Feasibility of Oil-Palm Fronds for Biomass Gasification.

By

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ABSTRACT

Biomass Gasification means incomplete combustion of biomass resulting in the production of combustible gases consisting of Carbon Monoxide (CO), Hydrogen (H_2), and traces of Methane (CH_4). This mixture is called syngas or also known as producer gas. Gasification is a century old technology and was used extensively during World War II due to the shortage of liquid fuel. The technology disappeared soon after World War II when liquid fuel became easily available. Due to the current depletion of fossil fuels, increased energy demand, and environmental concerns, there is a renewed interest in the technology. The feasibility of using oil palm fronds in a biomass gasification system would be investigated by means of chemical and physical analysis. The present research is based on a concept of waste to energy utilizing the palm fronds currently viewed as agricultural waste into a value added product. Ultimately through the successful application of the present research on a large scale system, the nation's dependency on fossil fuel would be reduced creating an alternative energy source which is environmental friendly and also parallel to a carbon neutral economy.

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CHAPTER 1
INTRODUCTION

1.1 Project Background

The global concern on environmental issues and the fast depletion of fossil fuels resulting from the rapid global industrialization have imposed a great strain on developed and developing countries to find alternate sources of fuels that are environmental friendly as well as non-depleting. Due to this, renewable energy has been considered as the primary choice to energy sustainability to substitute fossil fuel. One of the most promising types of renewable energy is biomass.

Biomass sources include rice husk, vine shoot, sugarcane, wood, coal, and many more. Gasification means incomplete combustion of biomass resulting in the production of combustible gases consisting of Carbon Monoxide (CO), Hydrogen (H_2), and traces of Methane (CH_4). This mixture is called syngas or also known as producer gas. Syngas are capable of supporting further combustion which usually occurs in a separate location or chamber. Syngas can be used to run internal combustion engine (both compression and spark ignition), can be used gas a substitute for furnace oil in direct heat applications and can be used to produce, in an economically viable way, methanol – an extremely attractive chemical which is useful both as a fuel for heat engines as well as chemical feedstock for industries.

A number of biomass based energy conversion system for combined heating and power generation are already in existence, however most biomass plants use biomass feed very much the same way as the fossil fuel for firing in a boiler to produce heat or steam (Zulkifli, 2004). Some companies have also used the technique of biomass gasification for power generation using internal combustion engine, but did not take off in large scale due to the constraints on the engine capacity and thus limiting the load below 1 MW (Rahman, 2005).

Malaysia has also ventured into diversifying its fuel sources by investing into biomass to produce energy from readily available sources such as rice husk and rubber tree woods. Malaysia has the potential of becoming a major biomass energy contributor with a production of more than 70 million tones of agricultural wastes each year (Ali, 2004). Currently, most of the waste is disposed of through incineration and dumping, and only a small amount is used for energy generation for the industry's own consumption. Zooming into palm oil production, the industry generates more energy than it needs. Dealing with the excess waste has become an issue. (Zainal, 2007).

Palm oil industry waste offers the biggest potential for biomass energy utilization in Malaysia, as they are abundant, easily available and moreover there is a need to be disposed of cost-effectively. As shown in Figure 1.1, oil palm takes up 62.3% of the total nations agricultural land use (MPOB, 2006).

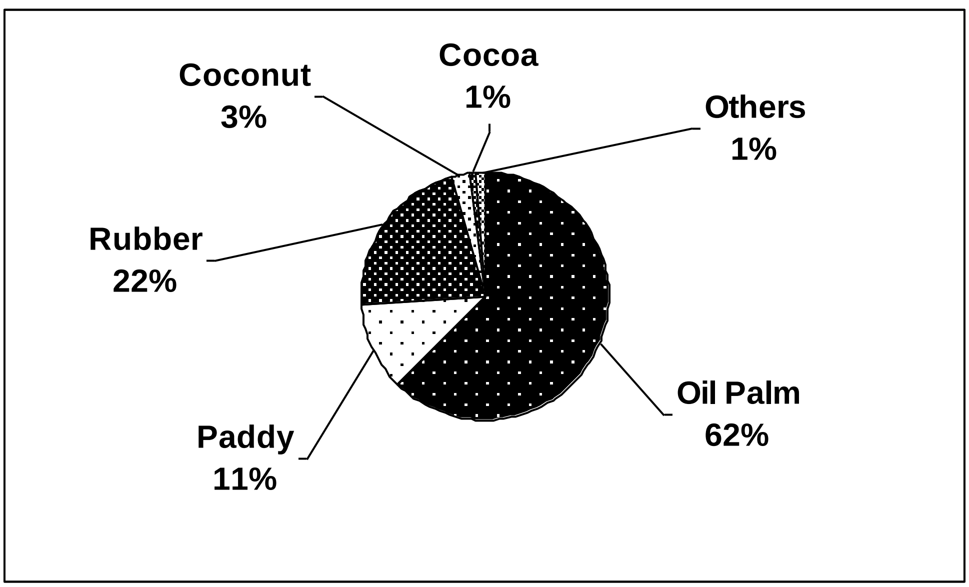


Figure 1.1: Percentage of agricultural land use in Malaysia, 2003.
Reproduced from MPOB (2006)

1.2 Problem Statement

There have been many studies on the oil palm trees in order to exploit its parts for various applications or products, however very little attention has been paid on the oil palm fronds. Oil palm fronds are readily available in abundant here as Malaysia is the largest producer of palm oil in the world. As shown in Figure 1.2, Malaysia produces 47% of the global palm oil supply (MPOB, 2004). Currently the oil palm fronds are used as fertilizers in plantations and there are also a small percentage of the fronds being used as livestock feed (Hassan, 1994). Exploring and exploiting the potential of oil palm fronds as a biomass feed would be a new challenge in energy industry. Furthermore there are very little references available on the usability of oil palm fronds.

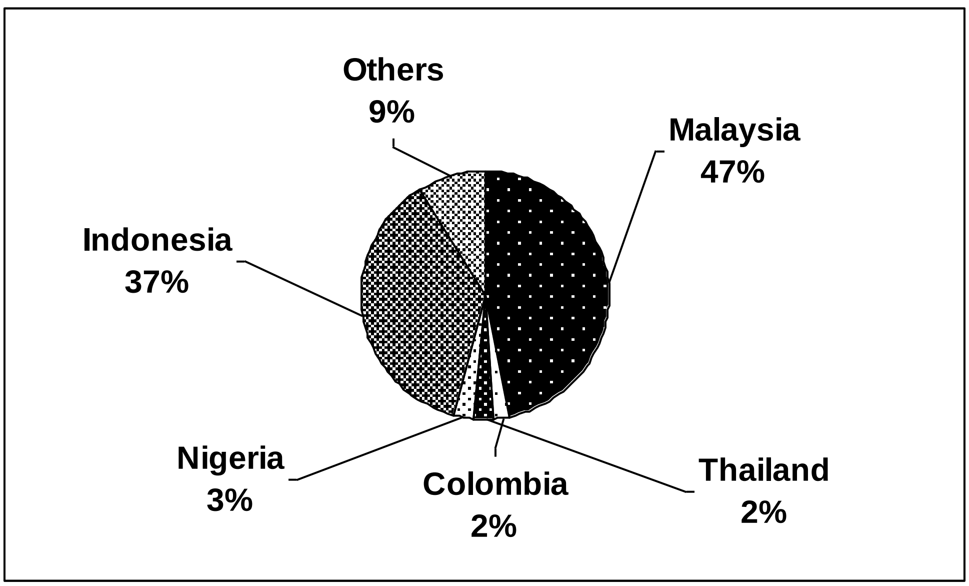


Figure 1.2: Global Palm Oil Production, 2006.Reproduced from MPOB (2004).

1.3 Objectives

The objective of the present project is to investigate the feasibility of oil palm fronds for biomass gasification system in terms of chemical and physical characteristic of the biomass feed.

1.4 Scope of Study

The feasibility of using oil palm fronds for biomass gasification would be characterized by chemical and physical properties. Among the parameters of interest are the chemical analysis and energy content of the fronds. The carbon, sulphur, calorific value, moisture, volatile matter, fixed carbon and ash content, are among the details that will justify the feasibility of the oil palm fronds for biomass gasification system. The physical analysis would research into determining the frond bulk density value and also to capture the drying curve of for various drying conditions. The results from the present study can be applied for future study on a large scale gasification system.

1.4.1 Chemical Properties

The scope for chemical properties is studied by Ultimate Analysis, Higher Heating Value (HHV) also known as the Calorific test and the Proximate Analysis. The Ultimate Analysis provides a quantitative measure of Carbon, Hydrogen, Nitrogen and Sulphur in the leaves by means of its weight percentage. The Calorific test determines the calorific value of the oil palm frond. The Proximate Analysis quantifies the content of moisture, volatile matter, ashes, and fixed carbon in the fronds. It is vital to determine the elemental composition of the oil palm fronds which is an important property that defines the energy content and the environmental impact due to its usage in gasification.

1.4.2 Physical Properties.

The scope for physical properties is studied by experiments conducted to determine the fronds bulk density value. The natural drying time of the oil palm fronds is analyzed to gain an understanding of the process before applying it on a large scale

By the end of the study, the feasibility of using oil palm fronds for biomass gasification in terms of chemical and physical characteristic would be identified.

CHAPTER 2
LITERATURE REVIEW AND THEORY

A large population of the world is still not being serviced with energy needs at the minimum level even in the 21^{st} century. This is true with the developing nations like India, Bangladesh, Sri Lanka, Pakistan, Costa Rica, Brazil, Zambia and Uganda (Dassapa, 2004). Most of these countries are characterized by a large part of the population in scattered locales – in villages and hamlets. These remote locations make it uneconomical to extend the centralized grid. In addition their economic structure is not strong towards importing oil for power generation applications.

In addition, the alarming environmental issues such as global warming have urged for proper control of fossil fuel consumption by stricter emission regulations. The uncontrolled anthropogenic release of green house gases has induced in the increase of heat trapped in the atmosphere which has increased the global temperature by 2.5°C over the past fifty years (Hassan, 2004).

Further negligence towards the present scenario would make way for the future generations to see the detrimental effects of global warming which includes the increase in sea level (10cm-20cm) resulting in the submerging of lowlands, deltas and islands, and a change in weather pattern which would have a direct hit on the global food supply (Hassan, 2004). This has become one of the factors for the reduction in consumption of fossil fuel and the adopting of a suitable renewable energy device.

The renewable energy is mainly supplied by solar, wind and micro/mini hydel. However biomass is beginning to emerge as a promising source of renewable energy. Even though each of the above energy sources has niche market, biomass has been a key role in the renewable energy sector.

There has been a shifting of paradigm towards biomass for the energy sector. The modern bio-energy has received comparatively little fiscal and financial incentives unlike its counterparts, namely the solar photovoltaics (Dassapa, 2004). However for reasons like the cost effectiveness and availability factor, biomass-based technologies are becoming popular as they have edge over other renewables.

2.1 Biomass

Biomass, in the energy production industry, refers to living and recently dead biological material which can be used as fuel for industrial production. Most commonly biomass refers to plant matter exploited for use as biofuel, but it also includes plant or animal matter used for production of fibers, chemicals, or heat. Biomass may also include biodegradable wastes that can be burnt as fuel (Mckendry, 2001). It excludes organic material which has been transformed by geological processes into substances such as coal or petroleum. It is usually measured by dry weight. Sources of biomass energy lead to agricultural crop residues, energy plantations, and municipal and industrial wastes.

Biomass is part of the Carbon-Cycle (Auke, 1998). Carbon from the atmosphere is converted into biological matter by means of *photosynthesis*. On decay or combustion of the carbon, it goes back into the atmosphere or soil. This happens over a relatively short timescale and plant matter used as a fuel can be constantly replaced by planting for new growth. Therefore a reasonably stable level of atmospheric carbon content results from its use as a fuel. It is commonly acceptable that the amount of carbon stored in biomass is approximately 50% of the biomass by weight (Mckendry, 2001).

2.2 Gasification

Biomass Gasification means incomplete combustion of biomass resulting in the production of combustible gases consisting of Carbon Monoxide (CO), Hydrogen (H_2), and traces of Methane (CH_4). This mixture is called syngas or also known as producer gas.

Gasification is a process that converts carbonaceous materials such as coal, petroleum, or biomass, into carbon monoxide and hydrogen by reacting the raw material at high temperatures with a controlled amount of oxygen (Phillipe, 2001). It is a very efficient method for extracting energy from many different types of organic materials, and also has applications as a clean waste disposal technique.

At present, gasification of fossil fuel is widely used at industrial scale to generate electricity. However, almost any type of organic material can be used as the raw material for gasification. Within the last few years, gasification technologies have been developed that use plastic rich waste as feed. In a plant in Germany, such a technology is being applied to convert plastic wastes to produce energy and also methanol (Jayson, 2007). In Berrybank, Australia, a power plant is generating 2900 kW of power from wastes contributed from neighboring pig farms (RISE, 2006). Small scale rural biomass gasifiers have been applied in a large extent, especially in the state of Tamil Nadu in India. Most of the application systems are of 9 kW systems used to satisfy the needs for small villages located in very remote part of the country (Anil, 2006).

Biomass gasification has advantages over other methods of producing energy. It serves as an alternative technology for renewable energy using palm oil mill biomass. In addition the emission levels from biomass gasification are much lower than the conventional incineration or boiler chimney. Biomass gasification system has helped many developing countries to improve their balance of payment. It also offers a decentralized energy conversion system which operates economically even in small scale plant (Dassapa, 2004).

Efficiency of conversion for gasification is higher between 22%-37% as compared to biomass combustion technology that gives only 15%-25 % (Rahman, 2005). It requires less flue gas treatment with no black smoke emission as combustion takes place with only combustible gasses. Apart from that it has relatively less operational problems as compared to conventional boiler. The gasifier ash when mixed with solid from anaerobic pond yield a good fertilizer for plantations.

