

**DETERMINATION OF THE CHARACTERISTICS OF SOLID FUEL
DEVELOPED FROM A MIXTURE OF THERMOPLASTIC
WASTES AND CLAY MATERIALS**

**BY
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DECLARATION

I, Terence Oballim, do hereby declare that this research report contains my original work and has not been submitted in whole or in part to any University or Academic Institution for an academic award.

Signed: **Date:**

APPROVAL

This research by Terence Oballim was developed and carried out under our close supervision. The report is hereby cleared to be submitted to Board of Examiners and Graduate School of Kyambogo University with our due approval.

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DEDICATION

This work is dedicated to; my beloved mother Ventorina Akech, my wife Ajok Mirriam and my two sons Kimara Jonathan & Laloyo Jeremiah. You have always been there for me when I needed you most during this hectic period. May God, the Almighty, reward all of you abundantly for the love, care, protection, encouragement, kindness and guidance that you showed me.

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ABSTRACT

This study was driven by the fact that plenty of plastics which have potentials to be used as source of fuel are left as wastes in the environment without proper utilization. The study was directed toward the use of a particular type of plastics for making a plastic based solid fuel and to find its viability for use as source of energy. Polyethylene – terephthalate (PET) material obtained from waste mineral water bottles and ball clay were mixed to form PET – Clay Solid Fuel (PETCSF) product. Clay was mixed with plastics to avoid melt flowing or dropping of the fuel in the stove during combustion.

The parameters of the developed PETCSF those were determined to find its viability as source of energy were Mass of melt drops, mass combustion rate, mass of ash and the calorific value. The following Clay Plastic Ratio (CPR) 1:2.43, 1:2.33 and 1:1.20 were found to be sufficient in stopping melt dropping behavior of the developed solid fuel in the stove during combustion.

The calorific values of the PETCSF were found to be 14,335 J g⁻¹, 14,170 J g⁻¹ and 11,182 J g⁻¹ for CPR = 1:2.43, 1:2.33 & 1:1.20 respectively. Calorific values of an equal mass of charcoal, paper and Benzoic acid tablet (used as reference solid fuel materials) were 7,316 J g⁻¹, 12,475 J g⁻¹ and 24,239 J g⁻¹ respectively. The mass combustion rates for CPR = 1:2.43, 1:2.33 & 1:1.20 were found to be 2.45 g minute⁻¹, 2.43 g minute⁻¹ and 1.98 g minute⁻¹ respectively. The mass of ash left after combustion for the above respective CPR values were 36.64 g, 37.37 g and 50.73 g respectively.

When compared, the calorific value of the developed PETCSF was found to be about two times higher than for charcoal of an equal mass. Benzoic acid tablet had the highest calorific value. Thus, PETCSF is a viable source of fuel compared to charcoal in terms of the calorific value and moreover its combustion rate can be controlled by using a specific CPR of 1:2.43 as shown by the result of the study.

The population should be encouraged by the findings in this study and to begin thinking of using plastic based solid fuel as an alternative to charcoal and firewood which currently are the only predominant sources of fuel for majority of the population. The used plastic based solid fuel in an oxygen rich environment (or sufficient air circulation) is strongly recommended as complete combustion is guaranteed. Insufficient air supply may lead to incomplete combustion of the fuel and possibly release of particles (soot/smoke) which if inhaled may be harmful to the user.

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Energy is an important requirement that dictates the rate of development of a society or a nation. The availability of energy resource therefore becomes a foundation stone for the economic development or growth of any society or a nation as a whole. Energy is required at a small scale for domestic applications such as provision of lighting and heating in homes to large scale applications in industries and agricultural production. It is also required for construction and transport sectors development. Energy is required in huge quantity in its different forms such as electrical energy, thermal energy and mechanical energy depending on the application.

The demand for energy in Uganda has been increasing with increase in population. Uganda's population has continued to grow rapidly over time. The population increased from 9.5 million people in 1969 to 34.9 million people in 2014 (UBOS, 2015). Between 2002 and 2014 the population increased from 24 million people to about 35 million people representing an average annual growth rate of 3.0% (UBOS, 2015 & UN, 2015). The population growth rate in 2016 was at 3.2% (World Watch Institute, 2016). Based on the population growth rate of 3.2% it can be projected that the population will increase from 35 million people in 2014 to about 53 million people in 2030. This fast growing population is engaged in a number of economic and production activities as means to improve livelihood. These economic and production activities are vital for the country's growth and development and they require huge amount of energy for their sustainability. The demand for energy in the country is therefore bound to increase as the population continues to increase.

The major energy sources in Uganda include biomass, hydropower, geothermal, petroleum/oil, solar, and wind (Tumwesigye, et al., 2011; MEMD, 2008 and Adeyemi & Asere, 2014). Of all these sources, only biomass, hydropower and oil/petroleum contribute most to the total energy consumption in the country. Figure 1.1 is a pie chart showing the energy supply sources in Uganda (MEMD, 2008).

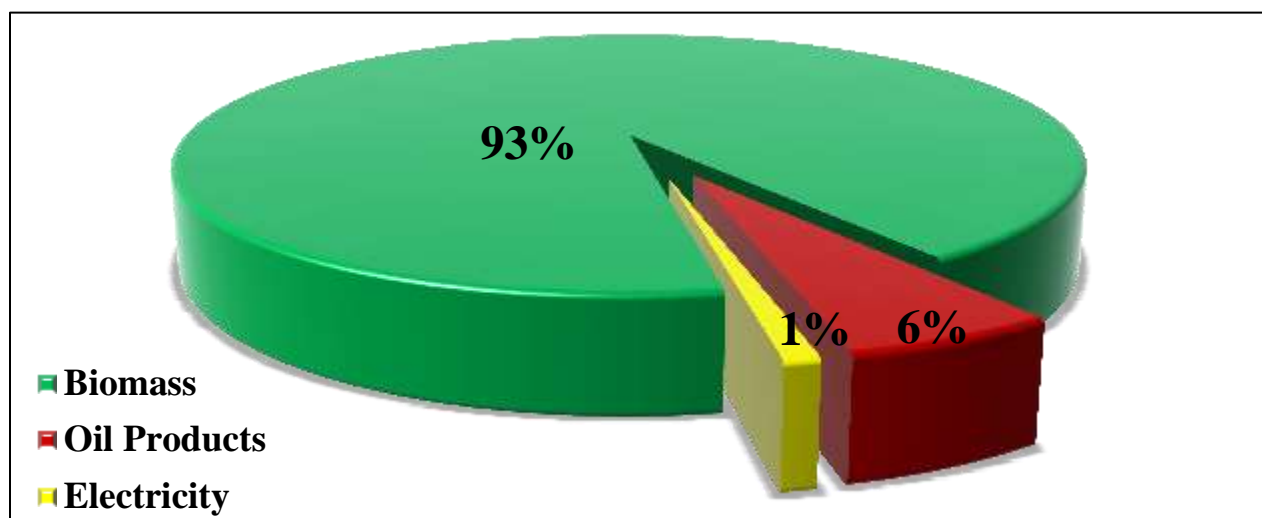


Figure 1.1: Pie chart of energy supply sources in Uganda. Source: (MEMD, 2008).

Biomass is the most predominant and important source of energy contributing to 93% of the total primary energy consumption in Uganda. Oil products (petroleum & diesel) contribute 6% while electricity (mainly hydropower) contributes only 1 % respectively to the country's total primary energy consumption as shown in figure 1.1 (MEMD, 2008). Out of the 93% of energy contributed by biomass, firewood accounts for 78.7%, charcoal 9.6% and crop residues 4.7% (MEMD, 2014). Over 90% of the population in Uganda depends on biomass for their energy needs. Uganda Bureau of Statistics (UBOS) conducted a survey between the years 2009/2010 on households' energy demands in the country and reported that, 82% of households use firewood for cooking while 15% use charcoal. The same report specified that firewood was most commonly used by rural households (86%) while charcoal is commonly used in urban and semi urban areas (70%). In Kampala alone as an example of urban setting, 76% of the population use charcoal as their main source of fuel for cooking (UBOS, 2009/10, 2014/2015). In rural areas energy is obtained mainly from biomass of which raw wood accounts for 80%, charcoal 10% and crop residues 4% (MEMD, 2008). The production of charcoal has been increasing from 333 ktoe in 2000, to 551 ktoe in 2005, 1799 ktoe in 2012 and to a higher value of 1,978 ktoe in 2015 with projected figure of 2,353 ktoe in 2017 (AFREC, 2017). The conversion of wood into charcoal is highly inefficient and it is estimated that 16 million tons of wood are converted into 1.8 million tonnes of charcoal every year (MEMD, 2013). The total nominal value of households' expenditure on charcoal and firewood consumption increased from Shillings 32.8 billion in 2005/2006 financial year to Shillings 409.1 billion in 2009/2010 financial year (UBOS, 2013). The value of charcoal and firewood

consumption increased by more than 10 times between financial years, 2005/2006 and 2009/2010 (UBOS, 2013).

Electricity supply activities in the country grew by 5.6% in 2014/2015 financial year compared to a lower growth of 1.9% in 2013/2014 financial year (UBOS, 2015). Total electricity production in 2015 was 276 kilo tons of oil equivalents (ktoe) with 74.6 percent produced from hydro, 19 percent from fossil fuels and 5.4 percent from biofuels and waste (AFREC, 2017). Final electricity consumption in the same year was 805 GWh (AFREC, 2017). It is estimated that Uganda needs 2000 Mega Watts (MW) of electricity by the year 2025 (Energy System, 2009), in order to sustain its growing population and keep on track with the increasing economic activities in the country.

Imported volume of petroleum products (petroleum, diesel and kerosene) increased by 13.4% and 8.2% for petrol and diesel respectively in 2014 compared to the imported volume of the same products in 2013. An 8.4% decreased in imported volume of kerosene was reported in 2014 compared to that in 2013 (UBOS, 2015). These statistics show the overwhelming demand for energy in the country to sustain production that can cope with population growth with wood being the major source of fuel in the country upon which the population will depend on for energy for many years to come.

This high dependence on wood and wood derivatives for fuel to provide energy to the majority of the population is putting unbearable pressure on the Uganda's forests and trees. Uganda is estimated to have a forest area of 2,347,400 Hectares, representing a forest area of 9% of the total land area (MEMD, 2016). Uganda's vegetation cover (trees, forests and woodlands) significantly reduced from 45% in 1890 to about 14% in 2010 and to 11.7% in 2013 (MEMD, 2016)., due to the ever increasing pressure and demand exerted by the rapid population growth and economic activities (MEMD, 2016). On average, Uganda has been losing 122,000 hectares (301,000 acres) of forest per year since 1990, for charcoal production (NFA, 2016). If the reduction in the vegetation cover is not curbed, Uganda's forest cover will not improve and attain the Uganda Vision target of 24% (MEMD, 2016). The reduction in the vegetation cover in Uganda is resulting into serious negative environmental and climatic impacts like prolonged dry spells, unpredictable climatic changes, increased global warming phenomena, desertification, and destruction of the ecosystem, soil degradation, which ultimately affect human in terms of productivity, besides jeopardy of conservation of natural resources. Trees/forests are known to be natural traps for the Carbon-dioxide (CO₂) a common Green House Gas (GHG) that leads to global warming through the destruction of the ozone layer in the earth atmosphere. The increased and continued burning of wood as fuel results in the emission of large quantity of carbon dioxide. The destruction of these

trees and forests for fuel only magnifies negative environmental and climatic effects on our eco - system. To mitigate the negative environmental and climatic effects resulting from cutting down of trees and destruction of forests in the country, many districts authorities in collaboration with national authorities such as National Environmental Management Authority (NEMA) and National Forest Authority (NFA) are putting embargo (a ban) on the production and supply of charcoal in order to conserve forests and trees to alleviate the negative environmental and climatic effects being experienced in the country. Such a move though good and worth taking on, also leaves the ever rising population with no alternative and affordable source of fuel to derive energy from since the main source of fuel in the country is biomass. This can be addressed if other combustible materials such as plastics are converted into fuel to provide thermal energy for most heating applications both at homes and in industries.

Plastic materials have unique properties including being light weight, tough, flexible, able to melt and solidify after cooling as well as release energy on combustion (Andrady & Neal, 2009; UNEP, 2009). Plastics are of two major types namely Thermoplastics and Thermosetting plastics. Thermoplastics are known to melt and solidify again and again when heated and can be molded into various shapes. They are also resistant to chemical attacks and fatigue. Thermoplastics have high molecular masses, are durable (take hundreds of years before degrading) and are cheaper to manufacture. Thermoplastics have gained wide spread usage worldwide and are continued to be demanded for due to their unique properties which make them suitable materials for various applications such as in spacecraft, in automobile, in industries, and commercial sector development. Plastic products are also used in; medical, educational, construction and domestic settings. As such, the demand, production and consumption of plastic materials and products derived from them have increased tremendously worldwide for these applications (UNEP, 2009; World Watch Institute, 2015). The world's annual plastic consumption has increased about 20 times from 5 million tons in 1950s to nearly 100 million tons in the year 2009 (UNEP, 2009).

