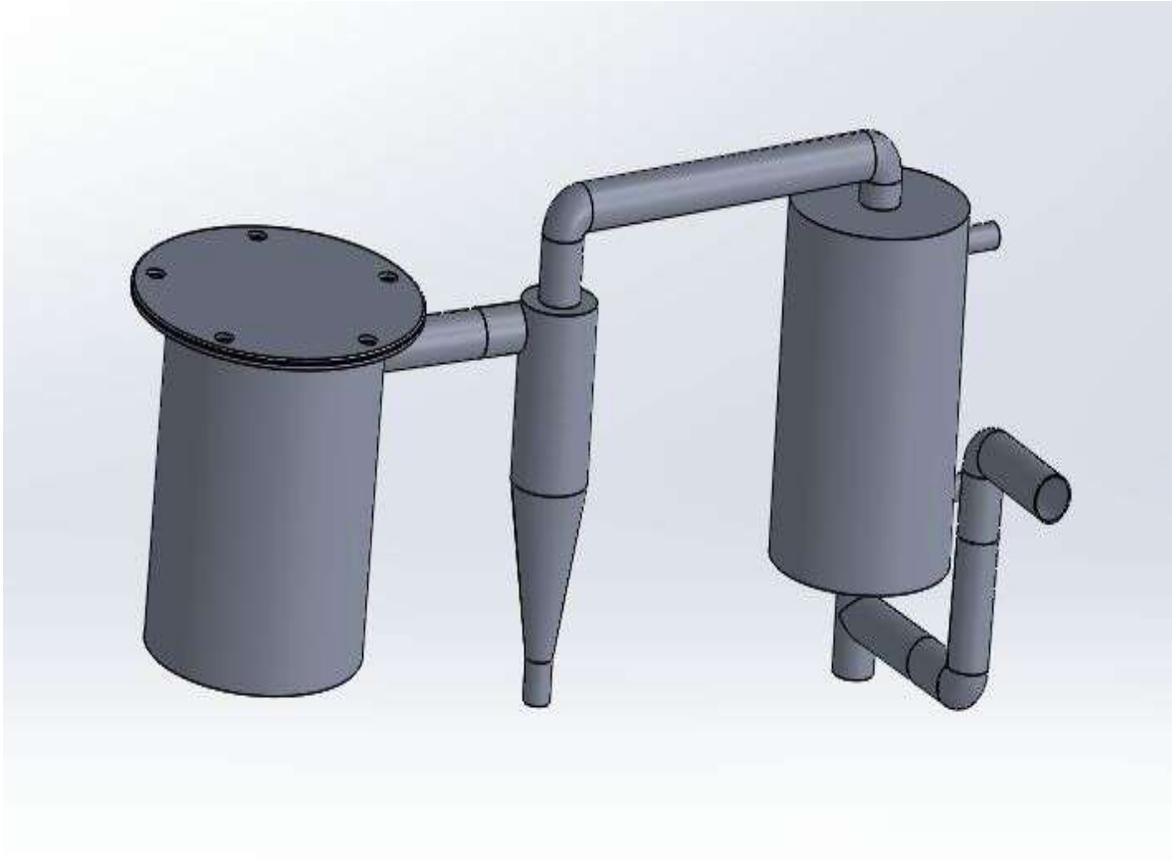


Figure (3.1) shows a model for pyrolysis system designed by solidworks.

The testing device is consist of many components as follows

- **Pyrolysis reactor**
- **Cyclone separator**
- **Cooling system**
- **Pipes**

3.3.1 Pyrolysis reactor

The reactor was made from a metal with high melting point and 8mm thickness to resist the high temperature at which it exposed. The dimensions of the reactor is 27.5cm internal diameter and 40cm height. The bagasse particles located inside the reactor and the volatile particles leave the reactor through tube connected to the upper part of the reactor as shown in figure (3.2).

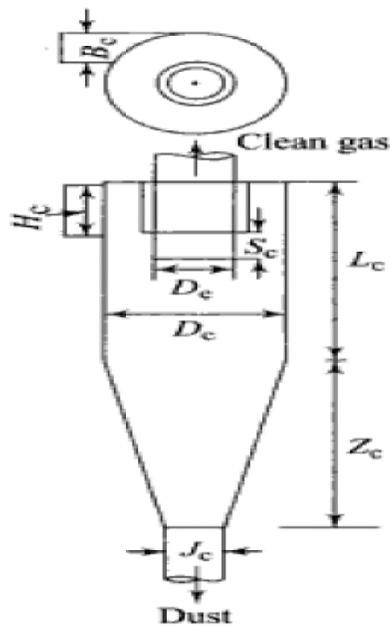


Figure (3.2) Pyrolysis Reactor

3.3.2 Cyclone separator

Cyclone separator is a device used to separate particles from gas, as discussed in chapter two.

3.3.2.1 Dimensions of a standard cyclone



$$D_c = 10\text{cm approximately.}$$

$$L_c = 2D_c = 20\text{cm.}$$

$$Z_c = 2D_c = 20\text{cm.}$$

$$S_c = D_c/8 = 1.25\text{cm.}$$

$$J_c = D_c/4 = 2.5\text{cm.}$$

$$D_e = D_c/2 = 5\text{cm.}$$

$$H_c = D_c/2 = 5\text{cm.}$$

Figure (3.4) cyclone standard dimensions [46].



Figure (3.5) cyclone separator

3.3.3 Cooling system

The main purpose of this device is to clean the syngas by reject the condensable gases, so we used a double pipe arrangement heat exchanger (1-1 counter flow) with dimensions of 5cm for the inner diameter, 10cm for the outer diameter and 45cm height. The hot flowed gases that coming from the reactor, passing through the cyclone separator, flows on the inside of the smaller tube, while the cooling water flows in the annular space between the two tubes, in order to condense the condensable gases and let the rest (incondensable gases) to flow.



Figure (3.6) cooling system.

3.3.4 Pipes

The purpose of pipes is to transfer flowed gases through the all component of the system and it must resist high temperature, steel pipes are used and the diameters of them are (1 inch to 2 inches). The length of the pipes as follow (15cm from the reactor to the cyclone – 50cm from cyclone to the cooling system).