In particular, biomass gasification is carbon neutral. Regardless of the final fuel form, gasification itself and subsequent processing neither emits nor traps greenhouse gasses such as carbon dioxide. The resulting gas mixture is called synthesis gas or syngas and itself a fuel.

2.3 Syngas

Syngas is the name given to a gas mixture that contains varying amounts of carbon monoxide and hydrogen generated by the gasification of a carbon containing fuel to a gaseous product with a heating value (Mckendry, 2001)

Syngas are capable of supporting further combustion which usually occurs in a separate location or chamber. The gasification product may also be transported over distance similarly to natural gas. Syngas can be used to run internal combustion engine (both compression and spark ignition), can be used gas a substitute for furnace oil in direct heat applications and can be used to produce, in an economically viable way, methanol – an extremely attractive chemical which is useful both as a fuel for heat engines as well as chemical feedstock for industries.

Examples include steam reforming of natural gas, or liquid hydrocarbons to produce hydrogen, the gasification of coal and in some types of waste-to-energy gasification facilities.

The syngas produced in large waste-to-energy gasification facilities is used as fuel to generate electricity. Syngas consists of primarily of carbon monoxide, carbon dioxide and hydrogen and has less than half energy density of natural gas. Syngas is combustible and often used as a fuel source or as an intermediate for the production of other chemicals. Syngas for use as fuel is most often produced by gasification of coal or other biomass sources such as rubber tree wood, rice husk, and willow woods (Mckendry, 2001). This study will focus in adding palm leaves as another source of a biomass feed for a gasification system to produce syngas.

Prior to the production of the usable syngas, gasification process occurs through two stages. In the first stage, *pyrolysis* releases the volatile components of the fuel at temperatures below 600ºC (Malcolm, 1995). In the second gasification stage, the carbon remaining after pyrolysis is either reacted with steam or hydrogen or combusted in air or pure oxygen. Typically the exothermic reaction between carbon and oxygen provides the heat energy required to drive the gasification reactions.

Production of syngas from the gasification of biomass takes the following paths (Alexander, 2002):

- $C + O_2 \rightarrow CO_2$ -393kJ/mol (exothermic)
- $C + H_2O \rightarrow CO + H_2$ +131kJ/mol (endothermic)
- $C + CO_2 \rightarrow 2CO$ +172kJ/mol (endothermic)
- $C + 2H_2 \rightarrow CH_4$ -74kJ/mol (exothermic)
- $CO + H_2O \rightarrow CO_2 + H_2$ -41kJ/mol (exothermic)
- $CO + 3H_2 \rightarrow CH_4 + H_2O$ -205kJ/mol (exothermic)

Combustion of syngas or derived fuel does emit carbon dioxide. However biomass gasification could play a significant role in a renewable energy economy, because biomass production removes CO_2 from the atmosphere.

While other biofuel technologies such as biogas and biodiesel are also carbon neutral, gasification runs on a wider variety on input materials, can be used to produce wider variety of output fuels, and is extremely efficient method of extracting energy from biomass. Biomass gasification is therefore one of the most technically and economically convincing energy possibilities for a carbon neutral economy (Peter, 2003).

2.4 Availability of Oil Palm Fronds

The palm oil industry in Malaysia is the third pillar of nation's economy and catalyst for rural development and resultant political stability. The industry provides direct employment to more than 40,000 people plus other multiplier effects and spin-offs. In 2003, the industry generated a net revenue of RM27 billion (MPOA, 2004).

The need to ensure a steady supply of resources and keeping the cost low for an economically sound energy generation has induced the necessity to diversify the type of biomass that can be exploited. Venturing into the Malaysian scenario, the nation generates approximately 70 million tones of agricultural wastes annually where palm industry being the major contributor.

The current available resource for biomass feeds are rice husk mainly used in the northern region of peninsular Malaysia, rubber woods, and also wood chipping from the furniture industry (Zainal, 2002). Palm biomass acts as the main important energy source. On the other hand, the main sources of biomass in Malaysia are domestic wastes, agricultural wastes, animal wastes, sewage sludge and wood chips. The percentage of agricultural wastes of biomass resources in 2006 is shown in Figure 2.1 below:

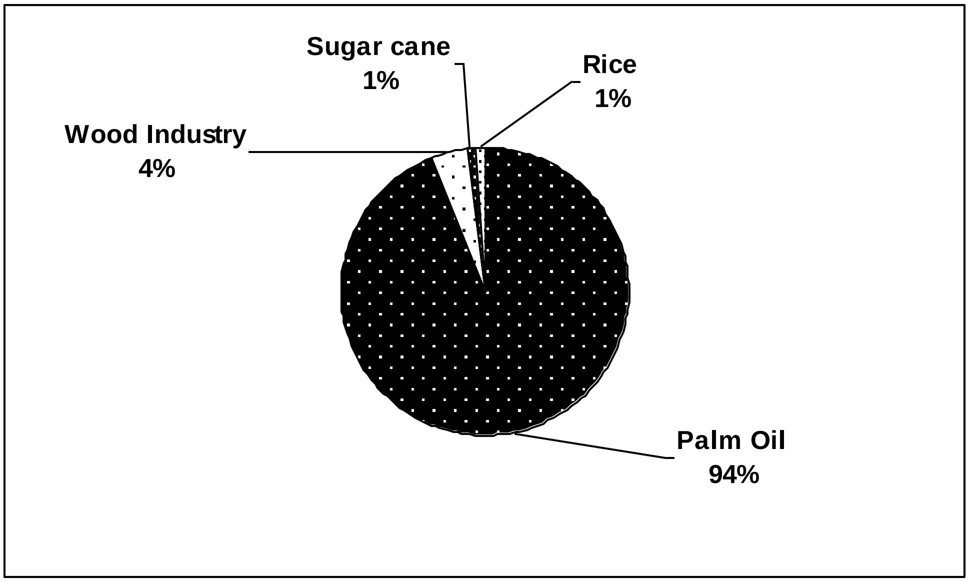


Figure 2.1: Percentages of agricultural wastes of biomass residues (MPOB, 2006).

Oil palm fronds in Malaysia are of abundance and are also readily available. Table 2.1 below, shows the total amount of fronds available from the year 1990 to 1998. Oil palm takes up 62.27% of the total nations agricultural land use. Approximately 26.21 million tonnes of oil palm fronds were available in the year 2000 from replanting and pruning (Salleh, 2005). The supply of these fronds has been increasing exponentially parallel with the industries growth. The government move to further promote palm oil industry to strengthen the position as a leader in oil palm/palm oil production makes it a steady and also economically sound choice as a biomass feed.

Table 2.1: Availability of Oil Palm Fronds, metric tonnes (Mohammed, 1986).

Year	Fronds		Total
	Replanting	Pruning	
1990	0.25	16.92	17.17
1992	0.64	17.64	18.28
1994	0.88	17.89	18.77
1996	0.83	19.09	19.92
1998	1.42	18.18	19.6

CHAPTER 3
METHODOLOGY / PROJECT WORK

3.1 Methodology

The feasibility of oil palm fronds for biomass gasification would be investigated by means of chemical and physical analysis. Prior to the investigation by conducting experiments, the basic analysis method and procedures involved are studied by means of literature review. For the first half of the semester the chemical analysis of the oil palm fronds would be investigated by means of Ultimate Analysis and Calorific Test. The second half of the study would further investigate the feasibility of the fronds by means of Proximate Analysis. Physical analysis would aim to determine the fronds bulk density value and the drying characteristic under various conditions. Given sufficient time and funds, the feasibility of the fronds would be further investigated by designing and constructing a downdraft gasifier that utilizes the fronds as biomass feed.

Prior to the design phase of the vessel, various types of gasifier would be studied to understand the nature of the processes that occurs in a gasifier and also to analyze the differences among the designs. As this is the first attempt of building a downdraft gasifier that uses oil palm fronds as the feed, the design would rather follow closely that of a downdraft gasifier that uses wood as the biomass feed as the nature of the biomass feeds are closely related. A few adjustment and refinement would be done to modify the vessel design to specially cater for oil palm fronds.

The design phase would take into consideration of safety factors, simplicity, easy maintenance and also the cost. The completed gasifier would be used to produce syngas, with oil palm fronds being the biomass feed. Several runs would be done to understand the operational behavior in the vessel. The final product of the gasification would be analyzed and quantified.

The proposed project flow is shown in the Gantt chart below:

No.	Activities / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Topic														
2	Data Gathering and Reseach on Topic														
3	Submission of Preliminary Report				17/8										
4	Confirmation of Scope of Study														
5	Research on oil Palm fronds														
6	Sample Preparation														
7	Submission of Progress Report I								21/9						
8	Umtimate Analysis														
9	Calorific test														
10	Seminar													26/10	
11	Submission of Interim Report														29/11

Figure 3.1: Project flow for Semester 1.

No.	Activities / Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Data Gatherong and Research on Gasifier.														
2	Design of Gasifier.														
3	Submission of Preliminary Report 2				16/2										
4	Literature Review														
5	Proximate Analysis														
6	Submission of Progress Report 2.							27/3							
7	Bulk Density Test														
8	Drying Test														
9	Poster										19/4				
10	Oral													5-May	
11	Hard bound Dessertation														29/11

Figure 3.2: Project flow for Semester 2.

3.2 Sample Preparation

The oil palm frond samples were collected from Nalla Estate located in Tronoh, Perak. Samples of fronds were obtained from 5 different trees at five different locations within the estate to assess the difference in quality and condition of each frond to one another.

The palm fronds were left to dry under the sun for a period of 3 days to ensure a dry sample. The samples were further dried in an oven at 55^{o}C for a period of 24 hours. This is referred as the pre-treatment process in which the moisture content in the fronds is completely eliminated.

The dried fronds are undergone first stage of grinding to prepare it in powder form using a Granulator. The granulated fronds are then turned into its powdery form using a Rock Lab Grinder by setting the grinding time at 3 minutes per load.

3.3 Chemical Analyses

Chemical analysis is necessary to justify the feasibility of using oil palm fronds in a gasification system. In the present work, chemical analysis will include, Ultimate Analysis, Calorific test, and Proximate Analysis. Each of the analysis would be discussed in the following sections.

3.3.1 Ultimate Analysis

The purpose of preparing a fine dry power is to analyze the chemical compositions of the oil palm fronds. The ultimate analysis or CHNS testing was performed using the Leco CHNS-932 machine. The CHNS machine works based on the principle that high temperature combustion is used as the means of removing the elements from the material. This analysis will report the (carbon, hydrogen, nitrogen, and sulphur) content in the frond samples. The parameter for ultimate analysis was set according to ASTM D 3176-89. The weight that would be used for the test would be 1mg in form of fine powder. A set of 5 runs would be conducted to obtain an average value for the composition of each Carbon, Hydrogen, Nitrogen and Sulphur in the palm fronds. High carbon content would highlight the possibility of the oil palm fronds to become a fuel source for the gasification process. Low sulphur content would portray the potential of the palm fronds as an environmental friendly renewable energy source as sulphur would and react with water, oxygen and oxidants to form acidic compound as found in acid rains.

3.3.2 Calorific Test

To determine the amount of energy stored in the oil palm frond, a Calorific Value Test would be done using a LECO AC-350 Bomb Calorimeter. Gross Calorific value of a fuel specimen is the heat produced by a complete combustion of a unit quantity of sample, at a constant volume, in an oxygen bomb calorimeter under standard condition. The parameter for the calorific test was done according to ASTM D 5865-07, Standard test Method for Gross Calorific Value of Coal and Coke. The test would be a judging parameter on the suitability or potential of the fronds as a biomass feed by means of comparing the value of data obtained against the predetermined existing data of various biomass resources. A set of 5 runs would be conducted to determine the average energy value contained in the oil palm fronds in units of kJ/kg.

3.3.3 Proximate Analysis

Proximate analysis is to be carried out to determine the percentage of moisture, volatile matter, fixed carbon and ashes in the oil palm fronds. Proximate analysis is an empirical technique in which the mass of substance is heated at a controlled rate and the mass loss is recorded as a function of time. The parameter of TGA analysis were set based on ASTM E 1131-98, Standard Test Method for Compositional Analysis by Thermogravimetry. The basic principle of a TGA analysis module is to record mass loss during programmed time or temperature profile. Changes in mass indicate moisture loss and phase changes which occur at set temperature indicative of the compound. It can be used to determine water of crystallization, follow degradation of materials, determined reaction kinetics, study oxidation and reduction.

Fuel with moisture content above about 30% makes ignition difficult and reduces the CV of the product gas due to the need to evaporate the additional moisture before combustion/gasification can occur (Mckendry, 2001). High moisture content reduces the temperature achieved in the oxidation zone resulting in the incomplete cracking of the hydrocarbons released from the pyrolysis zone.

High content of ash in a biomass feed can cause a variety of problems in the gasification process. Slagging formation in the gasifier, caused by melting and agglomeration of ashes will greatly add to the amount of labor required to operate the gasifier. Slagging can even lead to excessive tar formation and/or complete blocking of the reactor. Slagging is expected for fuels having ash contents of 12% (Osorio, 2005) or above and this is an indication for extra caution required while gasification.

The volatile matter content is a measure of the reactivity of a fuel to the gasification process. The volatile matter content of a biomass fuel directly affects the gasifier design and varies from one fuel to another (Laux, 2006).

Biomass generally has higher volatile matter content than conventional fossil fuel such as coal and this is a good indicator on the performance of the biomass fuel in a gasifier. Most biomass contains at average 80% volatile matter content (Renew, 2004).

The significant of volatile matter and fixed carbon content is that they provide a measure of the ease with which the biomass fuel can be ignited and subsequently gasified of oxidized, depending on how the biomass is to be utilized as an energy source. The volatile matter content is a measure of the reactivity of a fuel to the gasification process. The volatile matter content of a biomass fuel directly affects the gasifier design and varies from one fuel to another (Laux, 2006). Biomass generally has higher volatile matter content than conventional fossil fuel such as coal and this is a good indicator on the performance of the biomass fuel in a gasifier. Most biomass contains at average 80% volatile matter content (Renew, 2004). The fixed carbon content is the mass remaining after the releases of volatiles, excluding the ash and moisture contents. Average value for fixed carbon for a biomass fuel is 21.1% (Richards, 2005).