In Uganda plastics import in primary and non-primary forms into the country has increased over time. In 2012, plastics import in primary and non – primary form was at 2.6% and 0.6% respectively (UBOS, 2013). There were no data on the importation of plastics both in primary and non-primary forms in previous years to compare with data published in 2012. Being a landlocked country, Uganda imports majority of its plastics and packaging requirements from regional and international suppliers and has emerged as a major importer of plastics in the East Africa. This information indicates how much plastics are being consumed in the country. Thus, the demand for plastic products is rising rapidly in Uganda. Most of these plastic products are single use types and

end up being discarded as wastes shortly after acquisition by the users. Therefore, as demand for and consumption of plastic products increase so is the accumulation of plastic wastes in the country. In fact 600 tons of plastics waste is generated daily in Uganda and 80% of these generated waste plastics remains uncollected or recycled (Okwoko, 2020). Waste management in Uganda is generally still very poor and rudimentary, characterized by dumping in environmentally sensitive areas like wetlands, streams, rivers, and forest edges and landfills (OAG, 2010). In many instances these wastes are left unutilized or uncollected (OAG, 2010).

Banga (2013) and Komakech et al., (2014) studied the composition by percentage weight of the different materials in the solid wastes in the Kampala Landfill. Figures 1.2 & figure 1.3 showed that on average 5.35% of the solid wastes delivered to the Kampala's land fill are plastic materials. The average 5.35% is only for the plastic wastes managed to be collected but there are many more uncollected or unmanaged plastic wastes in the country and these are very harmful to our environment. Littering, blocking (clogging) of drainage and sewage pipes and channels, contamination of water sources, killing of aquatic lives and soil degradation are some of the immediate negative impacts of waste plastics in the environment.

In addition, shortages of alternative source of fuels to provide the needed thermal energy for domestic applications such as for cooking has resulted into massive cutting down of trees and destruction of forests for charcoal production, a practice which is also negatively and severely depriving the environment of vegetative cover needed to moderate the climatic conditions. It is thus contributing to global warming phenomena and affects the rain pattern.

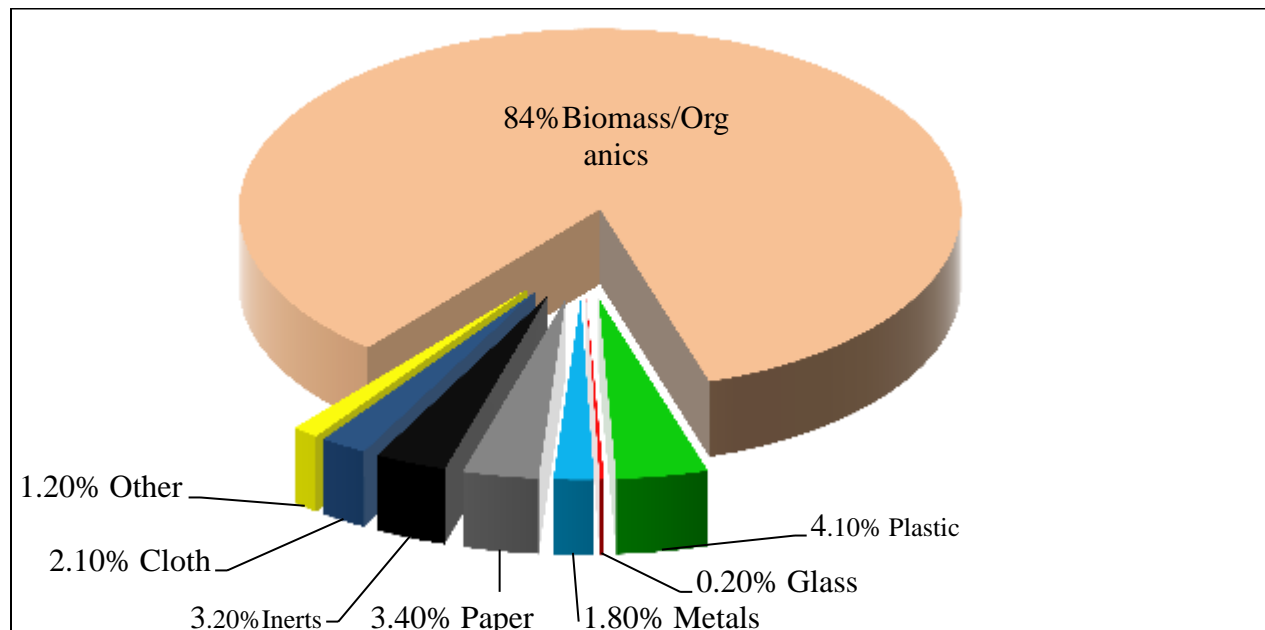


Figure 1.2: Pie chart of Solid Waste Composition in Kampala Landfill. Source: (Banga. 2013).

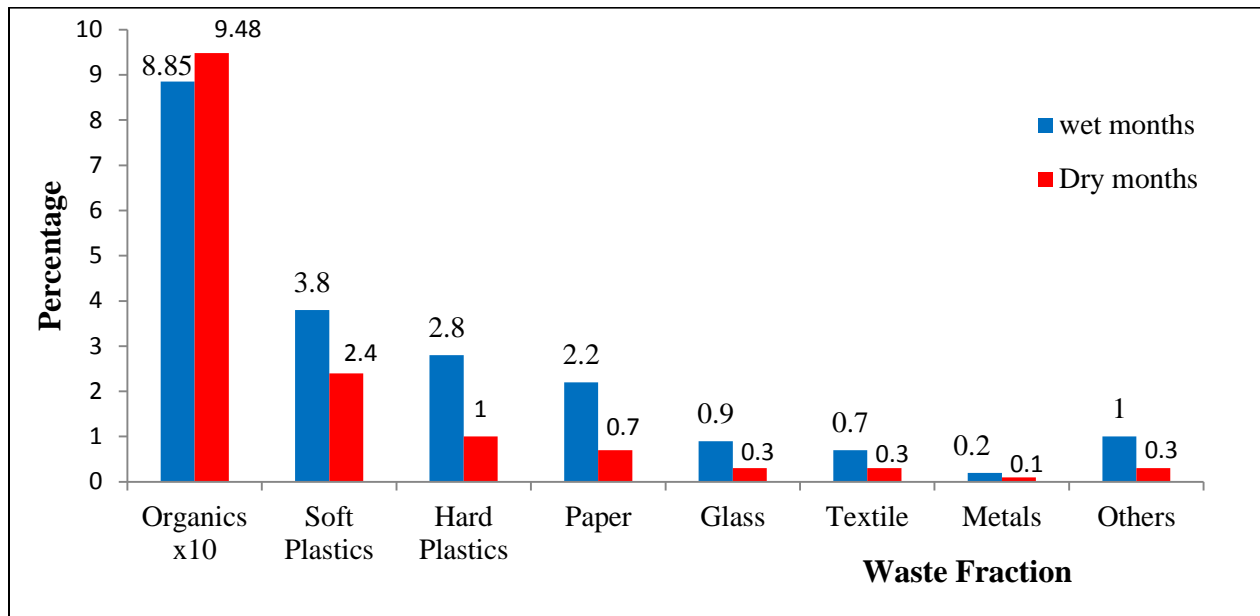


Figure 1. 3: Bar chart of Solid Waste delivered to Kampala Landfill during Dry and Wet Months. Source: (Komakech et al., 2014).

1.2 Statement of the Problem

Unavailability of electricity in most rural areas, high price of electricity in urban areas and the limited alternative sources of fuel in the country has left the population with no option other than to rely largely on wood (charcoal and firewood) for fuel both in urban and rural areas. Such a heavy dependence on wood and charcoal for fuel has led to massive cutting down of trees and forest to produce charcoal and firewood in the country – a practice which is harmfully affecting the environment and the climate. The rising demand and use of plastic materials as packaging material and particularly its use in large quantities for most domestic, industrial and other applications is producing huge quantities of unwanted disposable plastic products which end up as wastes into the environment. The management of plastic wastes is still very poor in the country and in many cases these plastics wastes end up in wetlands, water bodies and other open places. These disposable plastics wastes are affecting our environment and could be used as an alternative source of energy to cater for the shortages of fuel sources in the country since plastics are combustible.

However, the use of plastics as a fuel resource in the country has not yet been adequately explored. Therefore, determining the characteristics of the solid fuel developed from thermoplastics wastes would provide information on how viable plastic based solid fuel can be used as alternative source of energy.

1.3 Purpose of the study

The purpose of this study was to determine combustion characteristics of solid fuel developed from discarded (waste) polyethylene – terephthalate (PET) water & soda bottles mixed with different amount of ball clay with a view of finding the viability of the developed solid fuel being used as energy source.

1.4 The specific objectives of the study

The objectives of the study were to:

- i. Find the Clay – Plastic Ratio (CPR) for zero mass of melt drops of the solid fuel in the burner.
- ii. Determine the mass combustion rate of the solid fuel for zero melt drops in the stove.
- iii. Measure the mass of ash content of the solid fuel for zero melt drops in the stove.
- iv. Record the calorific value of the solid fuel for zero melt drops in the stove.
- v. Compare the calorific value of the solid fuel for zero melt drops in the stove with the calorific value of charcoal as a reference solid fuel.

1.5 Scope of the study

Solid Fuels samples were produced by mixing a fixed mass (300 g) of molten polyethylene – terephthalate (PET) with varying masses of clay powder. The primary material was the polyethylene – terephthalate (PET) type and in particular used mineral water plastic bottles and other packaging products made of PET material were used in this study. The secondary material used was ball clay. A special stove was also developed for the combustion of this type of fuel. The design of the stove was based on Bernoulli's principle, Venturi effect and the equation of continuity for compressible fluid flow.

The combustion characteristics (mass combustion rate, melt drops in the stove, flame duration and amount of ash residue) and the calorific value of the solid fuel were the dependent variables while the independent variable in this study was the amount of clay added to the plastic. The extraneous variables were the particle size of the clay, the type of clay, the type of plastic, the volume of air and the flow speed of air in the combustion chamber of the stove. The particle size of the clay powder used in the study was not more than 0.003 mm.

The combustion characteristics (mass of melt drops, mass combustion rate, mass of ash content and the calorific value) of the solid fuel samples were measured and analyzed. The calorific value of developed solid fuel was compared with calorific values of paper, and charcoal of equal mass.

1.6 Significance of the study

National Environment Management Authority (NEMA), Ministry of Energy and Mineral Development (MEMD), Municipal and District Authorities could use the above findings in this study to plan for the development and production of plastic based fuel resource in a bid to minimize the over dependence on wood and charcoal for energy and also in plastic waste management.

CHAPTER TWO: REVIEW OF RELATED LITERATURE

2.1 Introduction

In this chapter the different methods of treating waste plastics with the possibility of deriving useful energy out of them have been reviewed. Incineration, thermal degradation (pyrolysis) and gasification are the major means of getting viable energy from waste plastic materials that were reviewed. A brief review on the properties of plastics as potential feed stocks for fuel development was also done. The literature studies and findings similar to this had also been covered.

2.2 Potential of Plastics for Fuel Development

Plastics are versatile polymeric materials produced on a massive scale and used worldwide (Simoneit, Medeiros & Didyk. 2005). Plastics are long chained hydro – carbon materials made from petroleum (petrochemicals), oils and other organic or plant components like cellulose which contain huge amount of potential energy in their structural make up which make them high calorific value materials similar to that of fuel oil (Cleetus et al., 2013, Junjie & Xuhui, 2014 and Panda et al., 2010).

Plastics come in two different types of thermosetting plastics (or thermosets) and thermoplastics (UNEP, 2009). Thermosets or thermosetting plastics melts and solidifies once when heated and cooled (UNEP, 2009). An example of thermosetting plastics is Polyvinyl chloride (PVC). Thermoplastics on the other hand melt and solidify again and again when heated and cooled. Examples of thermoplastics include, Polypropylene (PP), Polyethylene (PE), Polystyrene (PS), and Polyethylene-Terephthalate (PET) (UNEP, 2009).

These plastics take infinitely many years to be decomposed by organisms such as bacteria and other microbial organisms in the soils, air and water. When these plastics are left as wastes in the environment they cause negative environmental consequences such as soil degradation among others.

When plastics undergo complete combustion in the presence of the oxidizing agent (e.g. oxygen) the long hydro – carbon chains in the polymer are broken down to carbon - dioxide (CO₂), water vapour, energy (heat) and other volatile flammable compounds (Didyk et al., 2000 and Simoneit et al., 2005). In an incomplete combustion (insufficient Oxygen), the products of the combustion of plastics are black soot, carbon – monoxide (CO), heat and sometimes nitrogen compounds if the oxidizing agent is air which make combustion of plastic harmful to human beings. If these harmful release from the combustion of plastic can be taken care of by ensuring that complete combustion is

allowed in the stoves then plastics wastes can be used as alternative source of fuel in solid form particularly if the melt flowing behavior of the plastics is addressed.