3.4 Samples preparation

The sugarcane bagasse is one of the most biomasses abundant in Sudan, in this study sugarcane bagasse was supplied from Kenana and White Nile sugar factories with very high moisture content of (50-52) %. Before the pyrolysis process, the sugarcane bagasse was dried by the direct sun light and atmospheric air about 10 days to reduce the moisture content of (5-15) %.



Figure (3.7) Drying of bagasse

3.5 Test procedure

For this experiment we preferred to use slow pyrolysis process. The slow pyrolysis was performed in system prepared locally in a good external workshop and was brought to the university campus.

In a typical experiment, a briquette of bagasse was introduced into the reactor at room temperature (40°C), and after the air has been tightened and properly closed within the reactor, heating was started. The following experimental steps has been conducted:

- Step (1): A total of 750 gram of biomass [sugar cane bagasse] was loaded in the reactor.
- Step (2): After loading the sugar cane bagasse, the reactor was fully closed and the heating system was turned on.
- Step (3): The temperature started to increase with time, during that the vapor was beginning to evaporate after a few mints.
- Step (4): The total time that required for the first experiment was 50minutes.
- Step (5): After 50 minutes, the outside temperature of the reactor was measured by putting a thermocouple type-K at the top of the reactor cover.
- Step (6): After 50minutes the sensor of gas analyzer has been located on the gas outlet, and four (4) results were recorded in intervals of 5mins each, taking into account that the syngas outlet was closed after each reading.
- Step (7): Samples were taken from the produced tar and bio-oil, and were sent to an outside laboratory. The results were recorded in Chapter Four.

The experiment was carried out twice for the two samples of bagasse, the first is the sample of White Nile sugar, and the second is the sample of Kenana sugar.

Chapter four

Results and discussion

4.1 Introduction

This chapter presents the experimental results as well as discussion of these results with regard to the production yields

4.2 Results

4.2.1 Design of testing rig

The device that has been used for the pyrolysis process is made from metal tubes with high thermal resistant, and different diameters that suit each and every work of the device parts.



Figure (4.1) Testing rig for slow pyrolysis of sugarcane bagasse

4.2.2 Experimental results

In the pyrolysis experiment of the White Nile bagasse, the results were as follow:

A homogeneous dark brown (semi black) liquid, a black high density tar, gas with blue flame when burned, and dark brown bio-char with some substances that has not been decomposed as remaining within the reactor after the slow pyrolysis process is completed.

In the pyrolysis experiment of Kenana bagasse, the results were as follow:

A homogeneous dark brown (semi black) liquid similar to the White Nile produced liquid, but a bit more quantity, a black high density tar, gas with blue flame when burned, and less quantity than the White Nile of dark brown bio-char with some substances that has not been decompositioned as remaining within the reactor after the slow pyrolysis process is completed.

4.2.2.1 Analysis of gas

Gas analysis was carried out using Kane gas analyzer which measure carbon monoxide (CO), unburnt hydrocarbons (HC), carbon dioxide (CO₂) and nitric oxide (NO). The results of gases analysis from pyrolysis of White Nile and Kenana bagasse samples are shown in figures below.

Figure (4.2) shows and compare CO₂ emissions between White Nile and Kenana bagasse samples with time. X axis shows the time, Y axis shows carbon dioxide emissions per volume. It is observed that the amount of emitted carbon dioxide from pyrolysis of Kenana bagasse started with high emission level, but it gradually decrease by time. While the amount of emitted carbon dioxide from White Nile bagasse started from low level of carbon dioxide emission, and gradually increased by time.

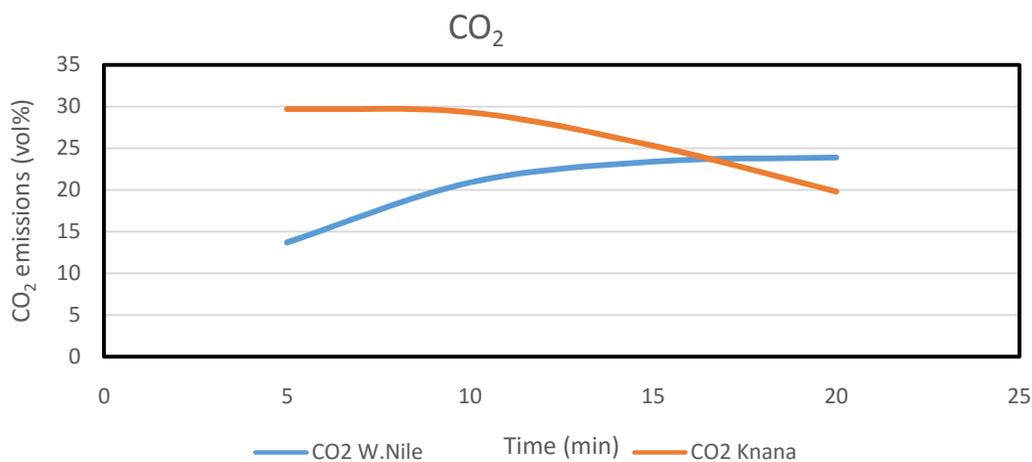


Figure 4.2 CO₂ emissions from slow pyrolysis for sugar cane bagasse

Figure (4.3) shows and compare NO emissions between White Nile and Kenana bagasse samples with time. X axis shows the time, Y axis shows nitric oxide emissions by part per million.

The ratio of NO emission used is part per million (ppm). The observation were that again in the case of Kenana bagasse it started steadily high for some time, and then gradually decreased. While, in the case of White Nile bagasse the emission of NO started at low level (nearly half Kenana emission) with a continuous increase by time, the emission level reached by White Nile bagasse was very close to the start level of Kenana bagasse NO emission.