3.4 Physical Analysis

Physical analysis for the present research would include the determination of the frond bulk density value and also understanding the drying characteristic under various conditions. Results from the physical analysis would further justify the feasibility of using oil palm fronds in a gasification system

3.4.1 Bulk Density Test

An important characteristic of biomass fuel is their bulk density. Bulk density is defined as the weight per unit volume of loosely fuel. Fuels with high bulk density are advantageous because they represent a high energy-for-volume value. These fuels need less bunker space for a given refueling time. Low bulk density fuels sometimes give rise to insufficient flow under gravity, resulting in low gas heating values and ultimately in burning of the char in the reduction zone. Inadequate bulk densities can be improved by briquetting or pelletizing.

The bulk density of a biomass material could also be related to transportation and storage cost. For an example, taking wood as a reference material for transport and storage costs, it has been determined that the average cost is USD$ 20/m^3 (Mckendry, 2001).

The bulk density of the oil palm frond is determined by measuring the sample weight with a lab scale and measuring its volume using Archimedes principle. The sample was drenched in water and the displacement volume was measured using a lab measuring cylinder. Five tests were conducted to asses the repeatability of the A set of 5 runs would be done to obtain the average bulk density value.

3.4.2 Drying Test

The parameter of moisture content in biomass fuels is an essential property that determines its efficiency when used in a gasification system. As discussed in previous section, fuels with moisture content above 30% makes ignition difficult and reduces the CV of the product gas due to the need top evaporate the additional moisture before combustion/gasification. The aim to understand the oil palm fronds drying characteristic would be part of the effort to determine the ideal precombustion state of the fronds to be used in a gasification system. The drying characteristic of the fronds would be investigated from the best suitable drying condition to the least suitable condition. The sample of study would be varied from samples in the form of fine powder, frond in the size of 15cm and raw frond of their original size. Sample domain would be varied from drying in the oven at 55ºC, drying under a 100W light source and finally drying of sample in the lab. Samples initial weight of 10gram are used and time taken to dry is measured in an interval of every 30minutes.

3.5 Gasifier

3.5.1 Design of Gasifier

The gasifier design for this research project is similar to that of an existing downdraft gasifier which utilizes wood as its biomass fuel. The design chosen for the research is that of a 22kW gasifier (Fontaine, 1998). Referring to figure 3.1 below, the main body of the gasifier is made of 3 major components which are the gasifier housing drum, fuel hopper and the fire tube. There is also a filter unit accompanying the gasifier to filter the hot syngas produced from the gasification of the palm-fronds.

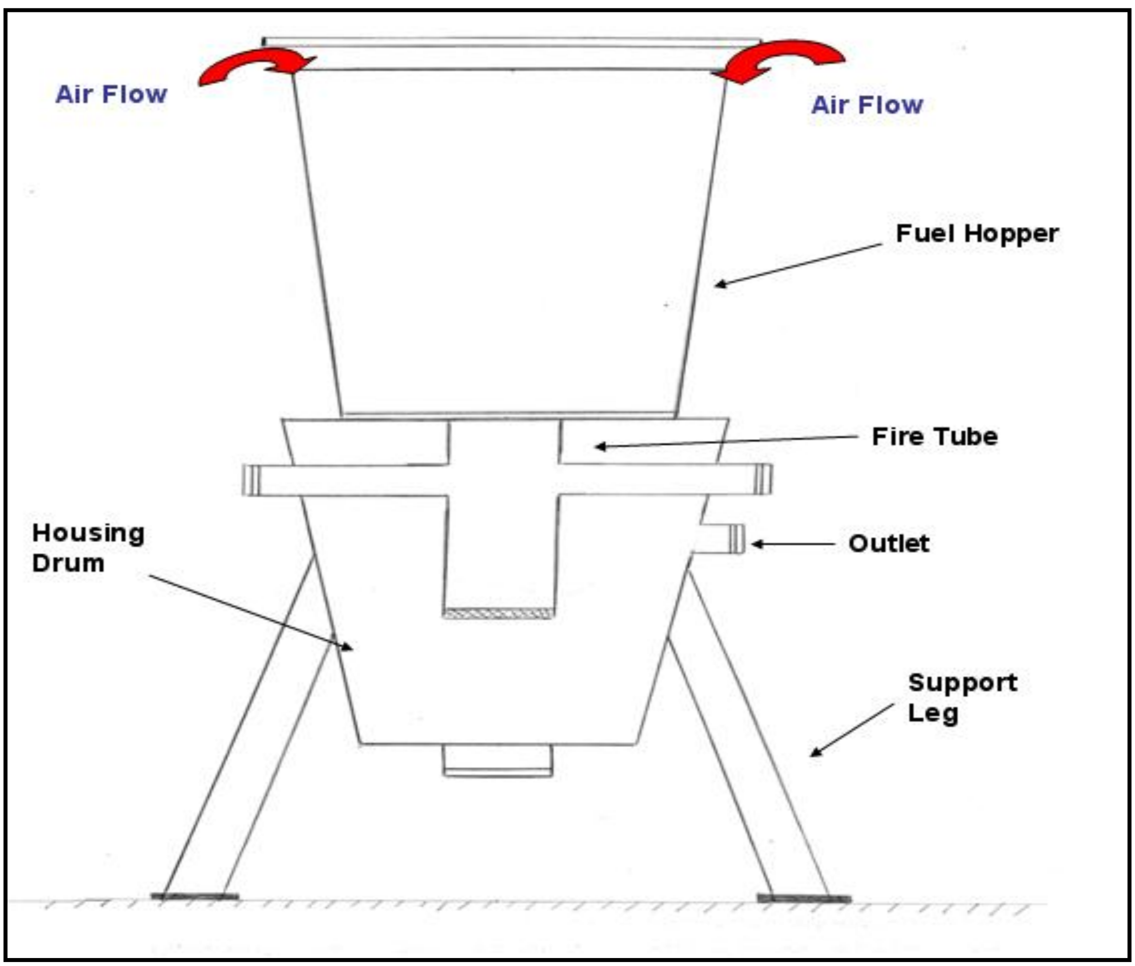


Figure 3.3: Simple sketch of the proposed Gasifier.

3.5.2 Gasifier Housing Drum

The main function of the housing drum is to contain the fuel hopper and fire tube. The housing drum is a cylindrical container with a shell length of 737mm and diameter of 457mm. The housing drum would be made of a 3mm thick mild steel plate rolled to the desired dimension mentioned earlier. The housing drum has four nozzles which would serve as the ash clean out port, ignition ports, and syngas exit. The bottom of the housing drum is to be coated with ½" of hydraulic cement for a height of 5". This serves as the protective layer to prevent the housing drum from melting under the high temperature resulting from the pyrolysis reaction taking place inside the fire tube.

3.5.3 Fuel Hopper

The fuel hopper plays a role as a container to store the palm-fronds before in enters the gasification process. The fuel hopper is located above the housing drum and is also connected to the fire tube by means of bolt and nuts. The fuel hopper would be a cylindrical container with a shell length of 610mm and diameter of 457mm. the fuel hopper would be constructed from a 3mm think mild steel plate rolled to the desired dimension mentioned earlier. Accompanying the fuel hoper is the metal cover which would be constructed from a 3mm thick mild steel plate as well. The cover and the fuel hopper would be connected by means of spring which would ensure a tight fit. The fuel hopper and the top cover are to be separated by a minimum clearance of 3/4". The clearance would be provided by three metal triangular stand offs which would be connected to the top cover by means of welding.

3.5.4 Fire Tube

The fire tube is the heart of the gasifier where the entire gasification process occurs. Temperature inside the fire tube is at the maximum as pyrolysis takes place in this region. The fire tube is made of two components, a metal pipe welded onto a circular metal plate. The metal pipe would have a length of 483mm and a thickness of 3mm. The critical dimensions of the fire tube has a direct relationship with the gasifier capacity, refer to appendix for complete details. The circular metal plate would be made from 3mm thick mild steel having an outer diameter of 527mm and inner diameter of 152mm.

3.5.5 Filter Unit

The main function of the filter unit is to cool down the hot syngas exiting the gasifier and also to filter the gas to remove tar and ash content. The filter is a cylindrical container with shell length of 330mm and a diameter of 362mm.The filter unit is made of thee major component namely the divider plate, top lid and also the filter unit housing. The divider plate serves to divide the filter unit into two different sections separating the filtered and raw gas from each other. The top lid would house the blower and also serves to supply the syngas into the filter unit. The material used for the filtration process would be same as the biomass fuel itself. Oil palm-fronds would be filled into the filter container serving as a filter material to remove tar and ash from the syngas.

3.5.6 Gasifier Drawing

The proposed gasifier drawing consists of all the components described in the previous section. Figure 3.4 below shows the completed and revised drawing for the proposed downdraft gasifier for a capacity of 22kW.

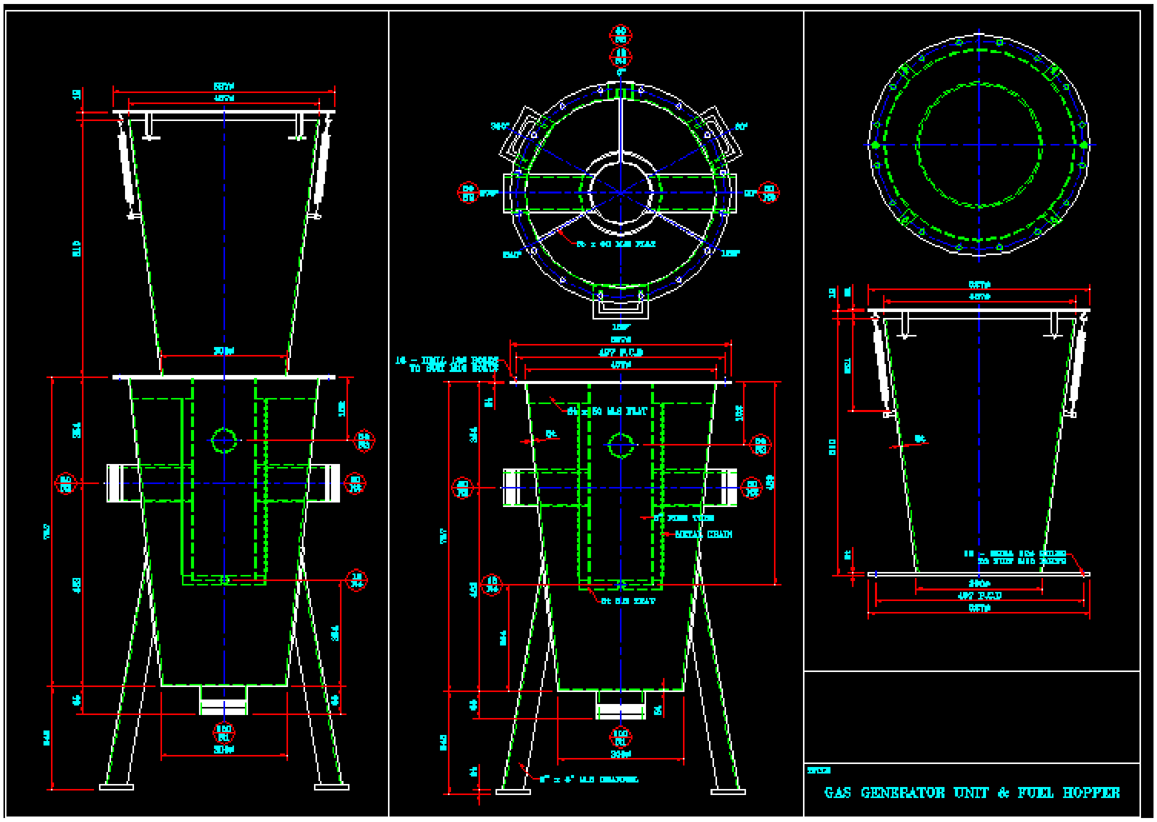


Figure 3.4: Downdraft Gasifier drawing

CHAPTER 4

Results and Discussion

4.1 Ultimate Analysis

The ultimate analysis or CHNS testing was performed using the Leco CHNS-932 machine. The result of the analysis is as shown in Table 4.1.

Table 4.1: Experimental Result of CHNS Test.