2.3 Sustainable Generation of Energy from Plastics Wastes

There are many ways by which fuel (energy) may be generated from plastics wastes. These include; pyrolysis, gasification and incineration of the plastics waste.

2.3.1 Generation of Fluid Fuels from Wastes Plastics

Fluid fuels include both liquid fuel and gaseous fuel and these are generated from waste plastics through pyrolysis and gasification techniques.

Pyrolysis (also called thermal decomposition) is processes where organic molecules are heated in the absence of oxygen till the material decompose into products including oils (liquids) and gases. The oils and gaseous products of pyrolysis are of low molecular mass products. In pyrolysis, plastic polymers of high molecular masses are broken down into small molecules (Awasthi et al., 2017). Pyrolysis breaks down the long hydrocarbon chains in the waste plastics to smaller molecular mass products which are highly useful as fuels and chemicals for various applications (Cleetus et al., 2013). Low temperature ($< 400\text{ }^{\circ}\text{C}$) favors the production of viscous liquids (oils) while high temperature ($> 600\text{ }^{\circ}\text{C}$) favors the production of gases of smaller molecules (Awasthi et al., 2017).

The products of pyrolysis processes include) a carbonized char (solid residues) and a volatile fraction, which can be condensed to give paraffin, isoparaffins, olefins, naphthenes, and aromatics hydrocarbons, while the remaining is a none condensable high calorific value gas (Cleetus et al., 2013). The quality, yield, product distributions (composition) and other physical and combustion properties of the products of pyrolysis depend on the type of the plastic waste, the method applied, the process conditions (e.g. reaction temperature, reaction time, and pressure), the catalyst (size, type, and ratio to plastics), and the reactor (type and design) used (Cleetus et al., 2013 and Panda et al., 2010). Pyrolysis process is a viable route for energy recovery from waste plastic material by converting the waste plastics into fuel oils, and gases (Awasthi et al., 2017).

Catalytic pyrolysis is a pyrolysis process which is carried out in the presence of a catalyst. Catalytic pyrolysis is different from the thermal pyrolysis or thermal cracking described above in that the former is carried out in the presence of a catalyst. The use of catalyst has several advantages such as a significant reduction in the degradation temperature and reaction time , increase in the conversion rates for a wide range of polymers at lower reaction temperatures, increase in the gaseous product yields under similar temperatures and reaction times, narrowing and better control over the hydrocarbon products distribution in Low density polyethylene , High density polyethylene

(HDPE), polypropylene (PE) and polystyrene (PS) (Park et al., 1999, Ohkita et al., 1993, Ding et al., 1997; Lee S.Y., 2001, Lee et al., 2002, Hwang et al., 1998; & Hwang et al., 2002). While thermal pyrolysis (cracking), results in a broad range of hydrocarbons ranging from C₅ to C₂₈, the selectivity of products in the gasoline range (C₅–C₁₂) are much more enhanced by the presence of catalysts (McCaffrey et al., 1995, Audisio, 1984; Park et al., 1999 and Aguado et al., 2000). Oils obtained by catalytic pyrolysis contain less olefins and more branched hydrocarbon and aromatic content (Ohkita et al., 1993). Numerous studies reported in the literature looked at the effects of catalyst on the product yield, product quality, and product distribution of the catalytic pyrolysis with the aim of getting a better catalyst for pyrolysis of plastic wastes (Ohkita et al., 1993, McCaffrey et al., 1995, Audisio, 1984; Park et al., 1999 and Aguado et al., 2000). Most commonly used catalysts for plastic waste pyrolysis includes silica alumina, zeolites (beta, USY, ZSM-5, REY, clinoptilolite, etc.), and MCM-41; these have large acid sites and thus the level of catalyst activity increases during pyrolysis process (Cleetus et al., 2013). Songip et al., (1993) studied the conversion of polyethylene to transportation fuel using HY, rare earth metal exchanged Y-type (REY), and HZSM-5 zeolites and silica alumina (SA). The study showed that REY zeolite was the most suitable catalyst producing plastic oil with the highest octane number and gasoline yield. REY had large pores and had proper acidic strength which made it the most suitable catalyst compared to the others. Y zeolite and ZSM-5 zeolite produced oils having a high octane number comparable to that of the oil by REY, but the gasoline yield by the formers was significantly low as compared to REY (Songip et al., 1993). Manos et al., (2010) studied the catalytic degradation of polyethylene by ultra-stable Y-zeolite catalyst and found that at low pyrolysis temperature the polymer did not fully degrade, and a solid residue is produced in the reactor bed. It showed that the catalyst has significantly reduced the degradation temperature as compared with pure thermal degradation in the absence of a catalyst. The products of the catalytic degradation were hydrocarbons in the C₃–C₁₅ range (Manos et al., 2010). Uddin et al., (1997) studied the effects of silica alumina with two different SiO₂/Al₂O₃ proportions; that is, SA-1 (SiO₂: Al₂O₃ = 83.3:16.7) and silica alumina SA-2 (SiO₂:Al₂O₃ = 21.1:78.9) and found that the liquid yield was 68 wt% for SA-1 as compared to 77 wt% for SA-2. The liquid products are distributed in C₅–C₂₀ range, that is, basically in the gasoline and diesel ranges (Uddin et al., 1997). It can be concluded that with silica alumina, high liquid yield can be obtained and that the yield and composition of the liquid products can be controlled by altering the SiO₂/Al₂O₃ ratio.

Jan et al., (2010) compared the effects of three non-acidic catalysts MgCO_3 , BaCO_3 and CaCO_3 when used as a catalyst under 450°C on pyrolysis products yield of plastics. It was observed that the % oil yield was (33.60%) for MgCO_3 , 29.60% for BaCO_3 and 32.20% for CaCO_3 catalyst. Some studies were also conducted to find the effect of catalyst contact mode with the plastic on the pyrolysis products. Catalyst can be added in the reactor during liquid phase or the vapour phase. In the liquid contact phase both the polymer/plastic and the catalyst are mixed together, placed in the reactor and then heated to the reaction temperature. While in the vapour contact phase (mode), the polymer is first volatilized and the catalyst is inserted in the path of the moving vapour, and as the polymer vapour move through the catalyst, it is degraded to obtain the required hydrocarbon products. However, as reported in there is no significant difference in the product yield between the two catalyst contact modes (Panda et al., 2010). Akpanudoh et al., (2003) studied the effect of polymer to catalyst ratio and concluded that with the increase in the amount of catalyst, a direct proportionality in terms of the effectiveness is not obtained. Increase in catalyst amount increases the conversion rate up to a particular limit, but a further increase in the catalyst percentage does not give any appreciable increase in the conversion rate (Akpanudoh et al., 2003). The Optimum polymer to catalyst ratio as obtained from studies is 4:1. Jan et al., (2010) however, found that a lesser catalyst ratio will provide similar degradation but only at slightly higher temperature thus for the process to remain economical optimization of the catalyst ratio and temperature needs to be done. Higher reaction temperature or high heating rates enhances bond breaking in the long hydrocarbon chains of the polymers thus favoring formation of lighter molecules. Conversion rate also increases with increasing reaction temperature thus at higher conversion rate the major products of the pyrolysis of plastics will be gaseous products with liquid products being minimum or nil showed that the effect of different catalysts on the liquid yield and the product distribution becomes less significant with increasing temperature (Cleetus et al., 2013 and Jan et al., 2010). The reaction taking place will be similar to thermal degradation (none catalytic pyrolysis). Kumar et al. (2015) actually developed synthetic crude oil using simple catalytic (activated carbon and calcium oxides as catalysts) and non-catalytic process on individual and mixed PP, PE, PS, PET followed by a laboratory scale distillation process. The comparison of physical properties, chemical properties, and gas chromatograms suggests that the oil can be further fractionated and used as appropriate gasoline or aviation fuel (Kumar et al., 2015). Nagori & Dohare., (2014) performed similar study on the cracking nature of P.P., P.E. and H.D.P.E. under catalytic methods (pyrolysis) with the application of a suitable catalyst. The percentage yield and the composition of the liquid product (synthetic diesel) varied with feed to catalyst ratio and reaction temperature range between 365°C –

435⁰C), optimum reaction temperature was 395⁰C at optimum reaction period of 35 min. The respective percentage yields were between 68 % - 84 % and maximum was 84 % for optimum reaction temperature 395⁰C and optimum reaction period 35 min. Hence selected catalyst was found suitable for the greater percentage yield of synthetic diesel at optimum reaction period and reaction temperature (Nagori & Dohare., 2014). Also characteristics of synthetic diesel derived from selected plastic waste (P.P. & P.E.) equated with the properties of waste plastic oil and regular gasoline (Nagori & Dohare., 2014). Nonetheless some researchers have attempted to improve on the pyrolysis of polymers (polyolefins) without using a catalyst (non catalytic pyrolysis) (Seth & Sarkar. 2004) and Serrano et al., 2003). However, these studies either yielded insignificant improvements or added another level of complexity and costs to the process. Inert gas flowing through the reaction does not affect the reaction directly, but it can slight change the liquid yield. Nitrogen is an inert gas and its flow rate is often chosen to be relatively high, in order to move the volatile primary products from the reactor and keep secondary reactions at a minimum. This actually favors the liquid yield. But studies of indicate that high carrier gas flow rate can enhance the evaporation of liquid products which are collected in the condenser and this falsifies the results of liquid yield (Jan et al., 2010). By course of experiments, it has been found that the optimum flow rate is 10 ml/min. Some studies have been carried out to find the effect of the reactor types and designs on pyrolysis of waste plastics to obtain fuels. Details of these studies can be found in Panda et al., (2010). Gasification is a thermal chemical process which converts carbon based materials into gaseous product containing carbondioxide, carbon mono oxide hydrogen and methane gas. In thermal chemical process the application of thermal energy to the material alters the chemical structure and properties of the material and completely new products (materials) with different chemical properties are produced. Gasification process has been proven through a number of researches carried out to be an effective way to convert biomass, waste plastics and Refuse Derive Fuel (RDF) into gaseous fuels (Awasthi et al., 2017). Gasification smelting system using iron-making and steel-making technologies has been described which reportedly produce dioxin-free and high-calorie purified gaseous products (Yamamoto et al., (2000). Gasification technique for waste plastics had been applied to polyethylene terephthalate, poly vinyl chloride and polypropylene types of plastics (Awasthi et al., 2017). The products of gasification process particularly the gases such as methane can be used for heating, lighting and power generation.

2.3.2 Generation of Solid Fuels

Incineration is a waste treatment process which involves the combustion at high temperature of the organic substances present in the waste usually in open fire or in kilns to produce flue gas, heat and

ash. The flue gas is often dispersed into the atmosphere (Knox, 2005). The ash is mostly the inorganic materials contained in the waste that form solid lumps or particulates which are often carried by the flue gas (Knox, 2005).

Plastic wastes in some developed countries such as in Japan, Denmark and Sweden are being incinerated directly in better incineration plants to generate steam for the production of electric power (Hopewell, Dvorak & Kosior, 2009). Incineration of plastics waste is thus, an alternate method in which energy is recovered from the waste plastics (Cleetus et al., 2013). The energy produced by incineration of polyethylene is of the same order as that used in its manufacture which makes it an attractive option to derive fuel out of this material (Cleetus et al., 2013). Energy generation by incineration of plastics waste is in principle a viable use of the waste plastics since hydrocarbon polymers can replace fossil fuels and thus reduce the CO₂ burden on the environment (Panda et al., 2010). However, this method of energy recovery from waste plastics produces greenhouse gases and toxic pollutants such as polychlorinated dibenzo para dioxins (PCDD) and polychlorinated dibenzo furans (PCDF) giving it a big disadvantage.

The calorific value is one important property of all combustible materials including fuel. It is defined as the quantity of heat energy released when a unit mass of the fuel is combusted. The calorific value of a fuel depends on the type of fuel and particularly its composition (materials). Some researchers had begun using plastic as a binder to bind loose biomass materials to form a strong solid fuel through densification process. Mitun et al., (2016) produced solid briquettes from loose biomass mixed with wastes plastics in Bangladesh and studied the calorific value of their briquettes. Their study found that the calorific value of the briquettes increased with increased percentage of the waste plastic in the briquettes.