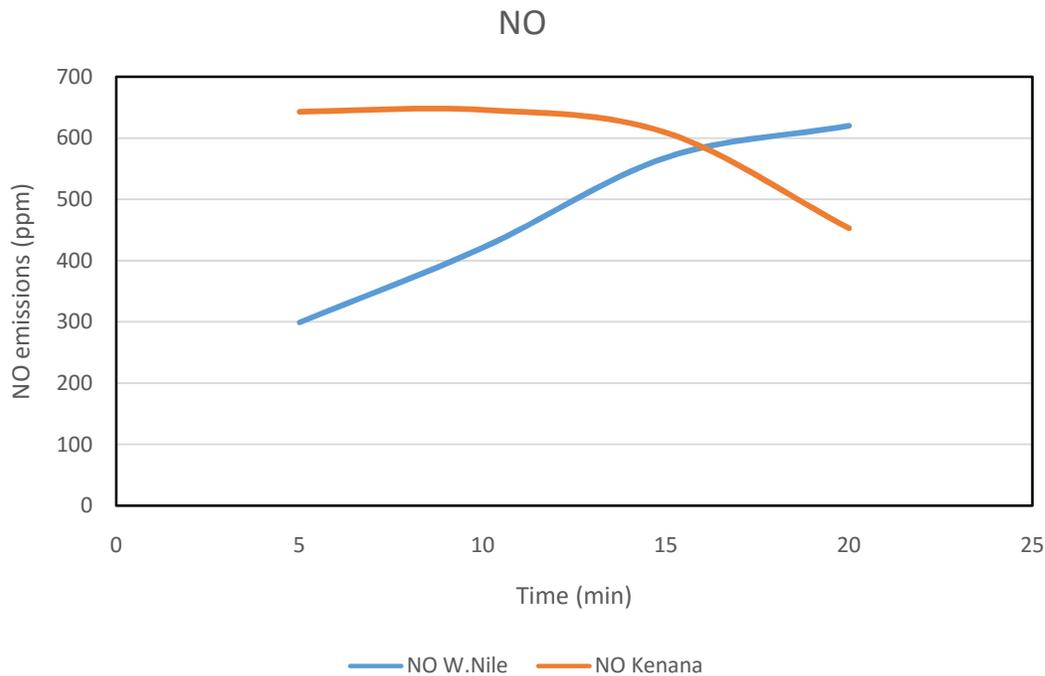


Figure 4.3 NO emissions from slow pyrolysis

Figure (4.4) shows and compare CO emissions between White Nile and Kenana bagasse samples with time. X axis shows the time, Y axis shows carbon monoxide emissions per volume. In Kenana bagasse CO emission level, it started quite high with a slight increase in the first few time intervals, but afterwards it started and continued to decreased gradually by time. In the White Nile bagasse, the CO emission level started slightly at low level, then a continuous somewhat sharp increase with compare to Kenana bagasse CO emission, then a slight decrease by time at a slower base. As seen from the graph, the emission of CO from White Nile bagasse remain lower than Kenana CO emission through the provided experiment time.

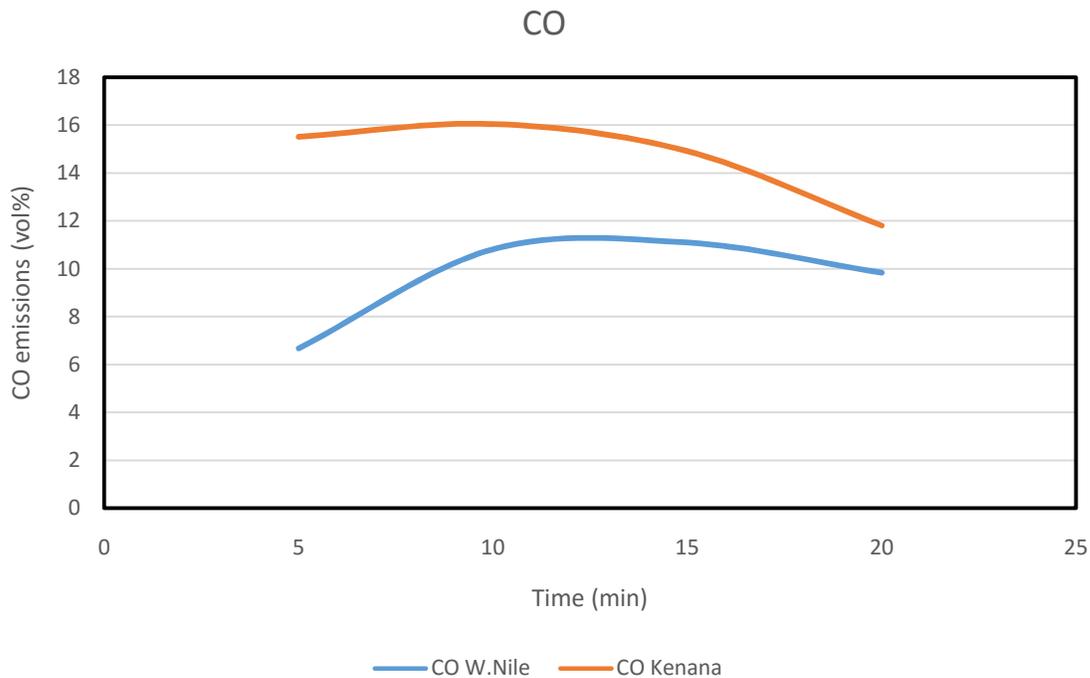


Figure 4.4 CO emissions from slow pyrolysis

Figure (4.5) shows and comparing of HC emissions between White Nile and Kenana bagasse samples with time, X axis shows the time, Y axis shows hydrocarbon emissions by part per million.

For Kenana bagasse HC emission level, it started slightly higher than the White Nile bagasse HC emission, then a semi-sharp increase until it reach the peak at the mid of the experiment time, then a slight decrease to the end of the experiment. For the White Nile bagasse HC emission, it follows the same trend but at the increasing part in the White Nile bagasse HC emission is less than the increase of Kenana HC emission. Also, for the HC emission of the White Nile bagasse, it didn't tend to decrease but rather reach a nearly flat emission level. Hydrocarbons emissions is the most important produced syngas from pyrolysis process due to its ability to flame. When igniting the produced syngas, a clear blue flame has been obtained. The gas analyzer used in the experiment, gives the total of all hydrocarbons produced from the pyrolysis process.