Element	**Carbon**	**Hydrogen**	**Nitrogen**	**Sulphur**
Test 1	43.06%	5.73%	2.22%	0.13%
Test 2	42.71%	5.46%	2.12%	0.10%
Test 3	42.19%	5.24%	2.19%	0.10%
Averaged Value	**42.55%**	**5.48%**	**2.18%**	**0.11%**
Standard Deviation				

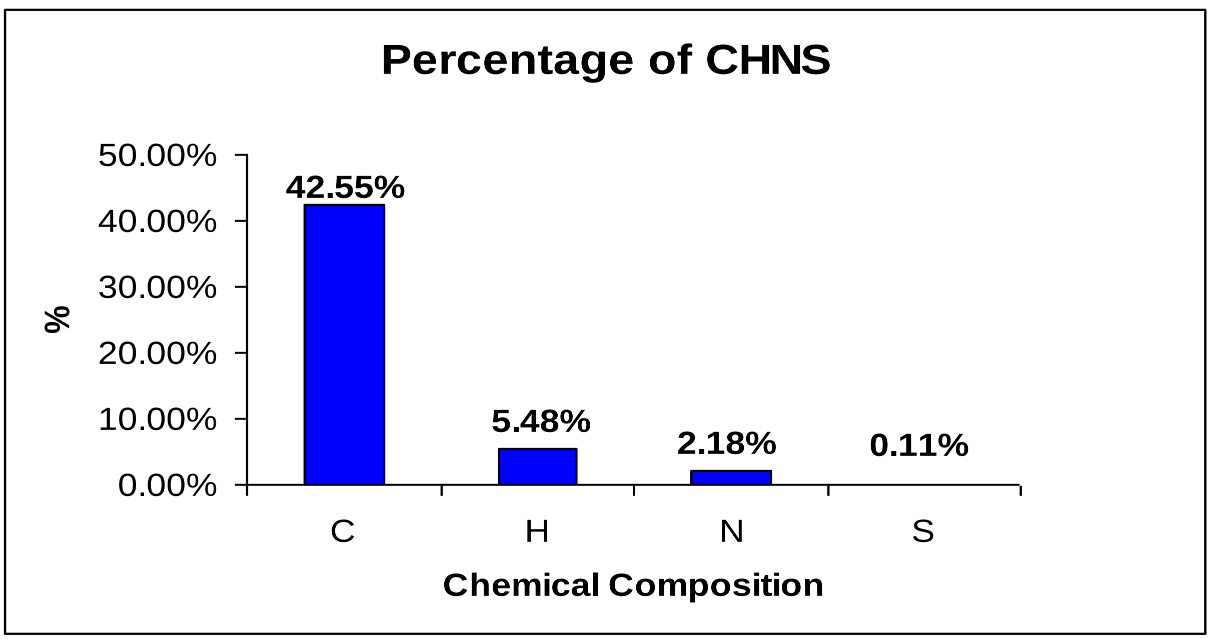


Figure 4.1: Ultimate Analysis for a sample of oil palm fronds

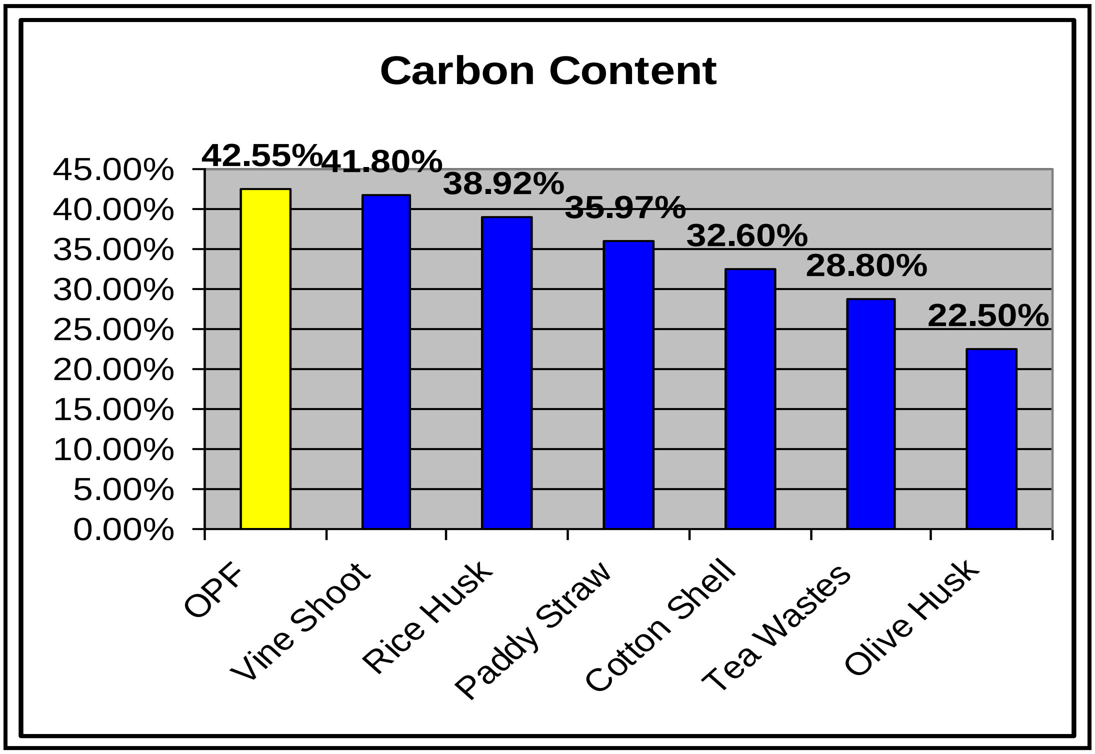


Figure 4.2: Comparison of carbon content of Oil Palm Frond (OPF) against those of other Biomass Sources.

As shown in Figure 4.2, the average value of carbon obtained, 42.55% wt is higher compared to other biomass feed source available such as paddy straw (35.97%), rice husk (38.92%) (Jigisha, 2006), olive husk (22.5%), cotton cocoons shell (32.6%), rice straw (41.4%), tea factory waste (28.8%) (Demirbas, 2001), and vine shoot (41.8%) (Ganan, 2006). The H: C and O: C ratios for the oil palm fronds are 0.13 and 1.17 respectively.

4.2 Calorific Testing

The calorific value of a material provides information regarding the energy content that maybe released when the referred material is burnt in air. The calorific value may be expressed both, as the higher heating value (HHV) and the lower heating value (LHV). The HHV may be defined as the total energy content released when the fuel is burnt in air, including the latent heat contained in the water vapor. It represents the maximum amount of energy potentially recoverable from a given biomass source. The LHV may be defined as the total energy content released when the fuel is burnt in air but excluding the latent heat contained in the water vapor. The result from the calorific test is shown in table 4.2 below:

Table 4.2: Experimental result of the Calorific test

Test No.	Calorific Value, J/g
1	18100
2	17933
3	18153
4	18022
5	17991

The calorific value for oil palm frond ranges from approximately 17933J/g to 18100J/g.

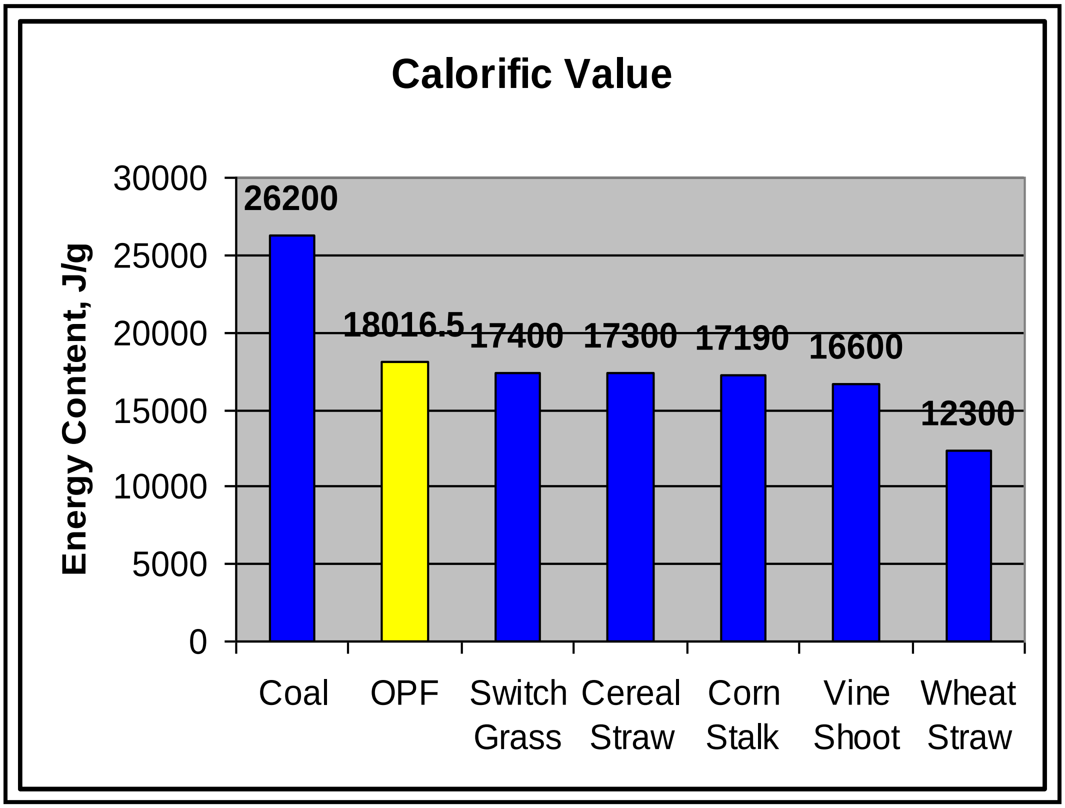


Figure 4.3**:** Comparison of the energy content of OPF against those of other biomass resources.

As shown in Figure 4.3, the obtained calorific value is higher than those of other available biomass feeds such as wheat straw (12300J/g), cereal straw (17300J/g), corn stalk (17190J/g), switch grass (17400J/g) (Mckendry, 2001) and vine shoot (16600J/g) (Ganan, 2006), but lower compared to conventional fossil fuels such as coal (26200J/g) (Ganan, 2006) .

4.3 Proximate Analysis

Proximate analysis was carried out to determine the weight percentage of moisture, volatile matter, fixed carbon and ashes in the oil palm fronds. The test was done using a Perkin Elmer TGA7 Analyzer. Software used for the test was PYRIS 2003. A set of 3 runs were conducted to obtain the averaged value for the desired parameters. For the purpose of this test, an average sample weight of 12.03mg was used parallel to the TGA analyzer requirement of sample weight between 10.00mg to 15.00 mg. The parameter of TGA analysis were set based on ASTM E 1131-98, Standard Test Method for Compositional Analysis by Thermogravimetry The proximate analysis results obtained are presented in table 4.1 and figure 4.4 below:

Table 4.3: Experimental Result for Proximate Analysis

Element	Moisture	Volatile Matter	Fixed Carbon	Ash
Run 1	5%	51%	38%	6%
Run 2	4%	51%	39%	6%
Run 3	3%	52%	38%	7%
Averaged value	**4.0%**	**51.3%**	**39.7%**	**6.3%**

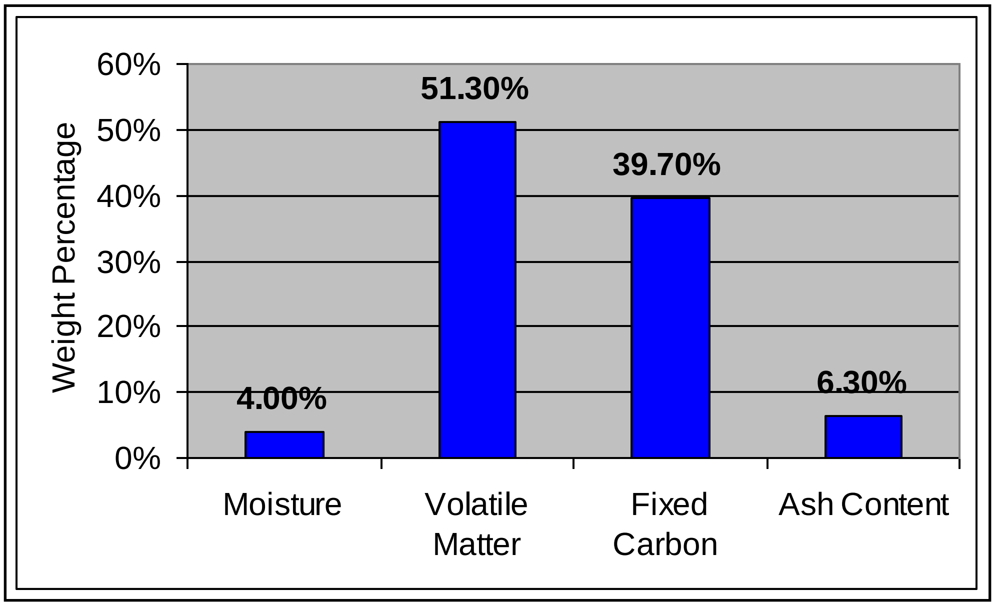


Figure 4.4: Proximate Analysis for a sample of oil palm frond.

The average moisture content obtained from the proximate analysis is 4.0 %. As fuels with moisture content above about 30% makes ignition difficult and reduces the CV of the product gas due to the need to evaporate the additional moisture before combustion/gasification can occur (Mckendry, 2001), the oil palm fronds are capable of performing well in a gasifier producing syngas with high heating value. The moisture content value obtained is lower than other available biomass fuels as shown in figure 4.5 below:

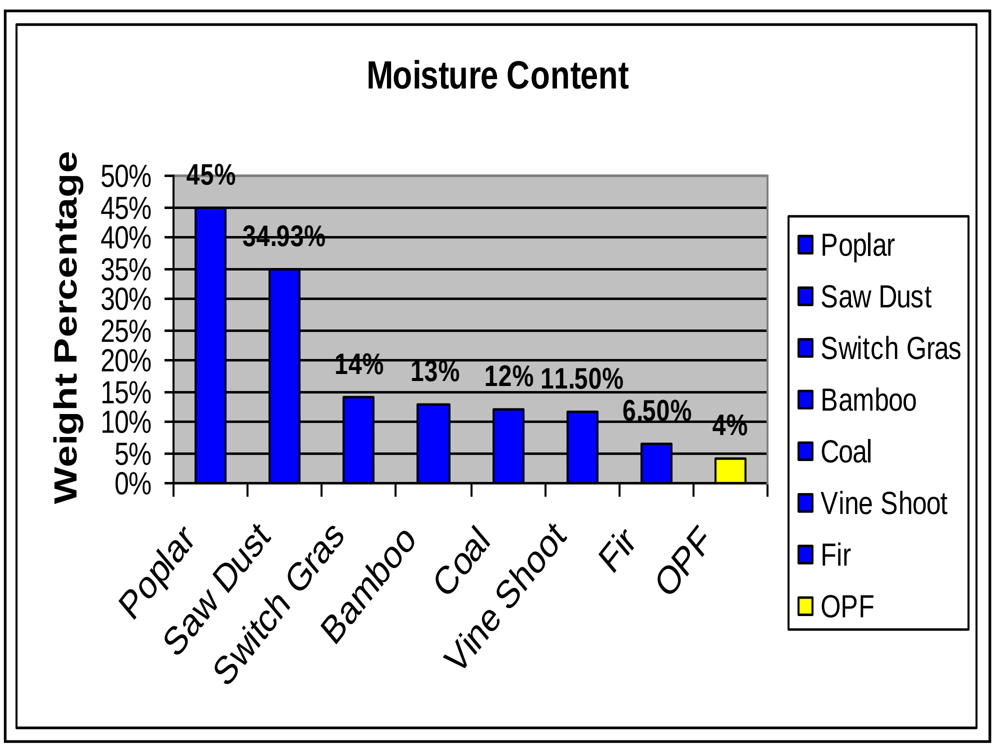


Figure 4.5: Moisture content of OPF against various biomass resources.