Zannikos et al., (2013) produced solid fuels (briquettes of uniform masses of 300 g, cylindrical in shapes) from bio-mass combined with plastic polyethylene (PE) in Greece. They studied the combustion rate and smoke level of the solid fuels. Solid fuels with polyethylene content greater than 40% burned intensely and lost their basic shape and mass rapidly due to high temperature (Zannikos et al., 2013). The smoke exceeded the smoke number scale level of +9 for PE content greater than 40%. For solid fuel samples with 70% biomass and 30% polyethylene the smoke emission was between 7 and 8 of the smoke number scale. Geometry of the solid fuel had no influence on the smoke emission level (Zannikos et al., 2013). The burning of the plastic in the mixture with biomass increases the carbon monoxide emissions from 10% to 30% as compared to carbon monoxide emission from sawdust biomass samples. When the proportion of biomass to plastic was 70 to 30 the carbon monoxide emissions increased by 10% in relation to the sawdust

biomass emissions (Zannikos et al., 2013). Shrestha & Singh, (2011) used both piston press and screw extrusion to produce briquettes from Municipal Waste mixed with plastic Polyethylene (PE) in Nepal. They further studied combustion (calorific value) properties of the fuel. They reported an increased in calorific value of the briquettes as the percentage of plastic (PE) was increased. The smoke number for the Residue Derived Fuel (RDF) of ratio 65: 55 briquettes was below harmful limits of +9 in sufficient air supply. Shrestha & Singh, (2011) concluded that the produced fuel briquettes might be suitable for use in industrial boilers, brick kilns, etc. But suitable control measures should be applied to capture harmful emissions. This Waste-to-energy conversion option provided an alternative energy resource by utilizing unused waste products. Even though these reported studies showed increased in calorific value of the fuels produced with increased amount of waste plastics, some of the findings seem to suggest that there is a maximum limit in the use of plastics in making solid fuels in combination with other combustible materials (UNEP, 2009; Zannikos et al., 2013). UNEP (2009) gave a 15% weight of plastic as the minimum required level and a 50% weight which will ultimately cause failure in the preparation of the pellets. Smoke and CO emissions are indicators of a poor fuel quality. Although the two are not the property of a fuel they are consequences of the combined factors of the fuel (such as composition of the fuel) and the combustion conditions (including temperature and Air/Oxygen sufficiency).

From the review of the literature, numerous studies have been conducted in the production of fluid fuels from wastes. Non catalytic pyrolysis and catalytic pyrolysis as described in the literature are two prominent techniques being employed in many parts of the world to produce liquid fuels out of waste plastics. Gasification is one process that has been proven through a number of researches to be an effective way to convert biomass, waste plastics and Refuse Derive Fuel (RDF) into gaseous fuels (Awasthi et al., 2017). Therefore, plastic wastes can be converted in to useful form such fuel source. Whereas production of fluid fuels from waste plastics have attracted lots of interests and funding for its steadfast growth per half in terms of the economic benefits, such venture has not been directed to the development of solid fuel from waste plastics. Apart from the derivation of energy directly from incineration of plastic to generate steam needed for the production of electricity in some developed countries mentioned earlier, there is limited data available in the use of plastics directly as solid fuel for domestic applications. In this work the interest was to develop solid fuel from thermoplastic materials and to determine its combustion characteristics as well as its calorific value.

CHAPTER THREE: METHODOLOGY OF STUDY

3.1 Introduction

In this study solid fuel was developed by mixing molten plastic with clay powder. A special stove/burner was also constructed for the combustion of the developed solid fuel. Selected combustion characteristics of the developed solid fuel such as mass of melt drops, mass combustion rate, and mass of ash were determined. The calorific value of the developed solid fuel was also measured by using a bomb calorimeter.

3.2 Preparation of the Clay Material

Ball clay was used in this study because of its plastic property, which made it easier to mix and blend uniformly with the molten polyethylene – terephthalate material. Ball clay was used solely for the purpose of holding the plastic together so as to reduce the rate of melt flowing of the plastics out of the combustion zone of the stove. The ball clay was extracted or mined from a village called Alune, in Lamit Parish, Akwang Sub - County, Kitgum District, in Northern Uganda (Appendix F) because of abundant quantity, easily accessible at no cost and of good quality.

The clay was extracted from a depth of about one meter below the soil surface to avoid sand. Sixty kilogram of unpurified clay was dug and processed into fine clay powder.

All of the sixty kilogram of the unpurified clay was placed in large plastic container and soaked with water. The soaking clay was left for three days so as to obtain thick slurry of clay and sand.

After the three days the soaked clay was vigorously agitated with hands and fresh water was added in order to obtain thin slurry of clay and sand. This thin slurry of clay and sand was again left in the plastic container for one day so as to allow for the formation of smooth and uniform slurry.

After the one day, the slurry was thoroughly stirred then carefully poured through a polyester filter of holes size of 0.0025 mm by 0.0030 mm. The filtered clay slurry was collected in a clean plastic container. The filtered clay was left in its container for one day so that the fine clay settles at the bottom of the container and the excess water remains at the top. This excess water was decanted and the remaining clay slurry dried. The dried clay was then pounded in a mortar using pestle to form fine powder clay as shown in Figure 3.1.



Figure 3.1: Clay powder.

The clay powder was then sieved through a filter of holes size of 0.0025 mm by 0.0030 mm to obtain a very fine clay powder of uniform size. Nine kilogram of fine clay powder was produced and then transferred into a transparent plastic bucket as shown in Figure 3.2.



Figure 3.2: Processed fine clay powder.

3.3 Preparation of the Plastic material

Polyethylene – terephthalate (PET) material was used because it is readily available in large quantity in the environment and it is also a combustible material. Discarded Polyethylene-Terephthalate (PET) mineral water and soda bottles were collected from the environment. The labeling stickers, the tops, and neck rings on the bottles were all removed. The mineral water and soda bottles were then thoroughly washed with water and soap to remove the dirt on their outer and inner surfaces. The washed bottles were allowed to dry.

The cleaned and dried plastic bottles were melted in metallic container fitted with a spout at its bottom as shown in Figure 3.3.



Figure 3.3: Picture of molten plastic in the boiler.

An empty pan of mass 67 g and of diameter of 17 cm was placed on a card board that was placed on an electronic balance. The card board was used to prevent the sauce pan holding the hot molten plastic from directly getting into contact with electronic balance.

The hot molten plastic was carefully drawn into the pan on the electronic balance until a mass of 300 g of the plastic was collected. The 300 g of molten plastic was allowed to cool and solidify in the pan to form the PET or plastic pellet.

3.4 Preparation of the PET – Clay Solid Fuel (PETCSF)

One pellet of plastic (300 g) was melted in a mixing pan and its temperature kept at 198 °C. Ten gram (10 g) of fine clay powder was then added to the hot molten plastic in the pan.

The plastic – clay mixture was kept at a temperature of 198 °C and stirred thoroughly for 10 minutes to form a uniform mixture of clay and plastic.

The mixture of PET and Clay was then allowed to cool and solidify in the same pan to form a circular PET – Clay Solid Fuel (PETCSF) containing 10 g of clay.

The procedures of mixing 300 g of hot molten PET with fine clay powder to form PETCSF were repeated for masses of clay equal to 20 g, 30 g, 40 g,, and up to 300 g. For each of the masses of clay five PETCSF samples were produced. Figure 3.4 shows a few of the PETCSF samples that were produced in this study.

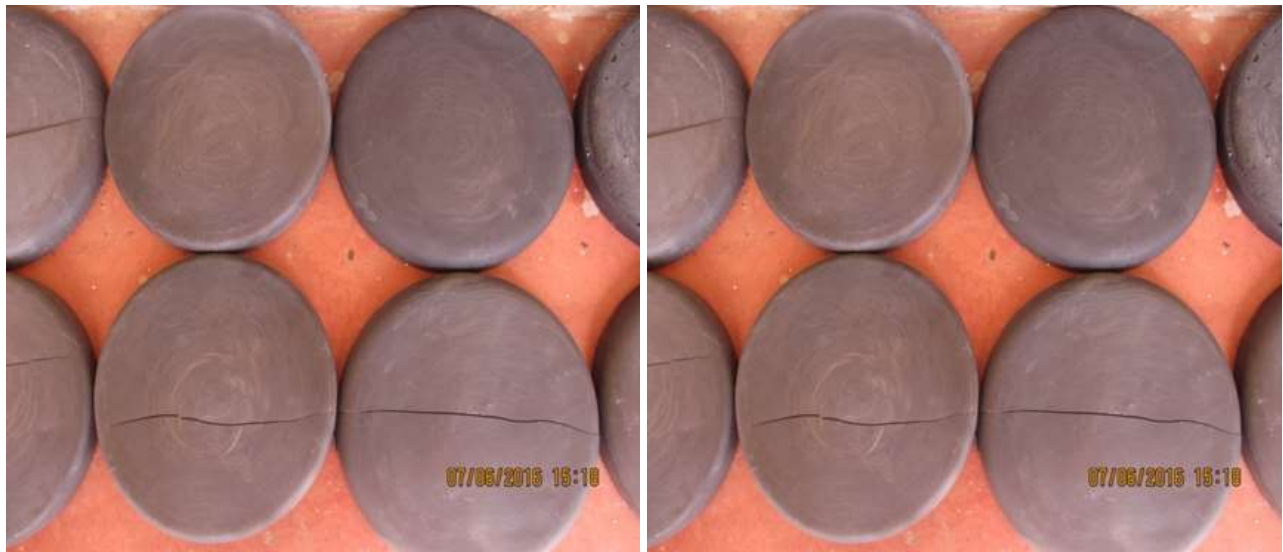


Figure 3.4: Picture of Solid Fuel Samples that were produced.

The mixing ratios of PET to Clay, the actual masses of the Solid Fuel samples measured after preparation and the percentage of clay in the solid fuel samples were as shown in Table 3.1.

Table 3. 1: Mixing Ratios and Actual Masses of the Solid Fuel samples produced.

Name of Solid Fuel Sample	Mixing Ratio		Actual Mass (measured) ± 0.01 g	Percentage of Clay
	Mass of PET ± 0.01 g	Mass of Clay ± 0.01 g		
PET0	300.00	0.00	299.80	0.00
PET10	300.00	10.00	308.30	3.23
PET20	300.00	20.00	316.10	6.25
PET30	300.00	30.00	329.10	9.09
PET40	300.00	40.00	334.80	11.76
PET50	300.00	50.00	347.20	14.29
PET60	300.00	60.00	356.20	16.67
PET70	300.00	70.00	362.00	18.92
PET80	300.00	80.00	369.20	21.05
PET90	300.00	90.00	381.70	23.08
PET100	300.00	100.00	390.60	25.00
PET110	300.00	110.00	401.20	26.83
PET120	300.00	120.00	409.20	28.57
PET130	300.00	130.00	419.70	30.23
PET140	300.00	140.00	420.10	31.82
PET150	300.00	150.00	439.50	33.33
PET160	300.00	160.00	445.50	34.78
PET170	300.00	170.00	454.80	36.17
PET180	300.00	180.00	469.20	37.50
PET190	300.00	190.00	472.90	38.78
PET200	300.00	200.00	474.10	40.00
PET210	300.00	210.00	488.90	41.18
PET220	300.00	220.00	490.00	42.31
PET230	300.00	230.00	505.90	43.40
PET240	300.00	240.00	516.60	44.44
PET250	300.00	250.00	529.80	45.45
PET260	300.00	260.00	533.60	46.43
PET270	300.00	270.00	539.70	47.37
PET280	300.00	280.00	552.20	48.28
PET290	300.00	290.00	557.50	49.15
PET300	300.00	300.00	573.20	50.00

The difference in mass arose from three major factors namely, evaporation of the melted PET, sticking of the molten mixture of PET and clay on the walls of the pan and the stirrer during cooling and solidification.

3.5 Preparation of Solid Fuel Samples for use in the Combustion Stove

Each of the PETCSF samples was broken to smaller pieces using a harmer and weighed in to two groups; A and B and stored in transparent white polythene bag as shown in Figure 3.5.



Figure 3.5: Picture of weighed solid fuels in transparent polythene bags (kaveera).

All solid fuel samples in groups A and B had equal mass of 110.0 grams. Solid fuels in group A were used to determine the mass of melt drops, the mass combustion rates and mass of ash content in the constructed stove. Solid Fuel Samples in B were used to determine the calorific values in the bomb calorimeter.

3.6 Preparing the solid fuel tablets (pellets) for use in a bomb calorimeter

The solid fuel had to be made into pellet form in order to determine its calorific value. A pellet making machine shown in Figure 3.6 was used for this purpose.



Figure 3.6: Picture of the pellet making machine.

A cotton thread of 10 cm length was looped over the solid metallic rod and folded downwards along the groove on the rod. The metallic rod was pushed into the hollow metal cylinder from the bottom and then placed on the flat table of the machine/compressor. Then 0.20 g of the solid fuel powder was measured then poured into the hollow metallic cylinder of the machine.

The handle of the compressor was rotated to push the piston down the hollow cylinder until it was hard to turn any more. This compressed the powder into a hard solid fuel pellet (tablet).

The table of the machine was turned sideways and the piston was pushed further downward by rotating the handle to release the solid fuel pellet out of the hollow cylinder.