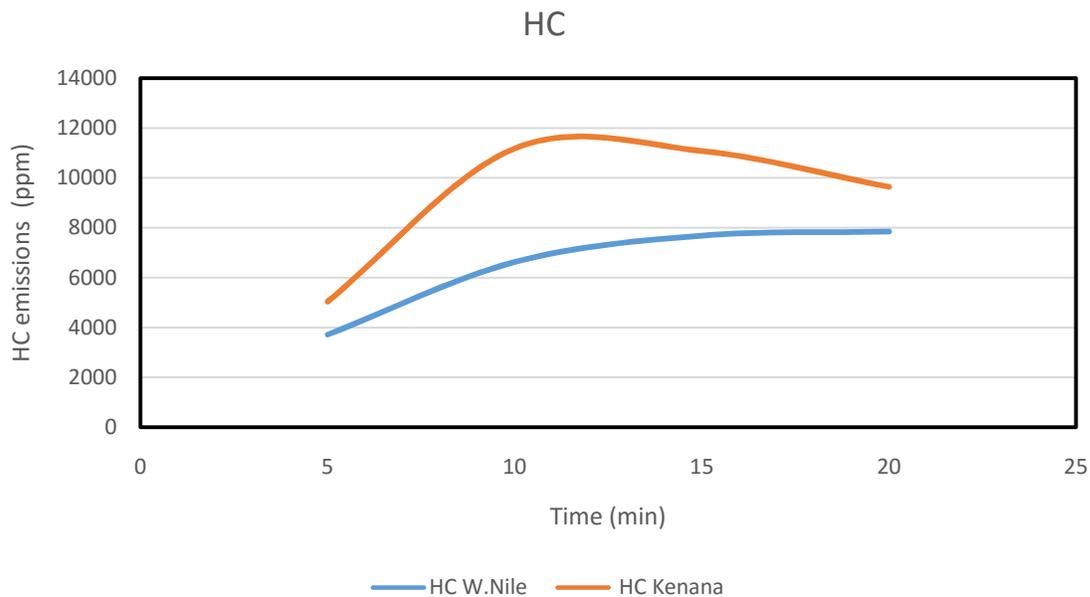


Figure 4.5 HC emissions from slow pyrolysis

The observed difference in the percentage of syngas emissions for Kenana and White Nile bagasse, is due to the difference in the soil, as well as the different irrigation mechanism.

4.2.2.2 Analysis of bio oil

- **Physical analysis**

The produced liquid oil from the slow pyrolysis of sugar cane bagasse, is divided to two types, bio-oil and tar, as stated before.

The yield liquids has been sent to the central laboratory for technical services and calibration, to analyze physical properties. The results are shown in the table (4.1) and (4.2) below, it has been observed that the calorific value is equal to (41.67 Mj/kg), which is more than the calorific value of all the previous studies that has been covered. The possible reason is the low level of water and humidity in the bio-oil.

Table (4.1) Sample (A) bio-oil

NO	Test	Test method	Result	Unit
1	Density@15°	ASTM D4052	1.07925	g/cm ³
2	Calorific value	Calorific value	41675.24	Kj/ Kg

Table (4.2) Sample(B) tar

NO	Test	Test method	Result	Unit
1	Density@15°	ASTM D4052	1.1309	g/cm ³
2	Calorific value	Calorific value	40671.56	Kj/ Kg

- **Chemical analysis**

Chemical analysis of bio oil was carried out using GC/MS, the result of analysis showed that the bio oil produced from slow pyrolysis process consist of 10 major components with intensity as shown in figure (4.2).

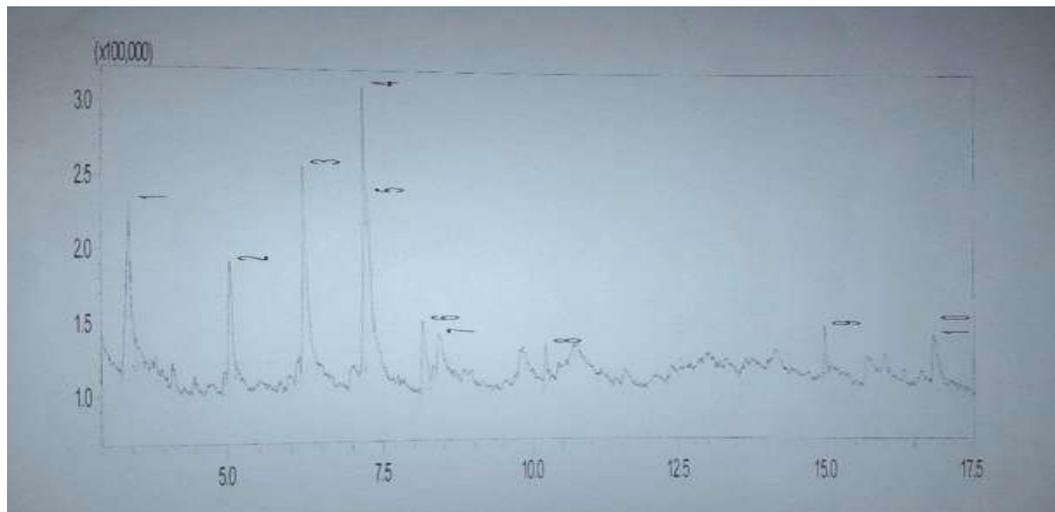


Figure (4.2) GC-MS chromatograms of aqueous phase and oil fractions

Table (4.3) the chemical components of bio oil.

peak	R.Time	Area	Area%	Name	Formula
1	3.436	633608	18.88	Propanoic acid	$C_3H_6O_2$
2	5.006	324113	9.66	Cyclopentanone	C_5H_8O
3	6.171	735973	21.93	2-Cyclopenten-1-one	C_5H_6O
4	7.150	555911	16.57	1-Hexanol	$C_6H_{14}O$
5	7.207	378610	11.28	Isobutyl acetate	$C_6H_{12}O_2$
6	8.114	234661	6.99	2Cyclopenten-1-one,2-methyl-	C_6H_8O
7	8.384	156806	4.67	Butanoic-acid 4hydroxy-	$C_4H_8O_3$
8	10.205	73270	2.18	1-Decene	$C_{10}H_{20}$
9	15.002	79530	2.37	1-Dodecanol	$C_{12}H_{26}O$
10	16.850	183307	5.46	1-Decanol	$C_{10}H_{22}O$
		3355789	100		

4.3 Testing mass balance

Table (4.3) Distribution of pyrolysis product yield from Kenana bagasse

	Mass (kg)	Mass wt%
Biomass	0.75	100%
Char	0.383	51%
Bio oil	0.060	8%
Tar	0.097	13%
Gas + Losses	0.21	27.9

Table (4.4) Distribution of pyrolysis product yield from White Nile bagasse

	Mass (kg)	Mass wt%
Biomass	0.75	100%
Char	0.422	56.2%
Bio oil	0.046	6.14%
Tar	0.066	8.8%
Gas + Losses	0.216	28.8%

The mass of the produced syngas has not been calculated, because of the difficulty of measuring the flow rate of the syngas produced, and there were losses due to a small leakage in the reactor, and in addition to losses in pipes.