The average volatile matter content obtained is 51.3 %. High volatile matter content favors high gas phase yields. The obtained value for volatile matter content of 51.3% is almost comparable to the commonly acceptable content of 76% (Renew, 2004). The volatile matter content obtained for the oil palm fronds against other biomass resources is shown in figure 4.6 below:

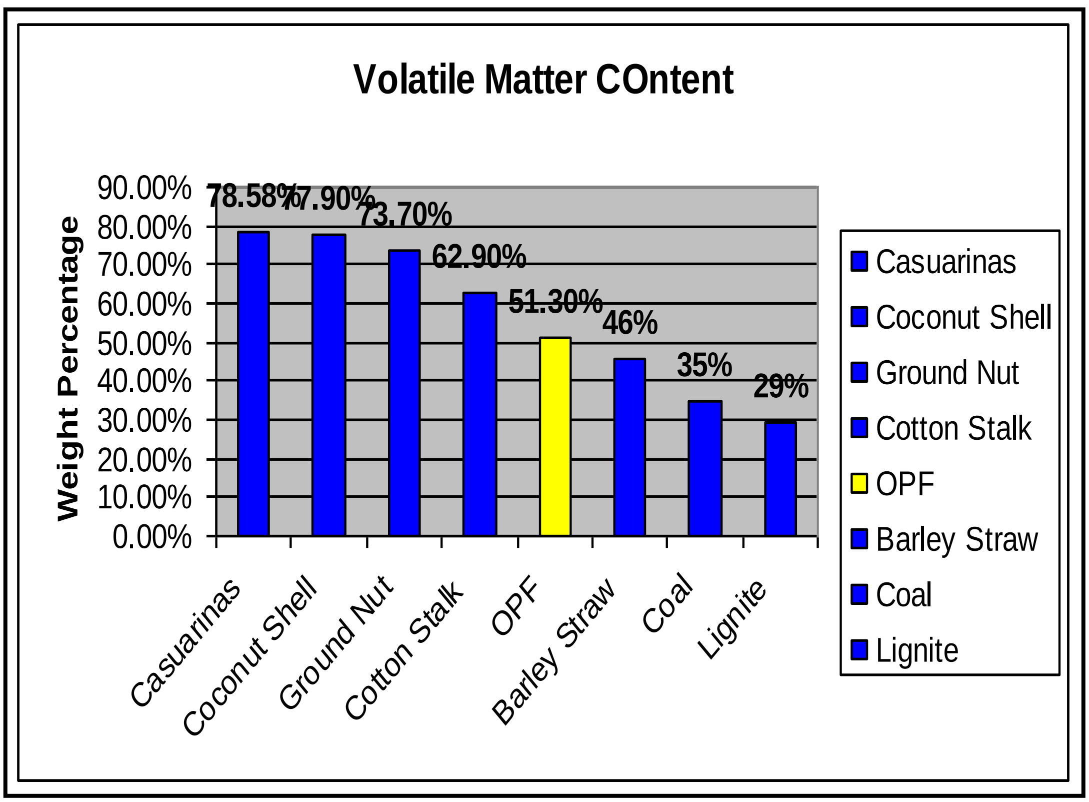


Figure 4.6: Volatile matter content of OPF against various biomass resources.

The averaged ash content value obtained from proximate analysis is 6.3%. The obtained value is lower than 12% (Osorio, 2005) which may cause the phenomena of slagging or clinkering. This indicates that the oil palm frond are able to be used as a biomass feed in a gasification system without inducing operational problems which will also result in the overall efficiency in terms of cost and performance. The obtained value for the ash content is generally lower than other available biomass resources as shown in figure 4.7 below:

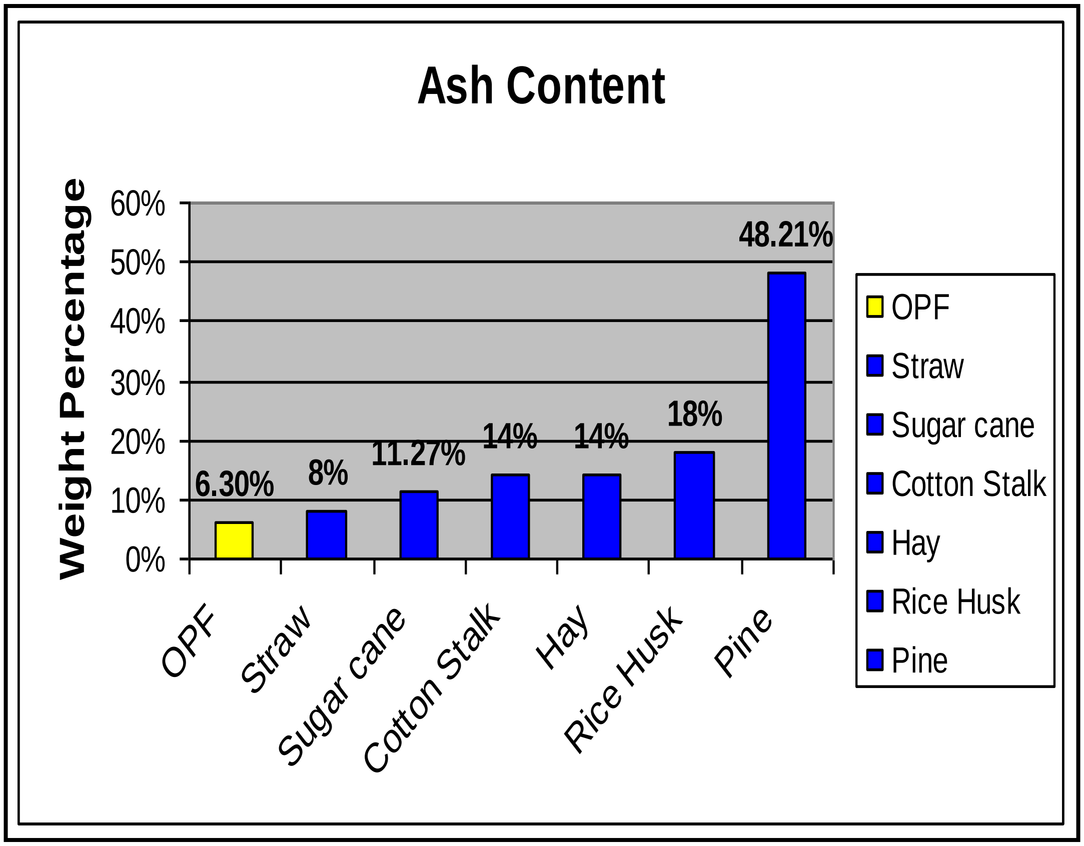


Figure 4.7: Ash content for OPF against various biomass resources.

4.4 Bulk Density Test

Bulk density is defined as the weight per unit volume of loosely fuel. Fuels with high bulk density are advantageous because they represent a high energy-for-volume value. Table 4.4 shows the bulk density value obtained through measurement:

Table 4.4: Bulk density value from experiment.

	Run 1	**Run 2**	**Run 3**	**Run 4**	**Run 5**

Mass of sample, kg	5	6.5	6.1	5.3	6.1
Displaced water volume, L	7.04	9.13	8.52	7.41	8.53
Density, kg/m3	710	712	712	715	715
Average Density, kg/m3	**712.8**				
Standard Deviation	**1.94**				

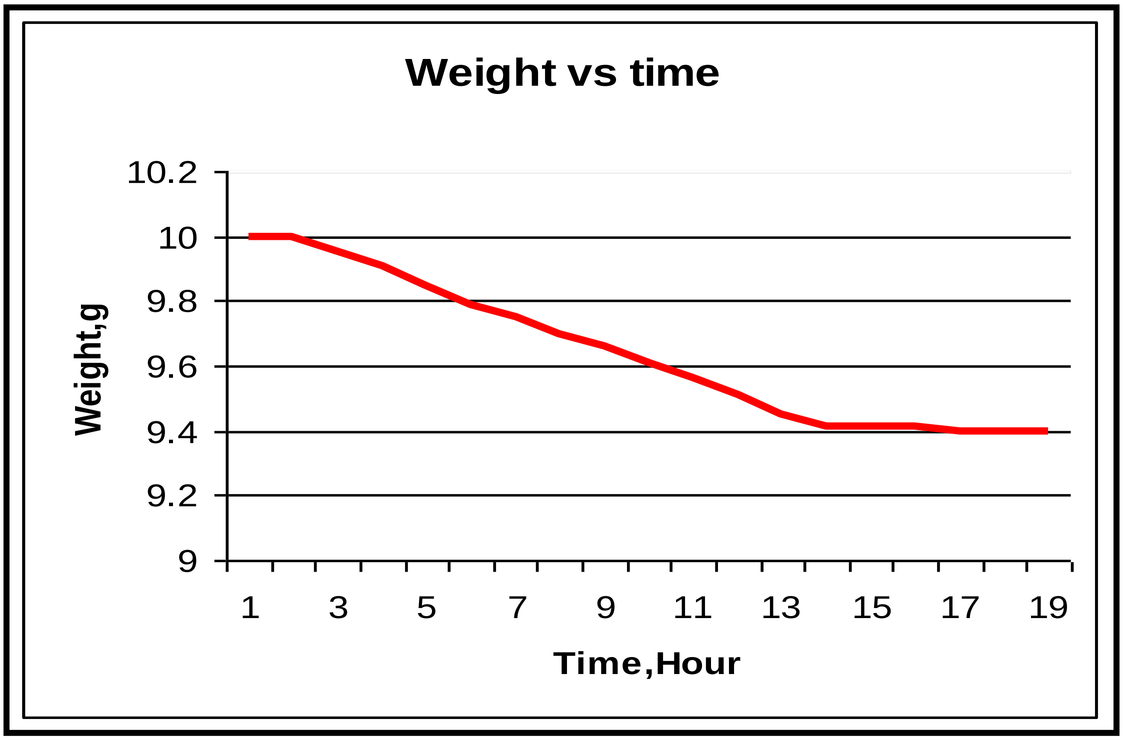
The average bulk density value for oil palm fronds was determined to be 712.8kg/m³. The bulk density for oil palm fronds are higher compared to other existing biomass fuels such as wood chips (230kg/m³), and straw (560kg/m³). A high bulk density value for a biomass fuel also indicates that the fuel takes less bunker space for a given refueling time.

4.5 Drying Test

4.5.1 Oven at 55ºC

The drying characteristic of a biomass fuel determines its efficiency and versatility to be used as feed for a gasification system. Fuels with high moisture level would adversely affect the gasifier performance as discussed in the previous section. Drying of the fronds in the oven at 55ºC is arbitrarily taken as the best drying condition.

4.5.1.1 Frond Samples in Powder form



The drying characteristic for frond samples in powder form in oven at 55ºC shown in figure 4.8 below. The averaged values for the drying of frond samples are attached in appendix.

Figure 4.8: Drying curve for fine powder of oil palm frond in oven at 55ºC

The moisture content from the drying curve analysis was determined to be 6%. Comparing to the moisture content from proximate analysis of 4% the value obtained is higher. The disagreement in value of moisture content is probably due to human factor during the measurement of the sample weight. The frond samples in form of powder took approximately 9 hours to dry before yielding a constant value for the weight measured. A constant weight reading is obtained during the first two hours of the experiment which is probably due to the samples needs to be heated homogeneously before the process of eliminating moisture begins.

4.5.1.2 Frond Samples of Size 15cm

The drying characteristic for frond samples of size 15cm in the oven at 55ºC is shown is figure 4.9 below. The detail averaged value for the drying of frond samples are attached in the appendix.

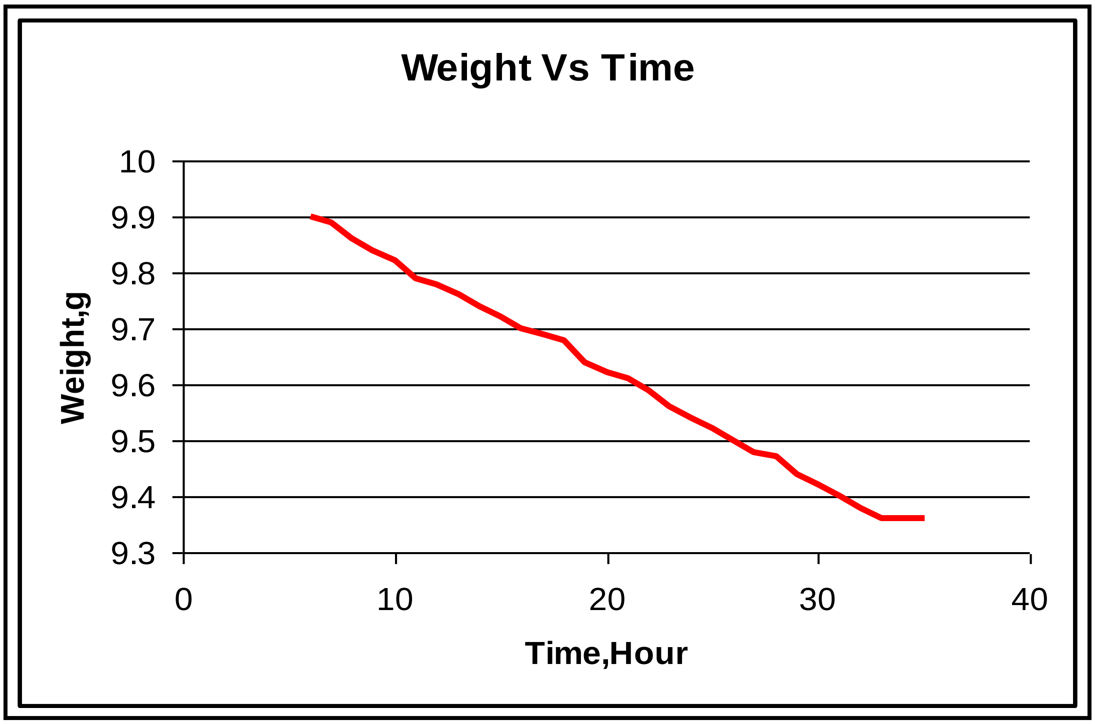


Figure 4.9: Drying curve for frond sample of size 15cm in oven at 55ºC

From the experiment done, the frond samples of size 15cm takes duration of 33 hours to yield a constant reading for weight. The final weight of the sample was measured to be 9.36 grams. The moisture content obtained from the drying test was determined to be 6.4% which is higher than the value obtained from the proximate analysis. The disagreement in value of moisture content is probably due to human factor during the measurement of the sample weight. The time to obtain a constant weight reading is higher than the time taken by the frond samples in powder form. It is evident than the drying capability is reduced as the area of exposure is reduced as the frond samples of size 15cm has smaller area of exposure than powder form.