The solid fuel pellet with the cotton thread stuck to it was then removed from the metal rod and secured in a safe dried container.

Four solid fuel pellets (tablets) were prepared from each of the solid fuel samples. Four pellets/tablets were also prepared from charcoal, paper and Benzoic acid tablet using 0.2 g of these materials for each of the four pellets prepared. The charcoal, paper and benzoic acid were used as reference fuel materials. Figure 3.7 was a schematic diagram of the steps followed in making the solid fuel tablets/pellets and Figure 3.8 shows the solid fuel tablet/pellet produced with cotton thread attached to it.

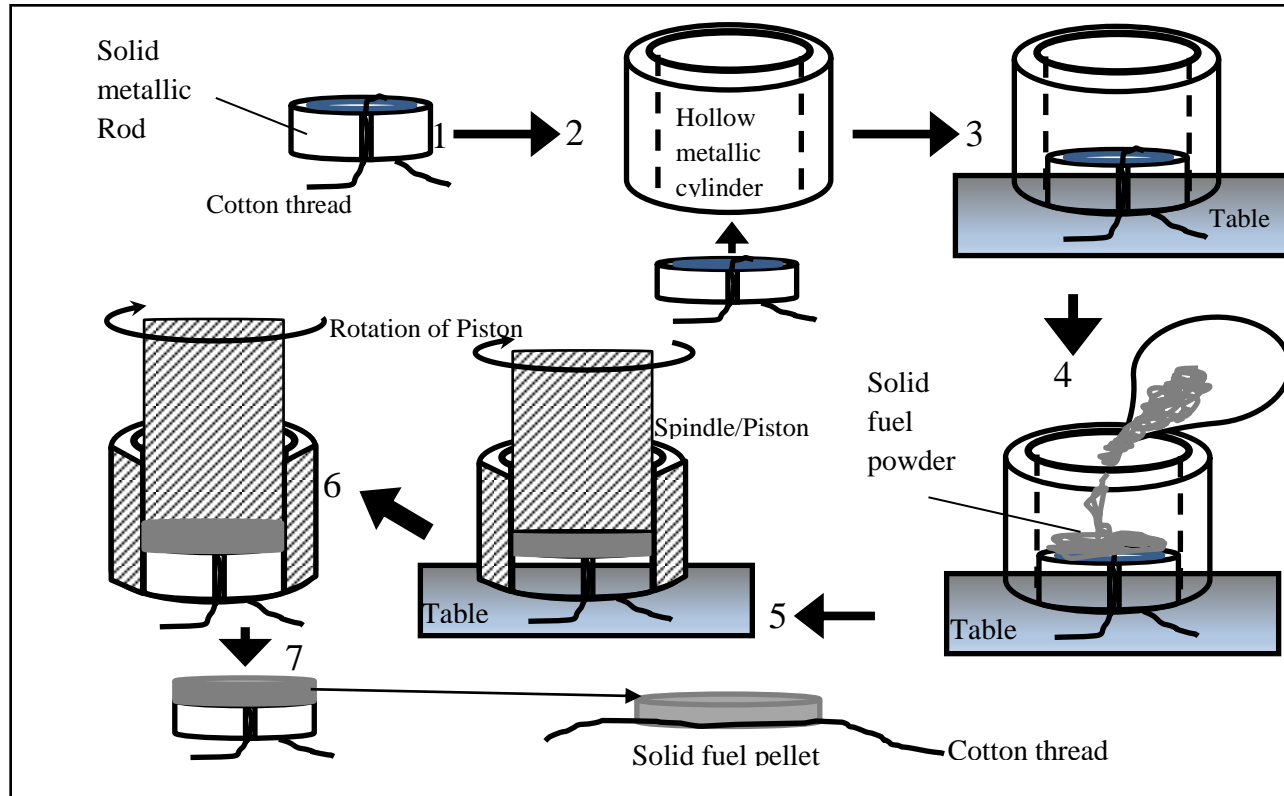


Figure 3.7: Schematic diagram of the steps followed in making the solid fuel pellets.

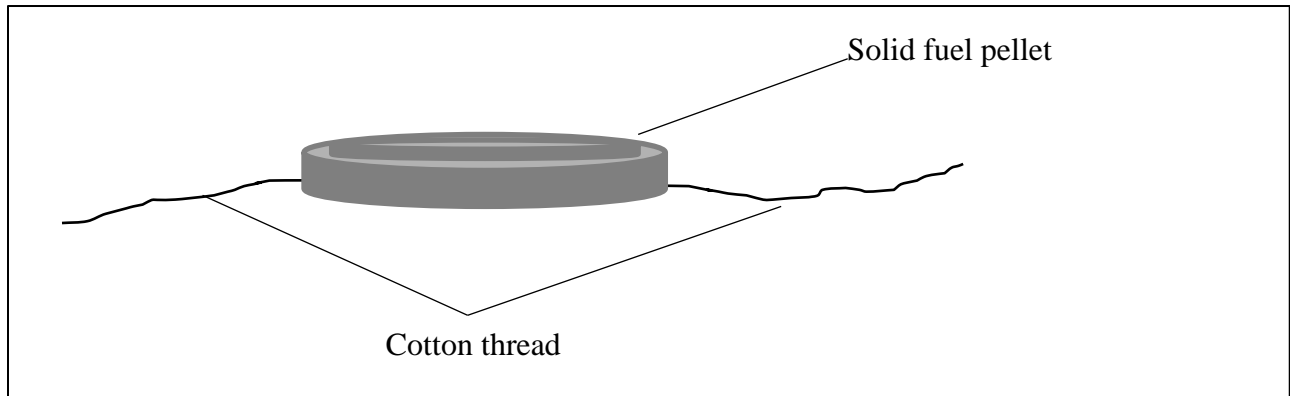


Figure 3.8: Solid fuel tablet/pellet with cotton thread attached.

3.7 Construction of the Combustion Stove

A special stove was constructed and used for the combustion of the developed solid fuel in this study. The stove was designed to supply adequate air to support complete combustion of the solid fuel. The stove had three major sections which included; combustion chamber, pressure reduction chamber and air supply chamber as shown in Figure 3.9.

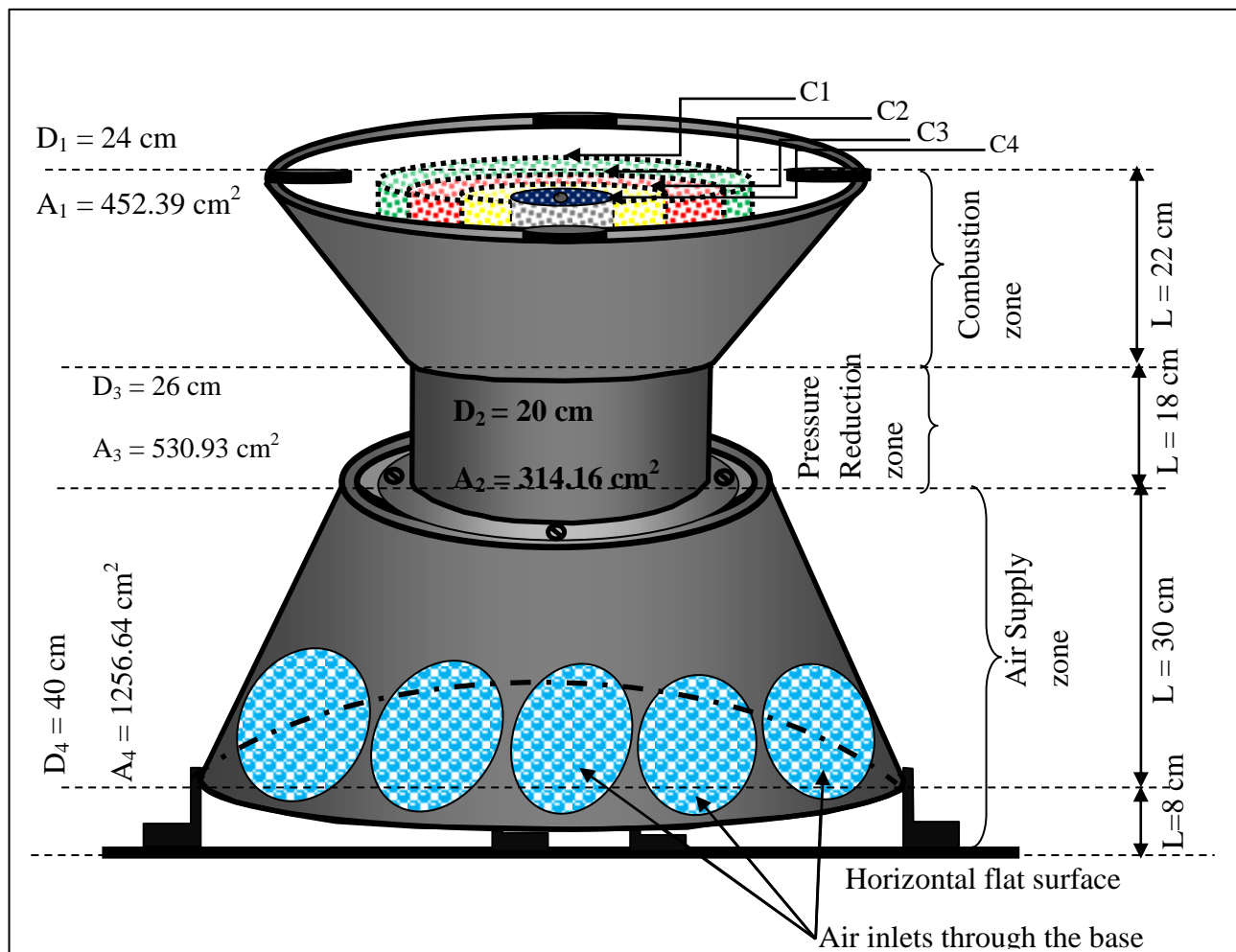


Figure 3.9: The Structure of the Combustion Stove.

The base of the combustion stove is a truncated vertical hollow cone forming the air supply chamber. Immediately above the air supply chamber is a cylinder with diameter less than that of the base and also less than that of the combustion chamber forming the reduced pressure zone. On top of the reduced pressure chamber is the combustion chamber with a truncated conical shape opening upwards of diameter greater than that of the reduced pressure cylinder. The combustion chamber has different feature to improve combustion of the solid fuel samples.

The Air supply chamber at the bottom or base of the stove has the top part of diameter, $D_3 = 26$ cm and cross – sectional area, $A_3 = 530.93$ cm². The lower part of the air supply chamber has a diameter, $D_4 = 40$ cm and cross – sectional area, $A_4 = 1256.64$ cm². This was constructed by first cutting a flat sheet of iron into the required shape and dimensions as shown in Figure 3.10, then it was rolled and joined to form the conical shape of dimensions stated above.

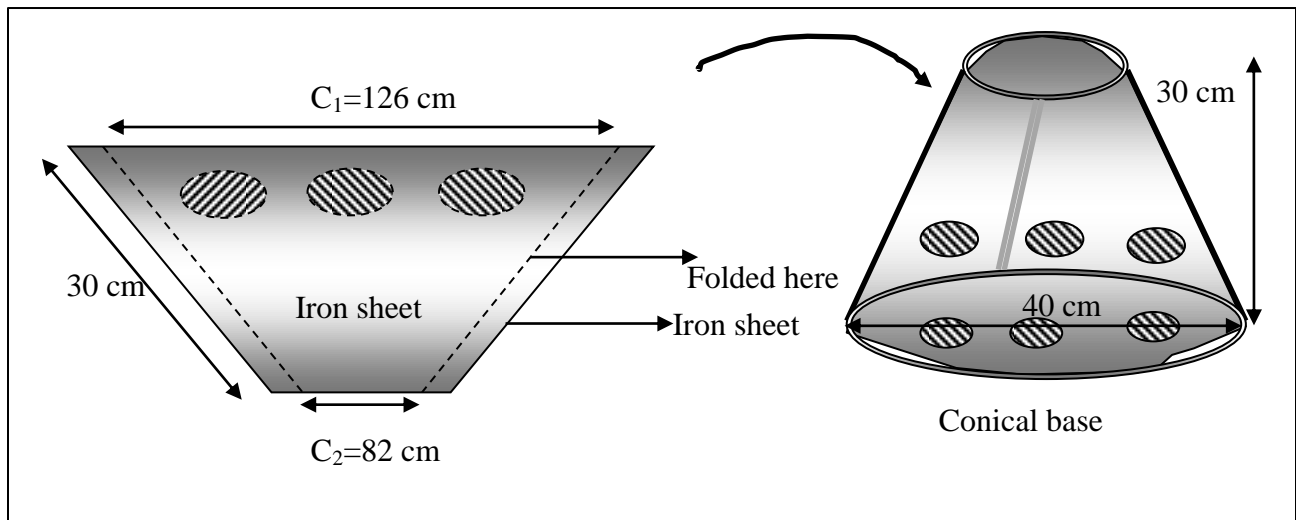


Figure 3.10: Dimensions of the iron sheet for making the air supply chamber.