Chapter five

Conclusion and recommendation

Conclusion and Recommendations

This study was focused on bio-oil and syngas composition that was produced from slow pyrolysis of sugar cane bagasse at time equal to (50 min) in two samples of bagasse, Kenana and White Nile respectively.

5.1 Conclusions

- The design and fabricate for the device was done to comply with the slow pyrolysis process, as intended, and the device is turned on to give the results, the result of slow pyrolysis of biomass (sugar cane bagasse) in both samples were bio-oil, tar, bio-char, and syngas. The major component is the bio-char of four products, since the volume and the process was slow pyrolysis.
- Analysis of the resulting syngas shows the presence of CO₂, CO, NO, and HC emissions, the volumetric ratio for CO₂ and CO emissions, is lower than the volumetric ratio of CO₂ and CO emissions, observed in previous studies.
- In addition, the physical analysis of bio-oil and tar obtained from slow pyrolysis process, were analyzed, and it is notes that the high amount of calorific values, compared to the values reached in other countries in previous studies, as mentioned at the end of chapter two. This increase in calorific value may be due to low water content in bio-oil, shown by the previous point, in the low level of oxygen, and therefore, the low level of water content. While the chemical analysis of bio-oil was performed by a GC/MS device, and the results were ten (10) chemical compounds, similar in their chemical composition to the chemical composition of the diesel.
- Carbon dioxide (CO₂) emissions from biomass burning when is used as fuel, equal to the amount of carbon dioxide (CO₂) withdrawn from the atmosphere by plants during photosynthesis. This shows that there is no-

increase in carbon dioxide (CO₂) emissions in the air, as opposed to burning fossil fuels.

5.2 Recommendations

- Its recommend to reduce the size of the compound pipes of the device, to increase the amount of syngas produced, and must take into consideration the rules of Gas dynamics in line with the device design to reach the most ideal settings to insure the maximum possible amount of syngas and bio-oil that can be produced from the process.
- The experiment should be carried out in less air as much as possible, to ensure that the process was performed in the absence of oxygen, and thus obtain good results, and increase in the amount of syngas produced.
- The cooling system must be designed to insure maximum heat transfer, and thus increase the bio-oil produced.
- To get out fuel (diesel and gasoline) it must crack the bio-oil by hydro-treatment (hydrogenation) and carbonization.
- Also it's recommended to improve the design of the device to operate in a fast pyrolysis process.
- In addition, it is recommended to use catalysts in the process of pyrolysis, to guide the process towards the desired results.

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Appendix

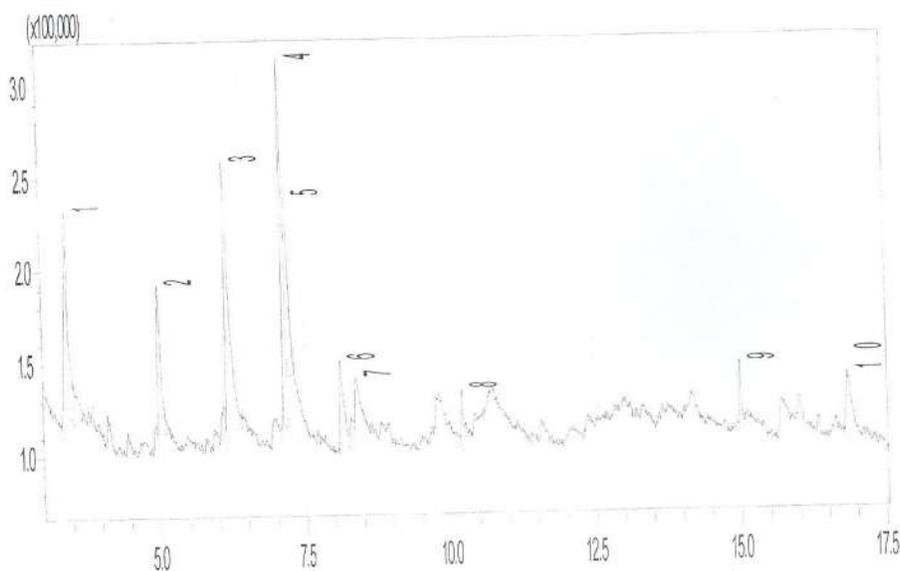


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Analyzed by : Babekir Siddig
Sample Type : Hydrocarbons
Sample Name : Bio oil
Customer name : Almuiz Ebrahim
Date : 24/10/2017

GC, MS Analysis



General manager:

Assoc.Prof.Dhia Eldien A/Elmagied

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Figure (A, 1) chemical analysis by GC/MS (1)

Peak Report TIC				
Peak#	R.Time	Area	Area%	Name
1	3.436	633608	18.88	Propanoic acid
2	5.006	324113	9.66	Cyclopentanone
3	6.171	735973	21.93	2-Cyclopenten-1-one
4	7.150	555911	16.57	1-Hexanol
5	7.207	378610	11.28	Isobutyl acetate
6	8.114	234661	6.99	2-Cyclopenten-1-one, 2-methyl-
7	8.384	156806	4.67	Butanoic acid, 4-hydroxy-
8	10.205	73270	2.18	1-Decene
9	15.002	79530	2.37	1-Dodecanol
10	16.850	183307	5.46	1-Decanol
		3355789	100.00	

Figure (A, 1) chemical analysis by GC/MS (2)