4.5.1.3 Raw Frond Samples

The drying characteristic for raw frond samples in oven at 55ºC is shown in figure 4.10 below. The detail averaged value for the drying of frond samples are attached in appendix.

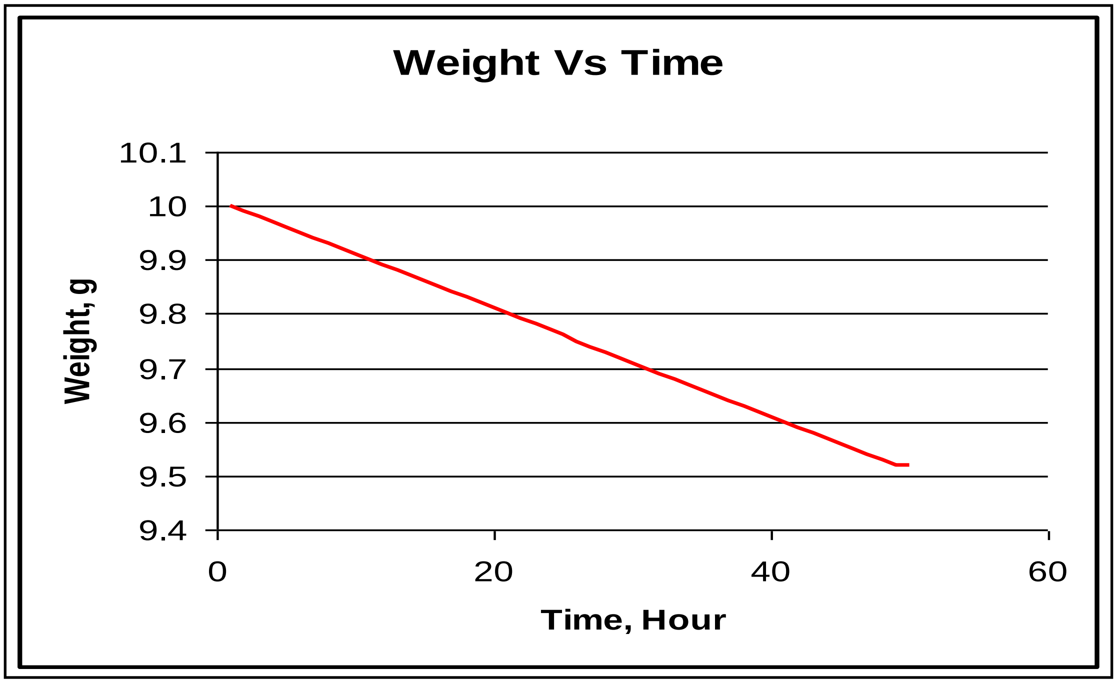


Figure 4.10: Drying curve for raw frond samples in oven at 55ºC

From the experiment done, the raw frond samples took a total duration of 49 hours to yield a constant weight reading. The final reading of the samples was determined to be 9.52g. The moisture content obtained from the experiment was determined to be 4.8% which is higher than the vale obtained from the proximate analysis. The disagreement in value of moisture content is probably due to human factor during the measurement of the sample weight. The time taken to eliminate the moisture content in the raw frond samples is higher than samples of size 15cm and samples in powder form. The best drying time is achieved by the samples in powder from given the same drying domain of 55ºC in the oven.

4.5.2 100W Light Source

The experiment for the drying of the frond samples using a 100W light source was to mirror the effect of leaving the frond samples to dry under direct sunlight. By using a light source, the domain of the experiment is controlled to rule out bad weather condition that may alter the test results. This experiment was also arbitrarily chosen to simulate a moderate drying situation which would be under the sun. The light source chosen for the research was OSRAM 100W, Class A CL 1000, 240V E27/ES model. The average temperature the frond samples were exposed to was determined to be 31^{o}C using an Lab Anemometer 320 I..

4.5.2.1 Frond Samples in Powder form

The drying characteristic for frond samples under a 100W light source is shown in figure 4.11 below. The detail averaged value for the frying of frond samples are attached in appendix.

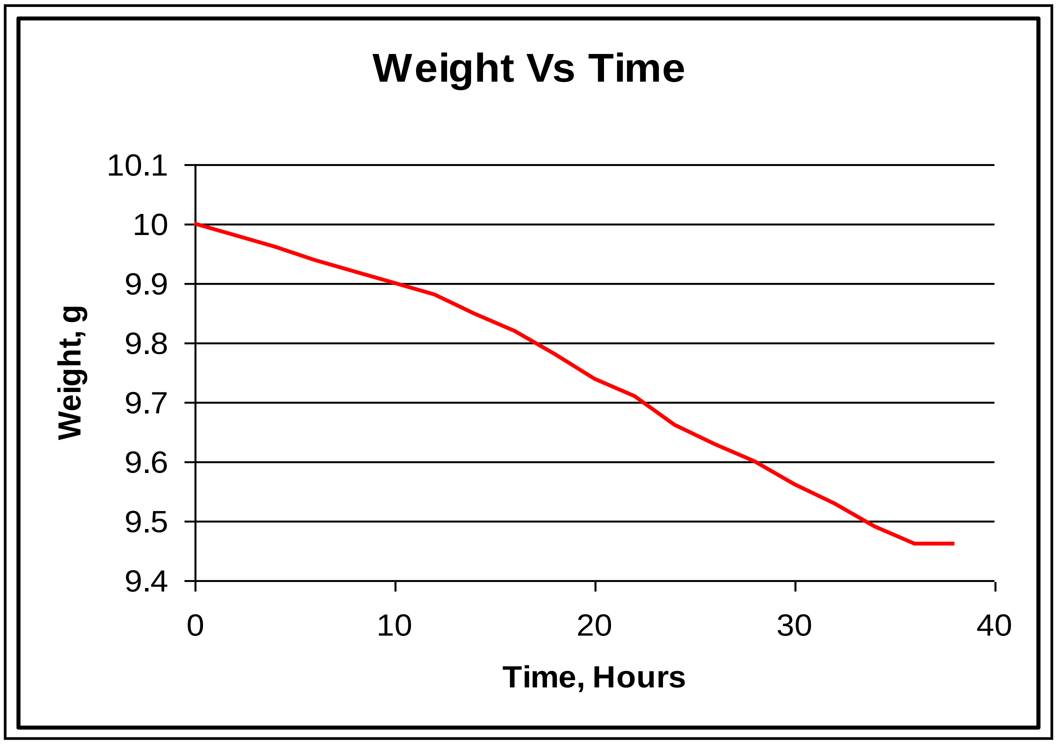


Figure 4.11: Drying curve for frond samples in powder form under a 100W light source.

From the experiment done, the frond samples in power form took a total of 36 hours before yielding a constant weight reading of 9.46 gram. The moisture content was determined to be 5.4%. The value obtained was higher than the moisture content obtained from proximate analysis. The disagreement in value of moisture content is probably due to human factor during the measurement of the sample weight. The drying time taken is higher than the same frond sample in oven at 55ºC.

4.5.2.2 Frond Samples of Size 15cm

The drying characteristic for frond samples of size 15cm under a 100W light source is shown in figure 4.12 below. The detail averaged value for the drying of frond samples are attached in appendix.

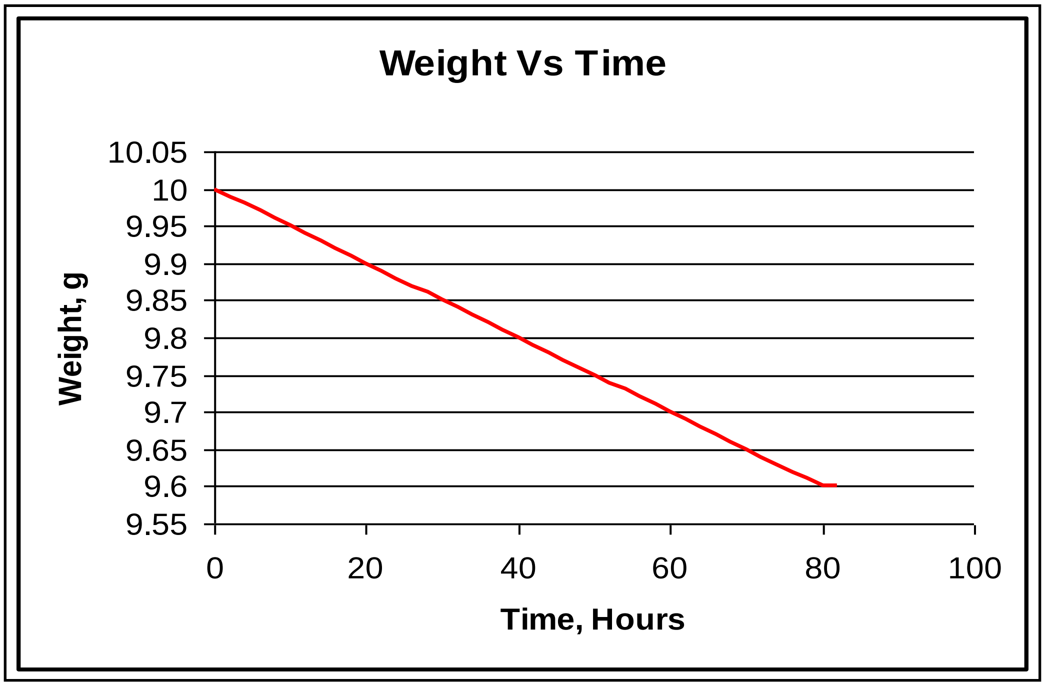


Figure 4.12: Drying curve for frond samples of size 15cm under a 100W light source

From the experiment done, the frond samples of size 15cm takes duration of 80 hours prior to yield a constant weight reading of 9.6g. The moisture content was determined to be 4% and this value agrees with the value obtained from the proximate analysis. The time taken to complete the drying process is higher than the frond samples in powder form. For the same samples of size 15cm, it takes longer to dry under the 100W light source than in the oven at 55ºC.

4.5.2.3 Raw frond samples

The drying characteristic of raw frond samples under a 100W light source is shown in figure 4.13 below. The details averaged value for the drying of frond samples are attached in appendix.

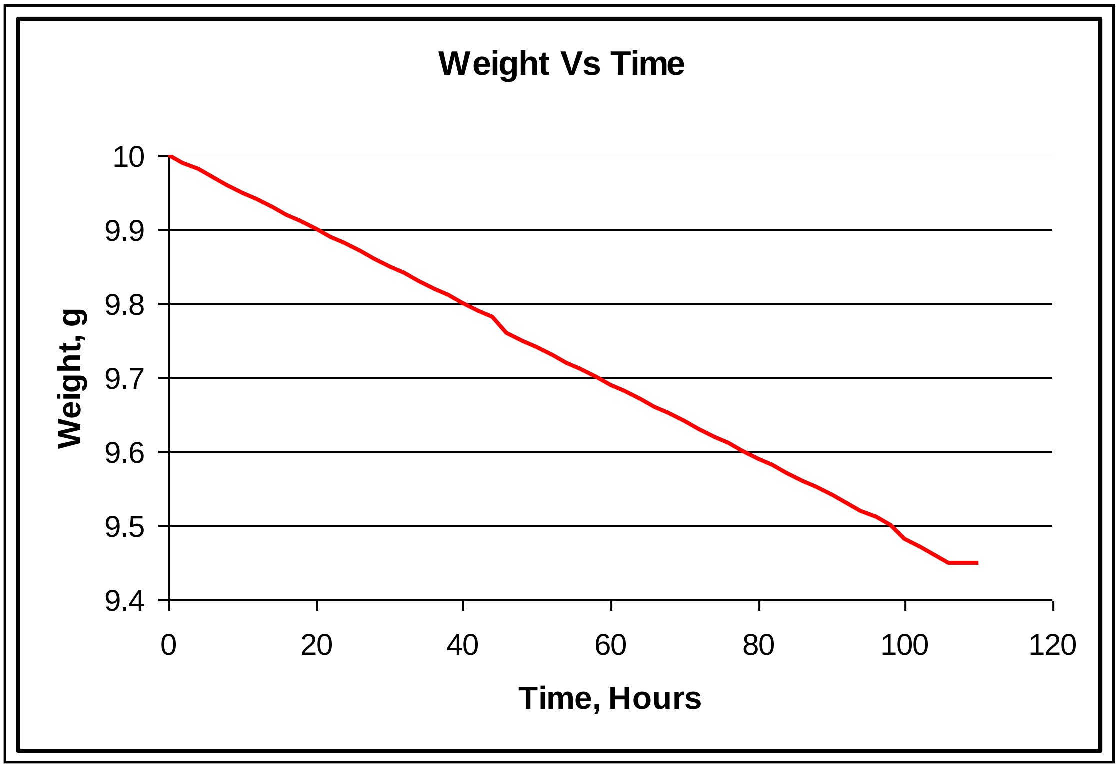


Figure 4.13: Drying curve for raw frond samples under a 100W light source.