$C_1 = 126$ cm and $C_2 = 82$ cm are the circumferences of the lower and top part of the air supply zone respectively. The length of this part of the stove is 30 cm. To this base were attached four short stands which allow the lower end of the air supply zone to stand by 8 cm off the ground surface.

The air inlets are holes of diameters 8 cm cut all round through the metallic wall of the base of the combustion stove so that air entered the stove from all directions. The air inlets were equally spaced from each other and at equal height of 10 cm from the lowest part of the base.

The Pressure reduction chamber is the middle cylindrical part of the combustion stove.

It was constructed by cutting the iron sheet into a rectangular shape with the required dimensions and the two ends of the sheet were folded by 2 cm off the edges and joined together to form the required cylindrical shape as shown in Figure 3.11.

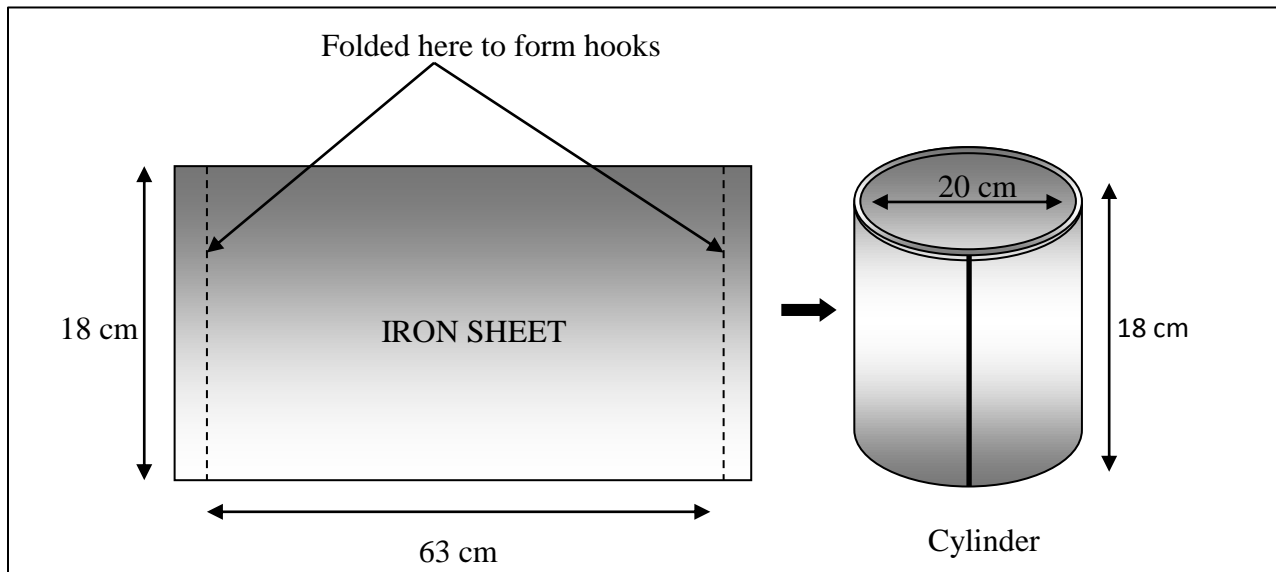


Figure 3.11: Dimensions of the iron sheet for making the pressure reduction chamber.

The constructed pressure reduction chamber has a cylindrical shape and of length, $L = 18$ cm, diameter, $D_2 = 20$ cm and cross-sectional area $A_2 = 314.2$ cm².

The Combustion chamber is the top part of the combustion stove.

It has the same shape as the air supply chamber but of different dimensions. The lower end has a diameter of 20 cm and cross-sectional area of 314.2 cm², while the upper end has a diameter of 24 cm and cross-sectional area of 452.4 cm². The length of the combustion chamber is 22 cm.

Inside the combustion chamber was placed a charcoal holder at 10 cm above the upper end of the pressure reduction cylinder. The structure of the charcoal holder is as shown in Figure 3.12.



Figure 3.12: Picture of charcoal holder with the central cylinder.

The diameter of the charcoal holder is 14 cm and its height is 10 cm. The charcoal holder also has a central perforated cylinder (C_4) of diameter 5 cm which opens directly into pressure reduction cylinder and closed at the top. Larger holes were made at the bottom and on the surface of the

charcoal holder as can be seen in Figure 3.12. The charcoal holder is where 150 grams of charcoal used to light the solid fuel was placed. The solid fuel holding cylinder was placed in and over the charcoal holder. The height of the solid fuel holding cylinder is 5 cm and the diameter is 12 cm. The structure of the solid fuel holder is as shown in Figure 3.13.



Figure 3.13: Picture of solid fuel holder.

Holes of diameters 2 mm were created on the surface of the solid fuel holder and a central opening of diameter 5 cm was cut at the bottom. This central opening was later fitted over the central cylinder, C_4 , when assembling all the cylinders in the combustion chamber.

In the solid fuel holding cylinder were placed three other perforated cylinders; C_1 , C_2 and C_3 also called flame holders, arranged concentrically and firmly secured in position with a uniform gaps of 2 cm between using four screws and nuts as shown in Figure 3.14. The overall diameter occupied by these three cylinders is 10 cm. All the four cylinders inside the combustion chamber were made with holes all over their surfaces of diameters 2 mm and the spacing between the holes is 4 mm as can be seen in Figure 3.14.



Figure 3.14: Perforated cylinders, C_1 , C_2 , and C_3 as flame holders.

All the cylinders were arranged concentrically inside the combustion chamber as indicated in Figure 3.14 and Figure 3.15 shows schematic diagram of the arrangement of the cylinders.

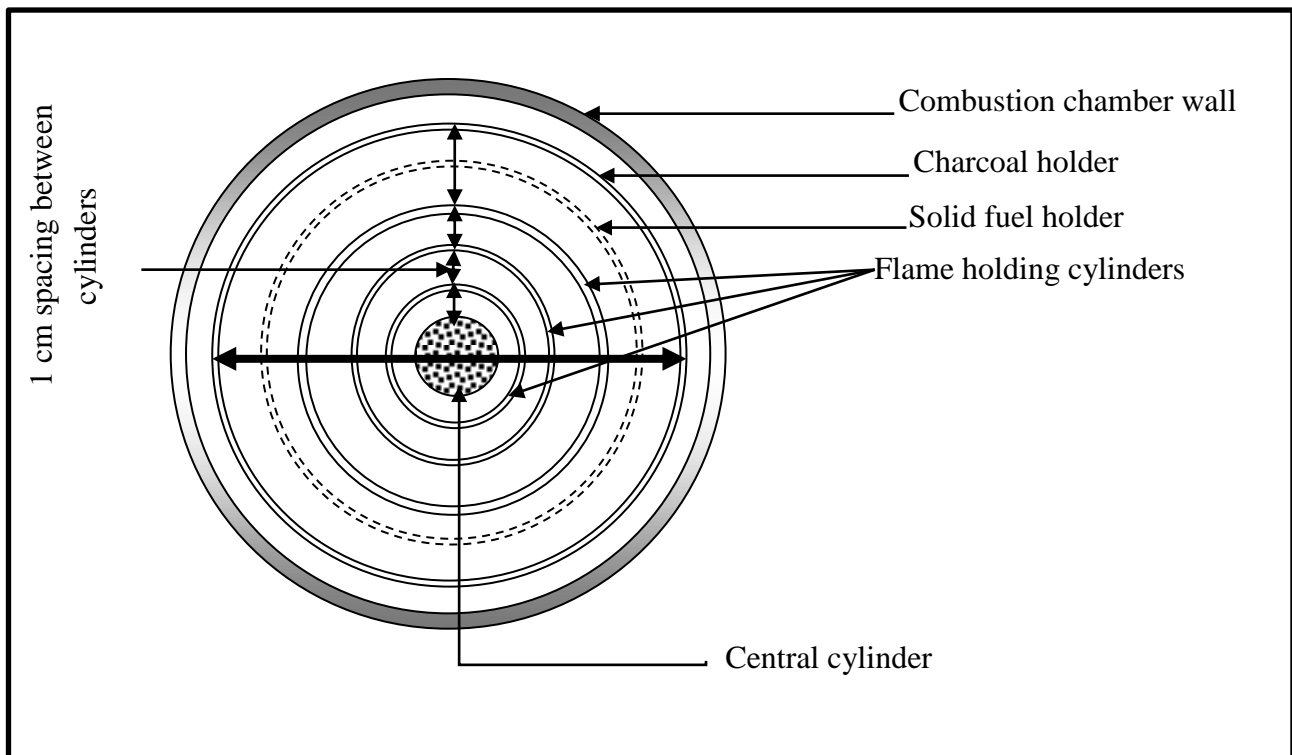


Figure 3.15: Schematic diagram of the arrangement of cylinders inside combustion.

Figure 3.16 is a picture of the charcoal holder, sample holder and flame holder cylinders assembled together.



Figure 3.16: Picture of the charcoal holder, fuel holder, flame holder assembled together.

3.8 Measurement of the characteristics of the developed solid fuel

The combustion characteristics of the developed solid fuel that were measured included, mass of plastics melt drops, mass combustion rate, and mass of ash content and flame duration. The calorific value of the developed solid fuel was also measured.

Mass melt drop is the total mass of all the melt droppings from the combustion of the fuel in the stove that was collected. It was measured in gram.

The mass combustion rate is the number of grams of the fuel that is combusted in a given time. In this study mass combustion rate was measured in gram per minute.

The mass of ash is the mass of the residues left after the solid fuel was combusted in the stove for a period of time.

The calorific value is the quantity of heat energy released when a unit mass of the fuel is completely combusted. In this study calorific value was measured in joules per gram (J g^{-1}).

Six different experiments were carried out in order to determine the characteristics of the solid fuel developed. The first experiment was an exploratory experiment carried out to determine the minimal mass of charcoal that was used to ignite the developed solid fuel, the second experiment was to determine the mass of plastic melt drops in the solid fuel and the sixth experiment was to determine the calorific value of the developed solid fuel with different percentages of clay and calorific values of charcoal, paper and benzoic acid.

3.8.1 Exploratory Experiments

Exploratory experiments were carried out using 400 g, 200 g, 150 g, 140 g, 130 g, 120 g and 100 g of charcoal as igniting source on four different solid fuel samples (PET₀, PET₁₀, PET₁₀₀, and PET₃₀₀) that contained 0 g, 10 g, 100 g and 300 g of clay respectively.

The 400 g of small charcoal pieces was placed in the charcoal holder and was then lowered in to the combustion chamber of the stove. Fifty milliliters of paraffin was sprinkled over the charcoal and then lit. The probe of a thermocouple thermometer was inserted in to the combustion chamber to monitor temperature changes inside the stove.

When all the paraffin was completely burnt out and the charcoal was left glowing red, 110 g Plastic pellet (containing 0 g of clay component) in its holder was then lowered into the combustion chamber and allowed to burn to completion. It took 30 minutes for the sample to burn out completely. The combustion period was then set to 30 minutes which was a long enough time for the solid PET pellet to undergo complete combustion. The melting temperature, temperature at which the flame first appeared and the flame duration were noted.

The above procedures were repeated for 110 g of PET₁₀₀ and PET₃₀₀ solid fuel samples using the 400 g of charcoal as ignition source. The PET₁₀₀ and PET₃₀₀ were all ignited by the 400 g of charcoal. The experiment was repeated using 200 g, 150 g, 140 g, 130 g, 120 g and 100 g of charcoal as ignition source for 110 g of each of the PET₀, PET₁₀, PET₁₀₀, and PET₃₀₀ solid fuel samples. The 140 g, 130 g, 120 g and 100 g of charcoal could not ignite the solid fuel samples used. The least amount of charcoal used as ignition source for all the solid fuel samples prepared in this study was 150 g. The characteristics of the developed solid fuel were then determined using apparatus listed in appendix E as described in the following sections.

3.8.2 Measuring Mass of Plastic melt drops of Solid Fuels

The combustion of plastic occurs when it is melted. The melted plastic should be held in the combustion chamber of the stove so that complete combustion can occur without melt dropping.

The 150 g of charcoal was placed in its holder and lowered inside the combustion chamber of the stove. The charcoal was lit and when it was glowing red, 110 g of fuel pellet in a holder was lowered into the stove to be burnt.

A metallic plate of known mass was then placed at the bottom of the stove to collect the melt drops from the burning fuel pellet. The pellet was allowed to burn inside the stove for 30 minutes to ensure that all of the fuel was completely burnt out.

After 30 minutes of combustion, the melt drops on the metallic plate were removed and the mass was measured using an electronic balance and recorded. The mass of the melt drops of 110 g of

PET pellet was measured for the second time using the same mass (150 g) of charcoal as ignition source. The average mass of the melt drops of the PET pellet was then obtained.