Instrument Information's:-

- Name : GC.MS
- Detector : Mass spectrometer
- Model : GC.MS-QP2010 Ultra
- Company : Shimadzu
- Country : Japan
- Column : Rtx-5MS...Length (30 m)...Diameter (0.25 mm)...Thickness (0.25 μl).
- Carrier gas : Helium
- Serial Number :020525101565SA

Figure (A, 1) chemical analysis by GC/MS (3)

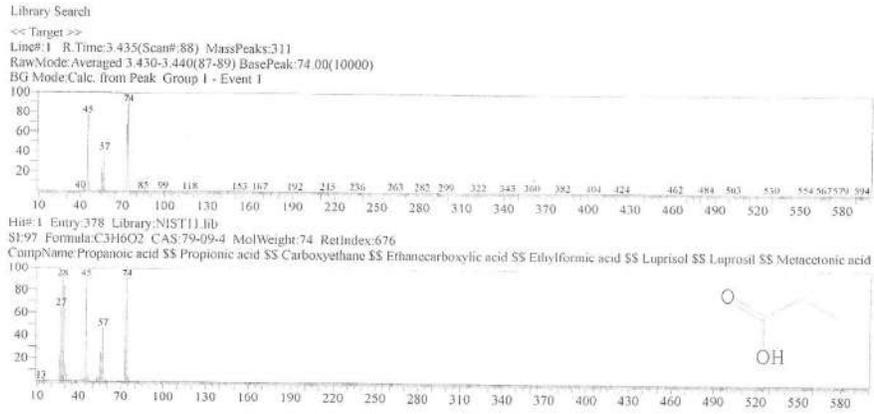


Figure (A, 1) chemical analysis by GC/MS (4)

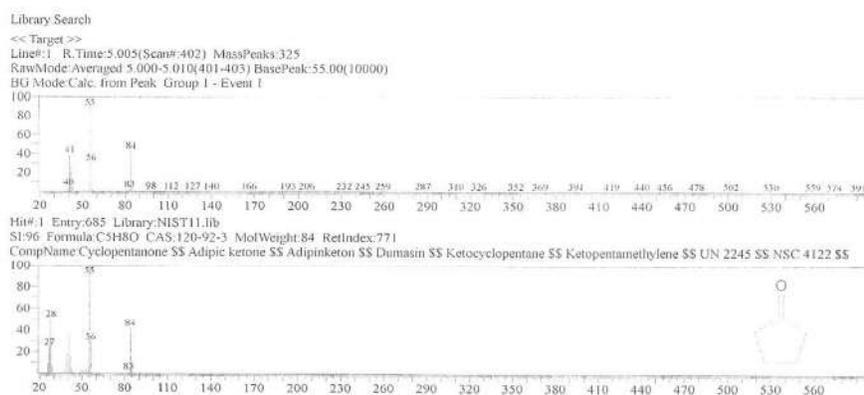


Figure (A, 1) chemical analysis by GC/MS (5)

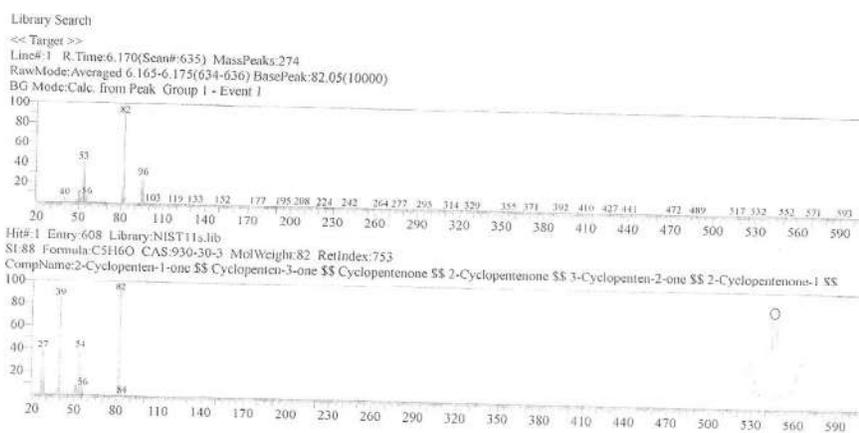


Figure (A, 1) chemical analysis by GC/MS (6)

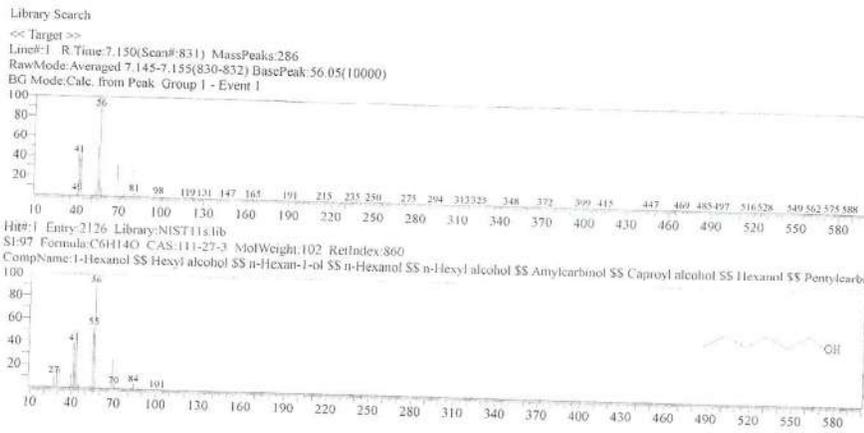


Figure (A, 1) chemical analysis by GC/MS (7)