From the experiment done, it was determined that the raw frond sample takes a duration of 106 hours before yielding a constant reading of 9.45g, under a 100W light source. The moisture content was determined to be 5.5% which is higher than the value obtained from the proximate analysis. The disagreement in value of moisture content is probably due to human factor during the measurement of the sample weight. The time taken for the raw frond samples is the highest. For a same given sample of raw fronds, it takes longer to dry under a 100W light source than in the oven at 55^{o}C.

4.5.3 Drying of Frond Samples in Lab

The experiment of drying the frond samples in the lab was to simulate the least favorable drying case of having no direct sunlight, no wind movement and a controlled environment. The purpose of the experiment was to gather an understanding on the drying characteristic of the fronds under a least favorable scenario and to compare the results with other drying situation. The average temperature in the lab was determined to be 27ºC and the average relative humidity was determined to be xxxxxxxx. The sample domains are to be varied from using frond samples in powder form, size of 15cm and raw frond samples.

4.5.3.1 Frond Sample in Powder Form

The drying characteristic for frond samples in powder form in the lab is shown in figure 4.14 below. The detail averaged value for drying of front samples are attached in appendix.

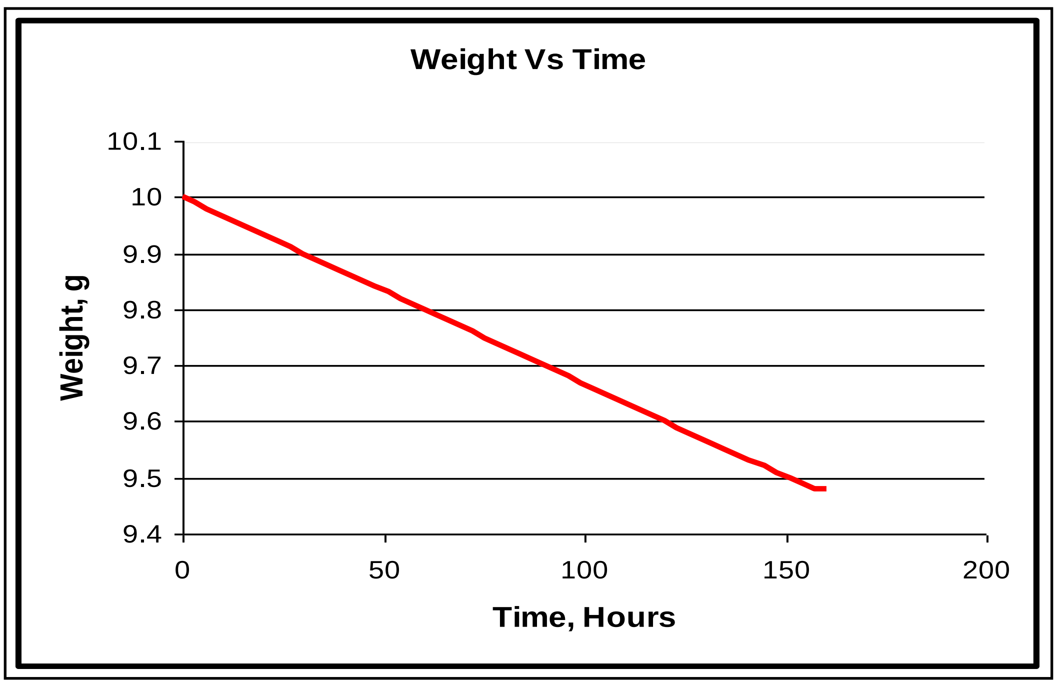


Figure 4.14: Drying curve for frond samples in powder form in the lab.

From the experiment done, drying of the frond samples in powder form in the lab takes approximately 157 hours to complete. The final constant weight reading was determined to be 9.48g which yields a moisture content of 5.2%. The moisture content obtained is higher than the results from proximate analysis and is probably caused by human factor error during the measurement of the sample weight. The frond samples take a longer time to dry compared to the drying in the oven at 55ºC and under a 100W light source. For a same given sample domain, drying under in the oven at 55ºC is determined to be the best as it takes the shortest time to eliminate its moisture content.

4.5.3.2 Frond Samples of Size 15cm

The drying characteristic for frond samples of size 15cm is presented in figure 4.15 below. The detail averaged drying value for drying of frond samples are attached in appendix.

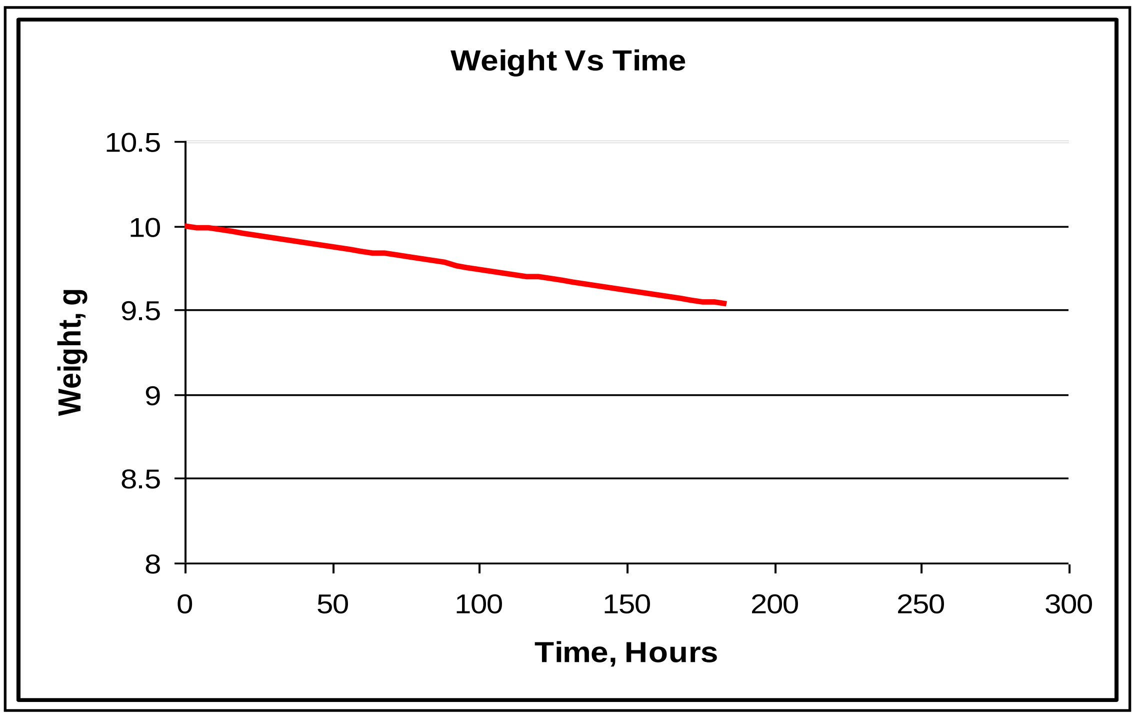


Figure 4.15: Drying curve for frond samples of size 15cm in the lab.

From the experiment done, the drying for the frond samples of size 15cm was still showing a reduction in weight after 184 hours. The time taken to yield a constant weight reading has to be determined by extrapolating the graph due to time constraint. Assuming average moisture content of 6%, the time taken to complete the drying process was determined to be approximately 236 hours to complete. For the same given sample domain, the drying in the lab takes the longest time compared to drying under a 100W light source and in the oven at 55ºC.

4.5.3.3 Drying of Raw Frond Samples

The drying characteristic for raw frond samples in the lab is shown in figure 4.16 below. The detail averaged drying value for the drying on frond samples are attached in appendix.

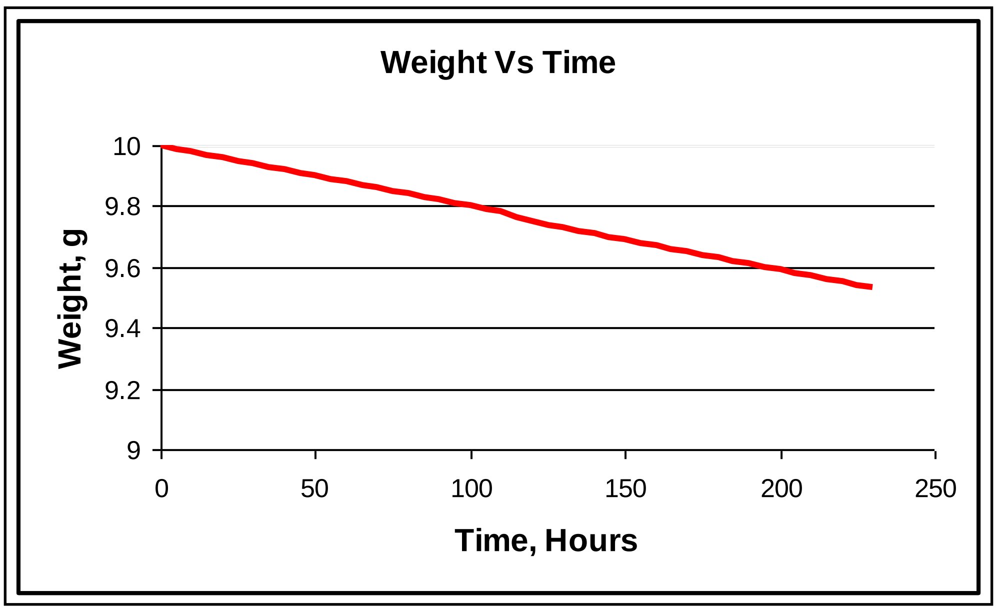


Table 4.16: Drying curve for raw frond samples in the lab.

From the experiment done, the drying for raw frond samples was still showing a reduction in weight after approximately 230 hours. The time taken to yield a constant reading of weight had to be determined by extrapolating the graph obtained due to time constraint. Assuming average moisture content of 6%, the time taken to complete the drying process was determined to be approximately 290 hours. For the same given sample domain, the raw frond samples took the longest time to dry compared to drying under a 100W light source and in the oven at 55ºC.

From all the experiments done to understand the drying characteristic of the oil palm fronds under various situations, it was determined that the best drying condition is in the oven at 55 followed by under a 100W light source and in the lab respectively. The drying time is also affected by the frond sample size where the best drying time is achieved by frond samples in powder form in all there different drying situations.

The differences in drying time for the frond samples in powder form are shown in figure 4.17 below:

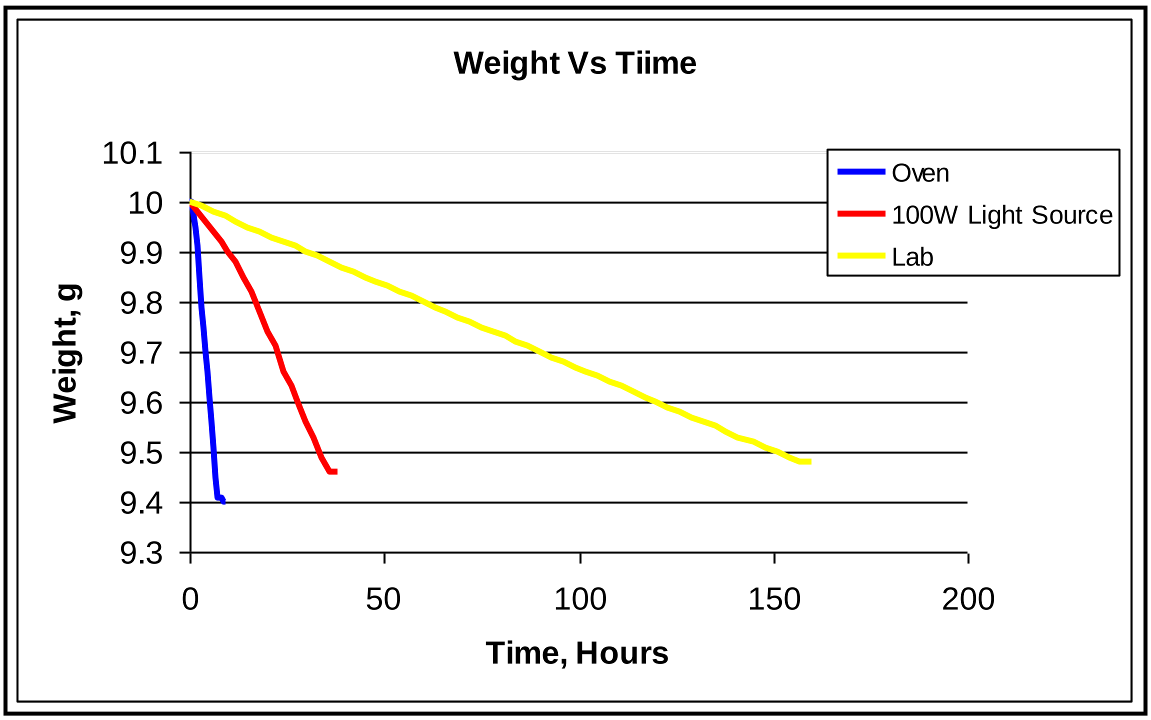


Figure 4.17: Drying time for frond samples in powder form under various conditions. Frond samples in power from takes approximately 9, 36 and 157 hours to completely dry in the oven at 55ºC, under a 100W light source and in the lab respectively. The differences in moisture content obtained is due to human error involved during the process of recording the weight loss and also the differences in the natural moisture content in the sample itself

The differences in drying time for the frond samples of size 15cm are shown in figure 4.18 below:

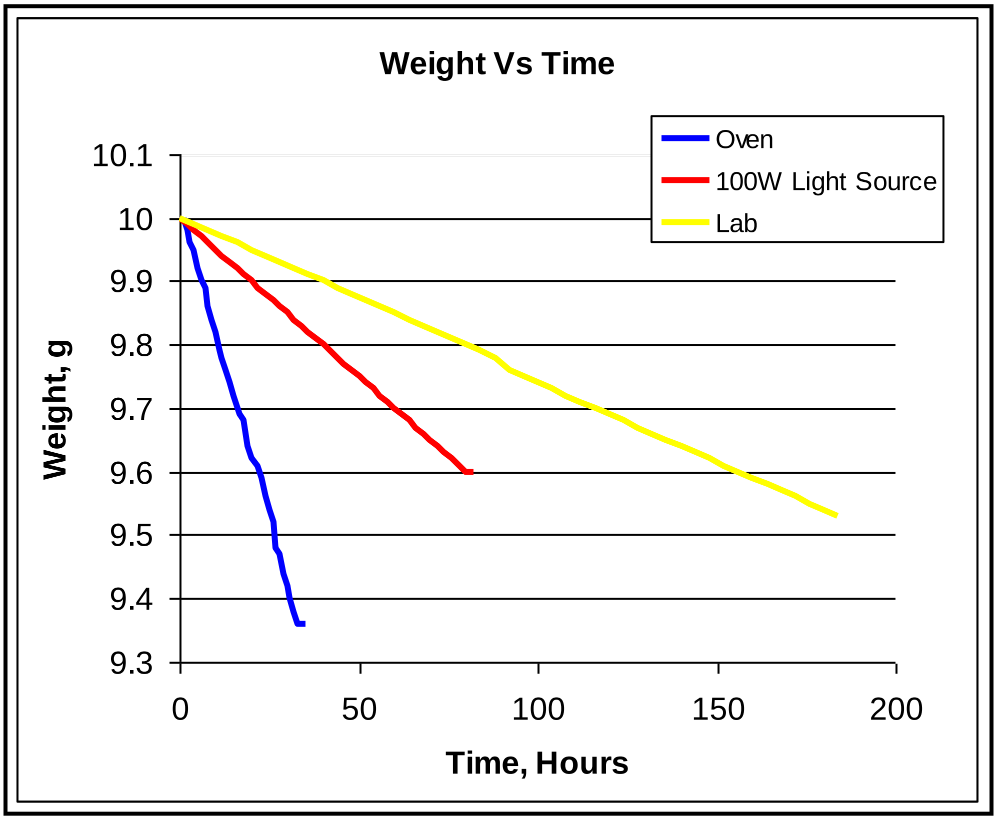


Figure 4.18: Drying time for frond samples of size 15cm under various conditions.

Frond samples of size 15cm takes approximately 33, 80 and 184 hours to completely dry in the oven at 55ºC, under a 100W light source and in the lab respectively. The differences in moisture content obtained is due to human error involved during the process of recording the weight loss and also the differences in the natural moisture content in the sample itself.

The differences in drying time for the raw frond samples are shown in figure 4.19 below:

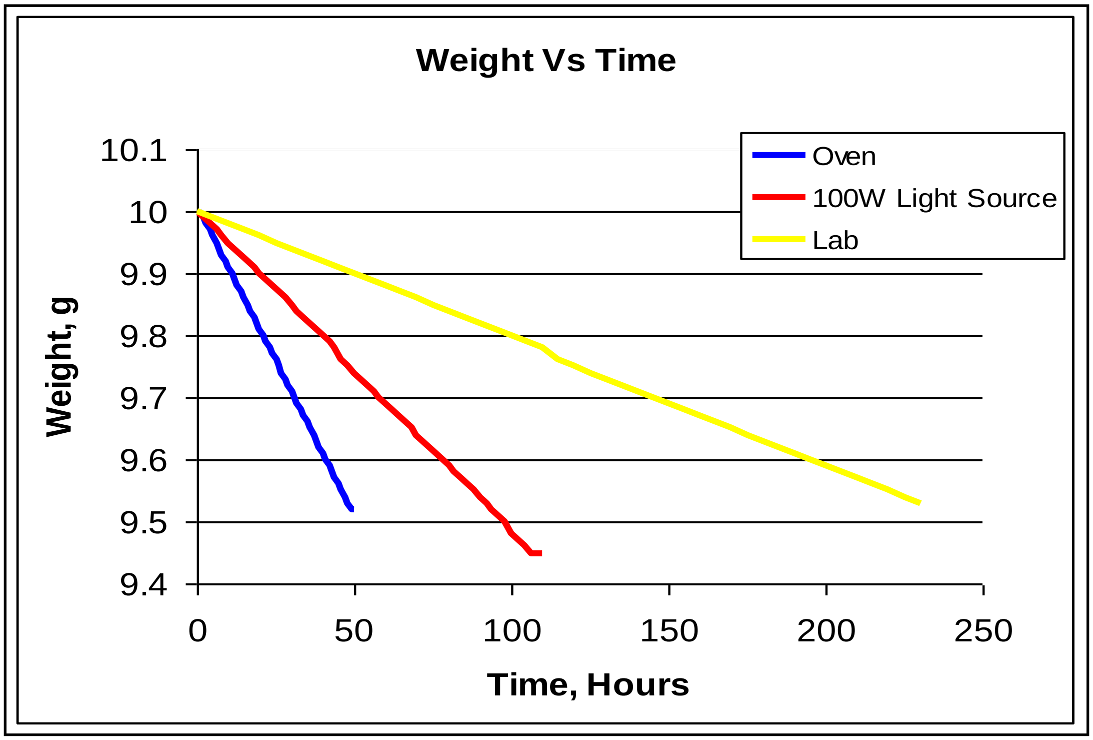


Figure 4.19: Drying time for raw frond samples under various conditions.

Raw frond samples take approximately 49, 106 and 230 hours to completely dry in the oven at 55ºC, under a 100W light source and in the lab respectively. The differences in moisture content obtained is due to human error involved during the process of recording the weight loss and also the differences in the natural moisture content in the sample itself.

CHAPTER 5

CONCLUSION

The feasibility of using oil-palm fronds for biomass gasification is evident from the results obtained from the present research. The fronds show positive results from both chemical and physical analysis as discussed in previous chapters. The project has successfully met all its predetermined objectives to justify the feasibility of using oil palm frond in a gasification system. For future works, the oil-palm fronds would be further investigated by investing in constructing a downdraft gasifier to gain an understanding on the operational behavior of the fronds. It is hoped that the present research would provide a platform for future application of the project on large scale. A successful application of the present work on a large scale system would provide an alternative way to produce energy that is renewable and environmental friendly.

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APPENDICES

Table 4.5 Averaged value for drying of powder samples in oven at 55ºC.

Time, hour	0.0	0.5	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Weight, gram	10	10	9.95	9.91	9.85	9.79	9.75	9.70	9.66

Time, hour	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5
Weight,gram	9.61	9.56	9.51	9.45	9.41	9.41	9.41	9.40	9.40	9.40

Table 4.6 Averaged value for drying of frond sample of size 15cm in oven at 55ºC.

Time, Hour	**Weight, g**	**Time, Hour**	**Weight, g**	**Time, Hour**	**Weight, g**
1	10	13	9.76	25	9.54
2	9.98	14	9.74	26	9.52
3	9.96	15	9.72	27	9.48
4	9.95	16	9.7	28	9.47
5	9.92	17	9.69	29	9.44
6	9.9	18	9.68	30	9.42
7	9.89	19	9.64	31	9.4
8	9.86	20	9.62	32	9.38
9	9.84	21	9.78	33	9.36
10	9.82	22	9.61	34	9.36
11	9.79	23	9.59	35	9.36
12	9.78	24	9.56		

Table 4.7: Averaged value for drying of raw frond samples in oven at 55ºC.

Time, Hour	Weight, g	Time, Hour	Weight, g	Time, Hour	Weight, g
1	10	18	9.83	35	9.66
2	9.99	19	9.82	36	9.65
3	9.98	20	9.81	37	9.64
4	9.97	21	9.8	38	9.63
5	9.96	22	9.79	39	9.62
6	9.95	23	9.78	40	9.61
7	9.94	24	9.77	41	9.6
8	9.93	25	9.76	42	9.59
9	9.92	26	9.75	43	9.58
10	9.91	27	9.74	44	9.57
11	9.9	28	9.73	45	9.56
12	9.89	29	9.72	46	9.55
13	9.88	30	9.71	47	9.54
14	9.87	31	9.7	48	9.53
15	9.86	32	9.69	49	9.52
16	9.85	33	9.68	50	9.52
17	9.84	34	9.67		

Table 4.8: Averaged value for drying of frond samples in power form under 100W light.

Time, Hour	Weight, g	Time, Hour	Weight, g
0	10	20	9.74
2	9.98	22	9.71
4	9.96	24	9.66
6	9.94	26	9.63
8	9.92	28	9.6
10	9.9	30	9.56
12	9.88	32	9.53
14	9.85	34	9.49
16	9.82	36	9.46
18	9.78	38	9.46

Table 4.9: Averaged value for drying of frond samples of size 15cm under 100W light.

Time, Hour	Weight, g	Time, Hour	Weight, g	Time, Hour	Weight, g
0	10	28	9.86	56	9.72
2	9.99	30	9.85	58	9.71
4	9.98	32	9.84	60	9.7
6	9.97	34	9.83	62	9.69
8	9.96	36	9.82	64	9.68
10	9.95	38	9.81	66	9.67
12	9.94	40	9.8	68	9.66
14	9.93	42	9.79	70	9.65
16	9.92	44	9.78	72	9.64
18	9.91	46	9.77	74	9.63
20	9.9	48	9.76	76	9.62
22	9.89	50	9.75	78	9.61
24	9.88	52	9.74	80	9.6
26	9.87	54	9.73	82	9.6

Table 4.10: Averaged value for drying of raw frond samples under 100W light

Time, Hour	Weight, g	Time, Hour	Weight, g	Time, Hour	Weight, g
0	10	38	9.81	76	9.61
2	9.99	40	9.8	78	9.6
4	9.98	42	9.79	80	9.59
6	9.97	44	9.78	82	9.58
8	9.96	46	9.76	84	9.57
10	9.95	48	9.75	86	9.56
12	9.94	50	9.74	88	9.55
14	9.93	52	9.73	90	9.54
16	9.92	54	9.72	92	9.53
18	9.91	56	9.71	94	9.52
20	9.9	58	9.7	96	9.51
22	9.89	60	9.69	98	9.5
24	9.88	62	9.68	100	9.48
26	9.87	64	9.67	102	9.47
28	9.86	66	9.66	104	9.46
30	9.85	68	9.65	106	9.45
32	9.84	70	9.64	108	9.45
34	9.83	72	9.63	110	9.45
36	9.82	74	9.62		

Table 4.11: Averaged value for drying of frond samples in powder form in the lab.

Time, Hour	**Weight, g**	**Time, Hour**	**Weight, g**	**Time, Hour**	**Weight, g**
0	10	54	9.82	108	9.64
3	9.99	57	9.81	111	9.63
6	9.98	60	9.8	114	9.62
9	9.97	63	9.79	117	9.61
12	9.96	66	9.78	120	9.6
15	9.95	69	9.77	123	9.59
18	9.94	72	9.76	126	9.58
21	9.93	75	9.75	129	9.57
24	9.92	78	9.74	132	9.56
27	9.91	81	9.73	135	9.55
30	9.9	84	9.72	138	9.54
33	9.89	87	9.71	141	9.53
36	9.88	90	9.7	145	9.52
39	9.87	93	9.69	148	9.51
42	9.86	96	9.68	151	9.5
45	9.85	99	9.67	154	9.49
48	9.84	102	9.66	157	9.48
51	9.83	105	9.65	160	9.48

Table 4.12: Averaged value for drying of frond sample of size 15cm in the lab.

Time, Hour	**Weight, g**	**Time, Hour**	**Weight, g**	**Time, Hour**	**Weight, g**
0	10	64	9.84	128	9.67
4	9.99	68	9.83	132	9.66
8	9.98	72	9.82	136	9.65
12	9.97	76	9.81	140	9.64
16	9.96	80	9.8	144	9.63
20	9.95	84	9.79	148	9.62
24	9.94	88	9.78	152	9.61
28	9.93	92	9.76	156	9.6
32	9.92	96	9.75	160	9.59
36	9.91	100	9.74	164	9.58
40	9.9	104	9.73	168	9.57
44	9.89	108	9.72	172	9.56
48	9.88	112	9.71	176	9.55
52	9.87	116	9.7	180	9.54
56	9.86	120	9.69	184	9.53
60	9.85	124	9.68		

Table 4.13: Averaged value for drying of raw frond samples in the lab.

Time, Hour	**Weight, g**	**Time, Hour**	**Weight, g**	**Time, Hour**	**Weight, g**
0	10	80	9.84	160	9.67
5	9.99	85	9.83	165	9.66
10	9.98	90	9.82	170	9.65
15	9.97	95	9.81	175	9.64
20	9.96	100	9.8	180	9.63
25	9.95	105	9.79	185	9.62
30	9.94	110	9.78	190	9.61
35	9.93	115	9.76	195	9.6
40	9.92	120	9.75	200	9.59
45	9.91	125	9.74	205	9.58
50	9.9	130	9.73	210	9.57
55	9.89	135	9.72	215	9.56
60	9.88	140	9.71	220	9.55
65	9.87	145	9.7	225	9.54
70	9.86	150	9.69	230	9.53
75	9.85	155	9.68		

FIRE TUBE DIMENSIONS.

Inside diameter (inches)	Minimum length (inches)	Engine power (hp)	Typical engine displacement (cubic inches)
2-	16	5	10
4-	16	15	30
6	16	30	60
7	18	40	80
8	20	50	100
9	22	65	130
10	24	80	160
11	26	100	200
12	28	120	240
13	30	140	280
14	32	160	320

*A fire tube with an inside diameter of less than. 6 in. would create bridging problems with wood chips and blocks. If the engine is rated at or below 15 borsepower, use a 6-in. minimum fire tube diameter and create a throat restriktion in the bottom of the tube corresponding to the diameter entered in the above table.

NOTES: For engines with displacement rated in liters, the conversion factar is 1 liter = 61.02 cubic inches.

The horsepower listed above is the SAE net brake horsepower as measured at the rear of the transmission with standard accessories operating. Since the figures vary when a given engine is installed and used for different purposes, such figures are representative rather than exact. The above Horsepower ratings are given at the engine's highest operating speed.