The mass of melt drops of PETCSF having 10 g of clay in it was measured for the first and second time. The average mass of melt drops of PETCSF was obtained.

The procedures of measuring mass of melt drops were repeated for PETCSF containing 20 g, 30 g, and up to 300 g of clay and for each two measurements were performed. The averages of mass of melt drops for PETCSF with different masses of clay were obtained.

The mass of melt drops was analyzed for the different percentages (or masses) of clay in the fuel.

3.8.3 Measuring the mass combustion rate of the solid fuels

The mass combustion rate of each of the PET solid fuel samples with different Clay – Plastic Ratios was determined by using 150 g of charcoal to ignite the solid fuel samples.

The 110 g of fuel pellet placed in a holder was lowered in the stove and placed on the hot glowing charcoal. The pellet was allowed to burn for 30 minutes.

After the 30 minutes of combustion the residue was removed from the stove and cooled. The mass of the fuel pellet and its holder was weighed. The mass of the pellet that was combusted was then obtained by subtracting total mass of residue and the holder from total mass of pellet and its holder.

The mass of PET pellet that was combusted was divided by 30 minutes to obtain the mass combustion rate of the pellet. The mass combustion rate of the PET pellet was obtained for the second time and the average mass combustion rate of the PET pellet was obtained.

The experiment was also carried out two times on 110 g of PET₁₀ sample using the 150 g of charcoal as igniter. The mass combustion rate in the first and second experiments were determined and the average mass combustion rate for PET₁₀ (PETCSF with 10 g of clay) was obtained.

The experiment was repeated for the PETCSF with 20 g, 30 g, 40 g....., and 300 g of clay and for each two measurements of the mass combustion rate were done. The average mass combustion rate was obtained for PETCSF with different percentage of clay.

The mass combustion rates of the 30 solid fuel samples were measured to determine the variation of combustion rate for the different clay – plastic ratios in the solid fuel samples.

3.8.4 Measuring the Mass of Ash Contents

When the solid fuel was combusted in the stove for a combustion period of 30 minutes, the residues left after the combustion period were collected as ash. After cooling the mass of the ash from the combustion of the solid fuel samples were measured using an electronic balance.

The masses of ash for two of each solid fuel samples with different clay – plastic ratios were determined when determining the mass combustion rate of the solid fuel samples. The average mass of ash for two of each of the 30 solid fuel samples was determined.

The data were used to determine the variation of mass of ash for the solid fuel samples with different clay – plastic ratios.

3.8.5 Measurements of the Calorific Values

The bomb calorimeter C 200 Model was used to determine the calorific values of the solid fuels. The bomb calorimeter C 200 model has a measuring cell cover, tank fillers, fill level display, keyboard, and display screen as shown in Figure 3.17.



Figure 3.17: Features of the bomb calorimeter C 200 Model.

The bomb head (decomposition vessel) is one of the major parts of the bomb calorimeter. Its main features are as shown in Figure 3.18.

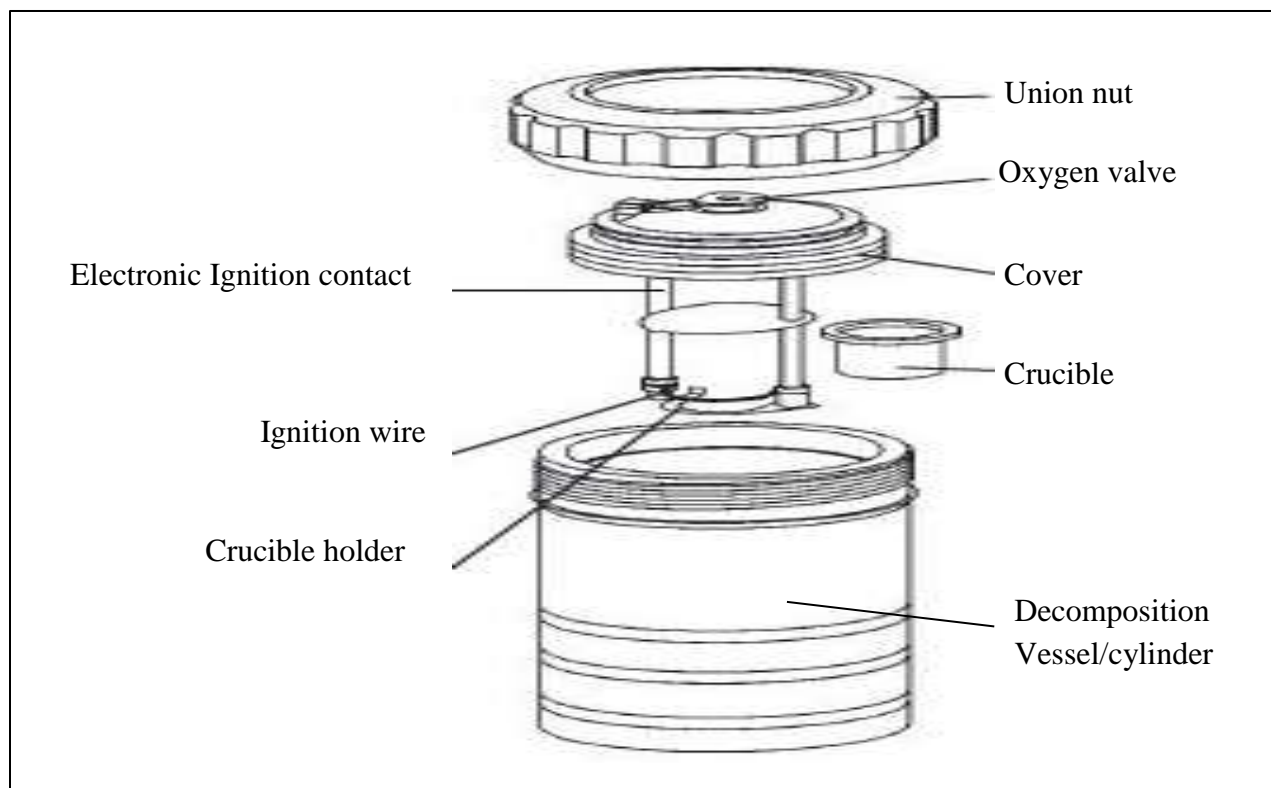


Figure 3.18: Main parts of the Bomb Head (Decomposition vessel).

When operating the bomb calorimeter, the appliance is first switched on at ON/OFF switch found at the back of the appliance. The appliance is now in a standby mode.

Press ON (F1) to work with the appliance. The start screen will appear. In the start screen you will be prompted with seven display elements during operation. These display elements include status line, footer, reading value, current temperature value, function keys (F1, F2, and F3), numerical keypad and the delete button. If you press the menu (F3) key, a menu will appear in the display which allows for six submenus (General, calibration, unit of measurement, language, measuring procedures and service) to be entered.

In order to ensure that the appliance works properly, some parameters need to be set the first time the appliance is used. These parameters include the language (by default is English), the date, the time, the reference (exact calorific value, 26460 J g^{-1} , of the calibration substance – Benzoic acid) and the unit of measurement as well as the measuring procedure (default: Isoperibol).

To prepare and perform measurements using a bomb calorimeter

The decomposition vessel was prepared as follows.

Unscrew the union nut and remove the cover using the handle.

Attach a cotton thread to the center of the ignition wire using a loop. Weigh out the substance directly into the crucible with an accuracy of 0.1 mg. Note the weight or enter directly into the calorimeter. If the substance is already prepared in tablet form with a cotton thread attached to it, tie it to hang between the ignition contact rods.

Insert the crucible into the crucible holder and if necessary put some little distilled water into the decomposition vessel.

Using a tweezers, align the cotton thread so that it hangs inside the crucible and immersed in the sample. This will ensure that the burning thread ignites the sample during the ignition process. Place the cover onto the lower section and push down until it presses against the stop piece in the lower section. Place the union nut onto the lower section and tighten by hand.

Now fill the decomposition vessel using the oxygen station C 248 to a pressure between 36 - 40 atmospheres and slide the ignition adaptor onto the decomposition vessel.

Place the decomposition vessel into the inner vessel (bucket) of calorimeter C 200. The decomposition vessel must be placed between the three locating bolts at the bottom of the bucket.

Pour 2 litres of tap water maintained at a constant temperature into the using the measuring cup. Keep an eye on the level indicator in the fill level display. The water level should not be below the level indicator or else the appliance will not operate. The calorimeter is now in awaiting mode.

Select measurement or press F2 button which will take you to the prepare measurement menu. Enter the noted weighted sample in the marked weighted sample field with an accuracy of 0.0001 g using the keyboard. Enter 1 for the calibration value to perform calibration and maintain 1 for the decomposition vessel if one decomposition vessel is used in the test.

Maintain the 50 J default value for the cotton thread ignition in QEXT1 that showed up on the display screen and enter 0J for a combustible crucible option that will be used. The default value is 0 J for other burning aids in QEXT2 option. Specify the test number of the measurement in the TestN0 option e.g. TestN0 = 0181209 represent the first measurement on 09 December 2018. Once all the necessary preparation works as described above have been done, the message storage filled will appear. Check that the tank is filled with water maintained at constant temperature and confirm by pressing continue or F1 button. The message will appear again vessel safe locked? Press OK. The message will appear close the cover.

Close the measuring cell cover by moving it to the left out of the locking position until it slides down by itself. The decomposition vessel comes into contact with the igniters via the ignition adaptor. The fill message will appear. The inner vessel/bucket will be filled with water in about 70 seconds. The measurement will begin as soon as the inner vessel is full.

The measurement process is fully automatic for the isoperibol procedure. The result will appear on the display screen once the measuring process is complete.

After the measurement open the cover to automatically empty the inner vessel. Remove the decomposition vessel and the ignition adaptor and safely release pressure in the decomposition vessel under well ventilated environment.

Open the decomposition vessel and check the crucible for signs of incomplete combustion. If combustion is incomplete, discard the test result and repeat the test.

Calibrating the bomb calorimeter

Before it was used, the bomb calorimeter was first calibrated by running a calorific value test using 0.2000 g of solid benzoic acid tablet as follow.

The 0.2000 g benzoic acid tablet was tied using cotton thread between the two electrodes of the bomb head. The crucible was placed on its holder between the electrodes and the benzoic acid table was made to sit inside the crucible.

The bomb head was then carefully placed inside the decomposition cylinder and pushed down as far as it could go. The union nut was then tightened firmly on to the decomposition cylinder.

The decomposition vessel was then charged (filled) with oxygen gas to a pressure of 36 atmospheres from the oxygen station that was supplied with the calorimeter. The ignition adaptor was then placed on the top of the decomposition vessel.

Fresh water was poured into the tank filler until the level reached the indicated mark on the fill level display. The measuring cell cover was carefully lifted out of the locking position and turned to the right. The decomposition vessel was then lowered into calorimeter bucket and well positioned on the three screws at the bottom of the bucket. The measuring cell cover was then lifted out of the locking position and turned to the left to close it. At this stage, water begun to fill the bucket automatically.

The mass (0.2000 g) of the benzoic acid tablet was entered using the key board on the calorimeter. At this stage everything was automated.

When the bucket was filled with water the machine took about 1 minute to equalize the temperature of the water in the bucket before automatically firing the benzoic acid tablet. The initial temperature of the water was displayed on the screen and this was recorded in the data collection sheet.

After equalizing the temperature of the water, the machine performed the measurement of the calorific value in three stages i.e. Pre – Test, Main – Test and Post – Test stage. The pre – test took about 6 minutes, the main –test took 8 minutes and the post – test took 1 minute. The changes in temperature were displayed on the screen after every one minute interval and these were recorded in the data collection sheet.

At the end of the post - test the calorific value of the benzoic acid tablet was displayed on the screen in joules per grams (J g^{-1}) and this was recorded in the data collection sheet. The bucket was emptied and the decomposition vessel removed from the bucket. The crucible was removed and then thoroughly cleaned with distilled water.

The calorific value of benzoic acid tablet was measured for the second time using the same mass of 0.2000 g of the tablet following the steps described above.

The calorific value of benzoic acid tablet was found to be 24,231 J g^{-1} and 24,247 J g^{-1} in the first and second measurements respectively and the respective initial temperatures were 24.0 $^{\circ}\text{C}$ and 23.8 $^{\circ}\text{C}$ for the first and second measurements respectively.

The calorific values of tablets prepared from PETCSF having 10 g, 20 g,,and 300 g of clay in them were then measured following the same steps as described above for the benzoic acid tablet. For each PETCSF of different masses of clay, 0.2000 g of the fuel was used and four measurements of the calorific value were made. The average of the calorific value was then obtained for each of the PETCSF with the masses of clay.

The temperature change was also recorded after every one minute interval. The initial temperature in each of the measurements for the PETCSF with different masses of clay was also recorded.