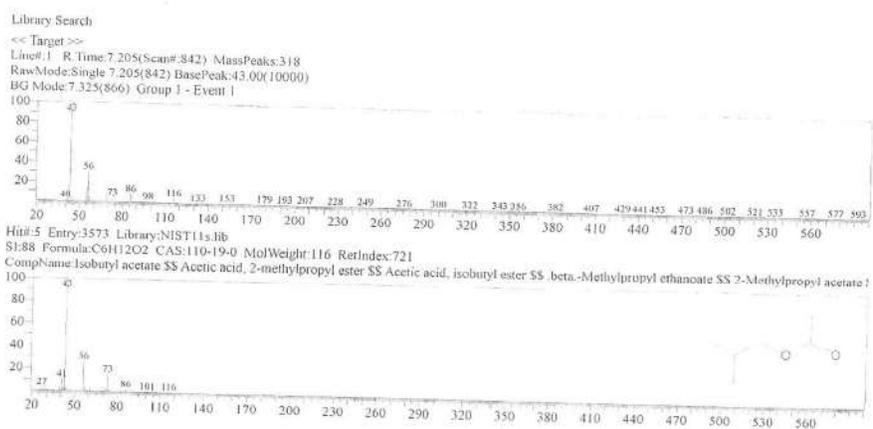
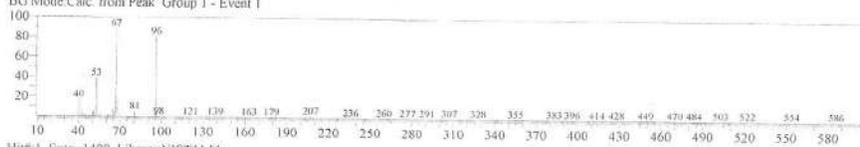


Figure (A, 1) chemical analysis by GC/MS (8)

Library Search

<< Target >>

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RawMode:Averaged 8.110-8.120(1023-1025) BasePeak:67.05(10000)
BG Mode:Calc. from Peak Group 1 - Event 1



Hit#:1 Entry:1400 Library:NIST11.lib
S1:96 Formula:C6H8O CAS:1120-73-6 MolWeight:96 RetIndex:843
CompName:2-Cyclopenten-1-one, 2-methyl- $\delta\delta$ 2-Methyl-2-cyclopentenone $\delta\delta$ 2-Methyl-2-cyclopenten-1-one $\delta\delta$

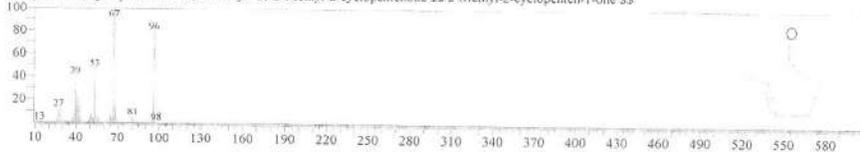


Figure (A, 1) chemical analysis by GC/MS (9)

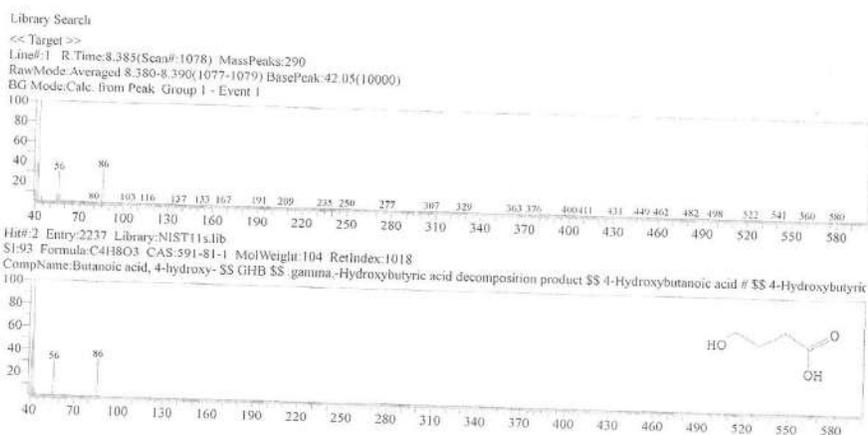


Figure (A, 1) chemical analysis by GC/MS (10)

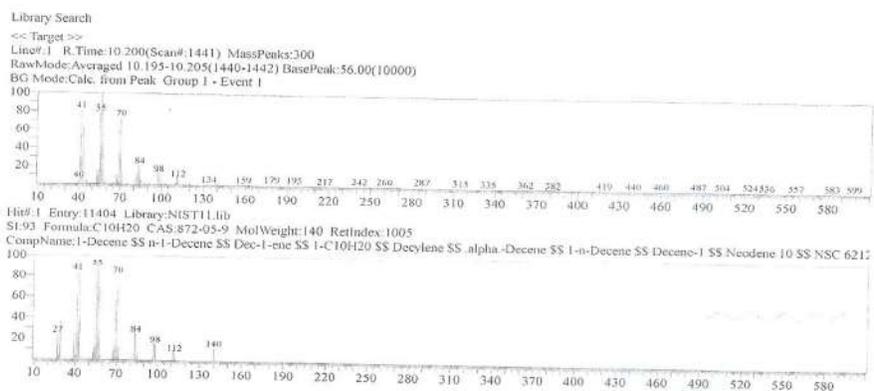


Figure (A, 1) chemical analysis by GC/MS (11)

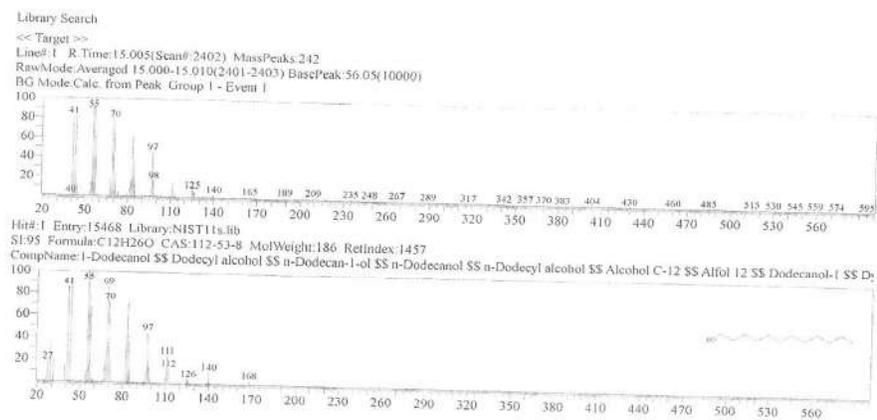


Figure (A, 1) chemical analysis by GC/MS (12)

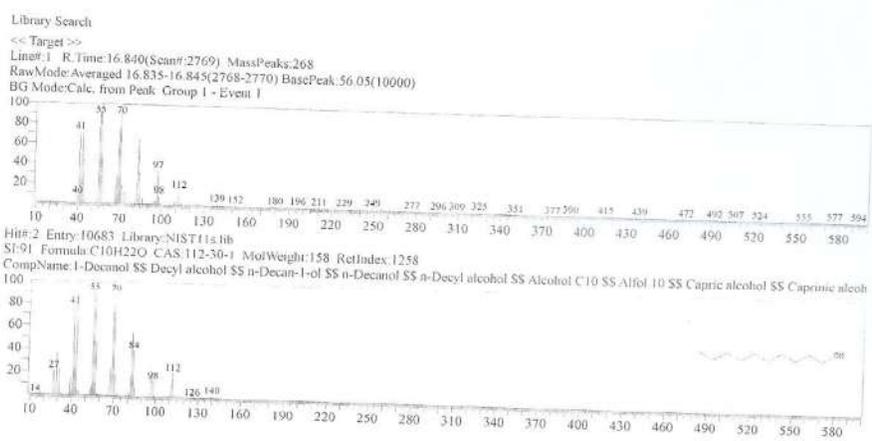


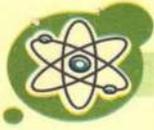
Figure (A, 1) chemical analysis by GC/MS (13)

Method of analysis:

GC/MS Conditions

The qualitative and quantitative analysis of the sample was carried out by using GC/MS technique model (GC/MS-QP2010-Ultra) from Japan's Shimadzu Company, with serial number 020525101565SA and capillary column (Rtx-5ms-30m×0.25 mm×0.25μm). The sample was injected by using split mode, helium as the carrier gas passed with flow rate 1.83 ml/min, the temperature program was started from 35°C with hold time three minutes and the rate was 7°C/min to 180°C then the rate was changed to 10°C/min reaching 280°C as final temperature degree, the injection port temperature was 300°C, the ion source temperature was 200°C and the interface temperature was 250°C. The sample was analyzed by using scan mode in the range of m/z 40-600 charges to ratio and the total run time was 30 minutes. Identification of components for the sample was achieved by comparing their retention times and mass fragmentation patterns with those available in the library, the National Institute of Standards and Technology (NIST), results were recorded.

Figure (A, 1) chemical analysis by GC/MS (14)



Test Report

THE SAMPLES DESCRIBED BELOW WAS TESTED IN CENTRAL LABORATORY FOR TECHNICAL SERVICES AND CALIBRATION BY USING NIST TRACEABLE REFERENCE EQUIPEMENT AND MATERIALS IN ACCORDANCE WITH ISO/IEC 17025:2005 REQUIREMENTS AND THE TEST METHODS REFERENCED BELOW MEETS ISO/IEC 17025:2005 .

Report No : 544-545

Issue Date:09/10/2017

Company: -----

Address: Khartoum

Representative: المعز ابراهيم أحمد

Telephone /E-Mail: 090722226

SAMPLES DATA

Sample Description: Fuel

Sample ID: C219/17/F568-569

Receiving Date: 08/10/2017

Sampling Location: Bio-oil , B

TEST METHODS & PROCEDURE

The test method used is describing against the testing parameters in the results tables

The reported test results are representing the tested sample only, and the sampling is conducted under the authority and responsibility of the laboratory customers

SIGNATURES

Approved By

Laboratories Director

Name : Najwa Elfaki Mustafa

Sign :

Date : 09/10/2017



Figure (A, 2) Physical analysis (1)



Test Report

THE SAMPLES DESCRIBED BELOW WAS TESTED IN CENTRAL LABORATORY FOR TECHNICAL SERVICES AND CALIBRATION BY USING NIST TRACEABLE REFERENCE EQUIPEMENT AND MATERIALS IN ACCORDANCE WITH ISO/IEC 17025:2005 REQUIREMENTS AND THE TEST METHODS REFERENCED BELOW MEETS ISO/IEC 17025:2005 .

Report No: 545 , Issue Date: 9/10/ 2017

DATES & CONDITION

Testing Laboratory: petroleum lab

Sample Description: Fuel

Sample Location: B

Test condition: Temperature: 29.6 °C

Sample ID: C573/17/F569

Receiving Date: 8/10/2017

Relative Humidity: 22 %

TEST RESULTS

No.	TEST	TEST DATE	TEST METHODS No.	RESULT	U _{Exp}	UNIT
1	Density@ 15 C°	9.10.2017	ASTM D4052	1.1309	-	g/cm ³
2	Calorific value	9.10.2017	Calculated value	40671.56	-	KJ / Kg
3						

SIGNATURES

Reviewed By
Technical Manager
Name : Mohamed Elfatih Mahmoud
Sign. : 
Date : 9.10.2017

Approved By
Laboratories Director
Name : Najwa Elfaki Mustafa
Sign. : 
Date : 9.10.2017



Figure (A, 2) Physical analysis (2)



Test Report

THE SAMPLES DESCRIBED BELOW WAS TESTED IN CENTRAL LABORATORY FOR TECHNICAL SERVICES AND CALIBRATION BY USING NIST TRACEABLE REFERENCE EQUIPEMENT AND MATERIALS IN ACCORDANCE WITH ISO/IEC 17025:2005 REQUIREMENTS AND THE TEST METHODS REFERENCED BELOW MEETS ISO/IEC 17025:2005 .

Report No: 544 , Issue Date: 9/10/ 2017

DATES & CONDITION

Testing Laboratory: petroleum lab

Sample Description: Fuel

Sample Location: Bio - oil

Test condition: Temperature: 29.6 °C

Sample ID: C573/17/F568

Receiving Date: 8/10/2017

Relative Humidity: 22 %

TEST RESULTS

No.	TEST	TEST DATE	TEST METHODS No.	RESULT	U _{Exp}	UNIT
1	Density@ 15 C ^o	9.10.2017	ASTM D4052	1.07925	-	g/cm ³
2	Calorific value	9.10.2017	Calculated value	41675.24	-	KJ / Kg
3						

SIGNATURES

Reviewed By
Technical Manager
Name : Mohamed Elfatih Mahmoud
Sign. : 
Date : 9.10.2017

Approved By
Laboratories Director
Name : Najwa Elfaki Mustafa
Sign. : 
Date : 9.10.2017



Figure (A, 2) Physical analysis (3)