The calorific value of charcoal was measured to give a reference value to which the value for the solid fuel could be compared. Two measurements of the calorific values of charcoal pellets were made following the same for measuring the calorific value described benzoic acid tablet. In each of the measurements 0.2000 g of the charcoal was used. The average calorific value of the charcoal was then obtained. The initial temperatures of water in the two measurements were recorded and the change in temperature was recorded after every one minute interval in each of the two measurements that was carried out.

The calorific value of paper (Pic fare product) was also measured as another reference value to compare with that of the solid fuel sample.

A piece of pic fare paper was carefully weighed until its mass was exactly 0.200 g. The paper was then folded to a smaller piece with a cotton thread attached to it and then tied between the electrodes and made to sit in the crucible.

The paper was fired in the bomb calorimeter and its calorific value was obtained following the steps described above for measuring calorific value of the fuel. Two measurements of the calorific value of the paper were made and the average value obtained. The initial temperatures and temperature change were also recorded in each of the two measurements that were carried out.

Determination of the clay to PET ratio for the solid fuel that was developed was also done. These were the clay – plastic ratios for which melt dropping behavior of plastic in the stove during combustion was zero. The clay – plastic ratios were determined using two ways.

The first way was to find where the curve of melt drop cuts the percentage of clay axis on the graph of melt drop against the percentage of clay that was plotted. The second way was to solve polynomial equation (1) from the graph of mass of melt drop against the percentage of clay for value of $M_{MD} = 0$. The percentages of clay for which the mass of melt drops was zero were then obtained and the mass of clay corresponding to these percentages were obtained. The clay –to – plastic ratios were then obtained for these masses of clay and the mass of the plastics for which the melt dropping behavior of the solid fuel in the stove was zero.

The mass combustion rate, the mass of ash and the calorific value of the developed solid fuel were then obtained for the clay – to – plastic ratios that gave zero melt dropping behavior of the solid fuel in the stove.

3.8.6 Statistical measures and formulae

The correlation coefficient, R , the coefficient of determination, R^2 , (or covariance), the adjusted R^2 and the P – values were the statistical measures determined in this study. The correlation coefficient, R also called Multiple R , determines how each of the dependent variables relates with the independent variable (percentage of clay) in the solid fuel it has a value between -1 and +1. Negative value of R indicates negative correlation while positive R shows positive correlation. R^2 is the proportion of variability in the dependent variables (mass of melt drops of plastic, mass combustion rate, mass of ash and calorific value) that is explained by the independent variable (percentage of clay). R^2 has value between 0 and 1 or 0% and 100%. The Adjusted R^2 is similar to R^2 but it takes into account the sample size and so it is a more reliable statistics than R^2 .

P - Value is a statistical measure that helps researchers to determine whether their hypothesis is correct. It helps determine the significance of results of the study. It has a value between 0 and 1. The P –Value is calculated from the Z - , F - or T - statistics. The level of significance (α) is a pre-defined threshold set by the researcher. It is generally 0.05. In this study the level of significance (α) was set to 0.01 i.e. at 99% confidence level. A very small p -value, which is lesser than the level of significance, indicates that you reject the null hypothesis. In other word, the result is true or

significance. P-value, which is greater than the level of significance, indicates that we fail to reject the null hypothesis. In this study the values of these parameters were obtained using Microsoft Excel (Spreadsheet) programs. However, they can also be obtained using the formulae in equation (1) – (5).

$$R^2 = 1 - \left(\frac{SS_{\text{residuals}}}{SS_{\text{total}}} \right) \quad (1)$$

Where, $SS_{\text{residuals}}$ = sum of the squares of the residuals (errors) and SS_{total} = total sum of the squares.

$$\text{Adjusted } R^2 = 1 - \left[\frac{(1 - R^2)(N - 1)}{N - P - 1} \right] \quad (2)$$

Where, R^2 is the sample R square, N = sample size and p = number of predictors (coefficients in the regression equation).

$$Z = \frac{x - \mu}{\sigma} \quad (3)$$

Where x is a value of set of data, μ is the mean of a set of data and σ standard deviation of a set of data from the mean.

$$T = \left\{ \frac{(\sum d)/N}{\sqrt{\{\sum d^2 - (\sum d)^2/N\}/(N-1)}} \right\} * N \quad (4)$$

Where d = difference between a pair of data, d^2 = square of the difference and N = sample size

$$F - \text{Value} = \frac{\text{larger sample variance}}{\text{smaller sample variance}} = \frac{\sigma_1^2}{\sigma_2^2} \quad (5)$$

Where, σ_1^2 is the larger sample variance and σ_2^2 is the smaller sample variance.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

4.1 Introduction

The combustion characteristics of the solid fuels investigated in this study included the plastic melt dropping behavior, mass combustion rates, mass of the ash and the calorific values. The relationship between each of the stated combustion characteristics and the percentage of the clay in the solid fuels was also analyzed to establish how significant such a relationship was. The first part of the investigation was to determine the optimum mass of charcoal required to ignite and maintain combustion of the fuel samples.

4.2 The Least Mass of Charcoal required to ignite the solid fuel samples

No ignition and hence no flame (combustion) occurred for masses of charcoal = 100 g, 120 g, 130 g and 140 g for all the solid fuel samples used in the exploratory experiments. It was found from exploratory experiments that 100 g, 120 g, 130 g and 140 g of charcoal could not ignite the 110 g of the solid fuel samples. The solid fuel samples containing 10 g, 100 g and 300 g of clay including the PET pellet each of mass 110 g were all ignited by 150 g of charcoal and underwent complete combustion in a period of 30 minutes (from the time fuel was entered into the stove to the time the observed flame went off).

The least mass of charcoal that was used to ignite all the solid fuel samples produced in this study was 150 g. The combustion period for all the solid fuel samples was set to be 30 minutes.

4.3 The Mass of Melt Drops of the Solid Fuel (M_{MD})

The first characteristic of the solid fuel to be determined was the mass of plastic melt drops from the combustion of the solid fuel samples. This was to determine the value of clay percentage in PET solid fuel that give the lowest (zero) value of plastic melt drops.

The average mass of melt drops from the combustion of each solid fuel sample was computed from the actual measured (experimental) values (Appendix A) and presented together with corresponding percentage of clay in Table 4.1.

Table 4.1: Average mass of melt drops and percentage of clay in the solid fuel samples.

Samples	Percentage of clay in solid fuel	Average $M_{MD} / \pm 0.1$ g
PET10	3.23	9.95
PET20	6.26	7.00
PET30	9.09	5.70
PET40	11.77	3.85
PET50	14.29	3.50
PET60	16.68	2.90
PET70	18.92	1.80
PET80	21.05	0.00
PET90	23.03	0.00
PET100	25.01	0.00
PET110	26.82	0.00
PET120	28.57	0.00
PET130	30.24	0.00
PET140	31.83	0.00
PET150	33.33	0.00
PET160	34.79	0.00
PET170	36.17	0.00
PET180	37.51	0.00
PET190	38.78	0.00
PET200	39.99	0.00
PET210	41.17	0.00
PET220	42.31	0.00
PET230	43.39	0.00
PET240	44.44	0.00
PET250	45.45	0.00
PET260	46.42	0.00
PET270	47.36	0.00
PET280	48.28	0.00
PET290	49.15	0.00
PET300	50.00	0.00

M_{MD} = mass of melt drops.

A graph of the average mass of melt drops against the percentage of clay in the solid fuel samples was drawn as shown in Figure 4.1. In Figure 4.1, the mass of melt drops from the combustion of the solid fuel appears to decrease exponentially with increase in percentage of the clay in the solid fuel samples. The physical interpretation of Figure 4.1 is that as more clay is added to the solid fuel melt dropping in the stove rapidly decreased and at a concentration of clay of about 30% and above mass of melt drops of the solid fuel became zero i.e. an exponential decay relationship was exhibited between the mass of melt drops of the solid fuel and percentage clay.

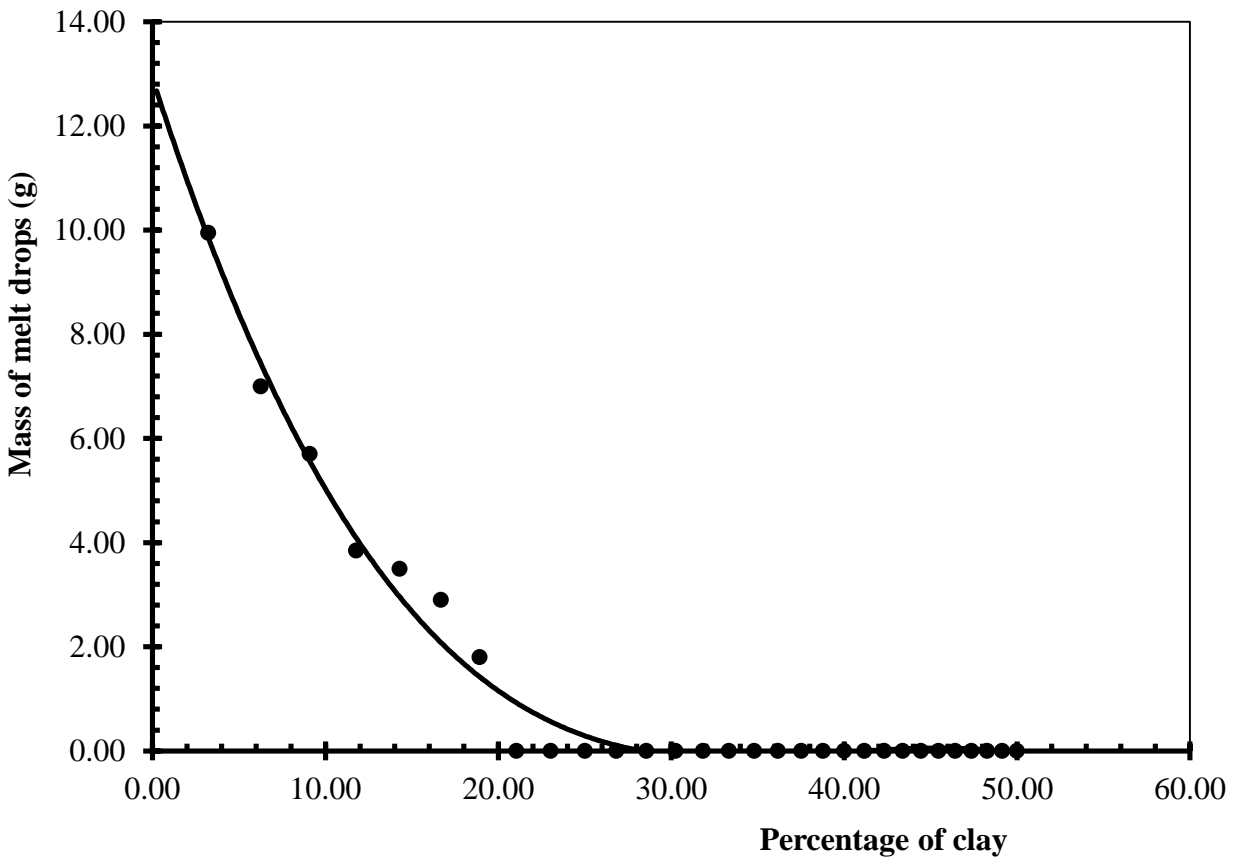


Figure 4.1: Variation of Mass of Melt Drops against Percentage of Clay.

To obtain the minimum possible amount of clay that would give zero melt dropping in the stove a cubical relationship between mass of melt drops (M_{MD}) and percentage of clay (PC) defined by equation (6) was fitted.

$$M_{MD} = -0.0002PC^3 + 0.0240PC^2 - 0.9605PC + 12.5590 \quad (6)$$

The significance of the cubical relationship between the percentage of clay and the melt drops of the solid fuels was analyzed by a nonlinear regression analysis technique at 99% ($\alpha = 0.01$) confidence level. The result of the nonlinear regression analysis statistics was presented as in Table 4.2.

Table 4. 2: Nonlinear Regression Statistics for Mass of Melt Drops.

Source	S	R-Sq.	R-Sq.(Adj)	
Cubic	0.3574	98.59%	98.38%	
ANOVA				
	DF	SS	F	P - Value
Cubic	1	6.819	53.40	0.0000

DF = degree of freedom, SS = sum of squares, F= F-Statistics

In Table 4.2, S is the standard errors, R –Square (or R^2) is the coefficient of determination or covariant and R-Sq (Adj) is adjusted R^2 . DF is the degree of freedom, SS was the sum of squares, F was the f-Statistic and P-Value was the significance of F. Standard error is the same as the standard deviation, it measures the variability of the actual values of mass of melt drops from that predicted by the cubic model.

R - Square (R^2) has value of 98.59% in Table 4.2. It was the proportion of variability in the dependent variable (mass of melt drops of plastic) that was explained by the independent variable (percentage of clay) as described by equation (6). The Adjusted R^2 has a value = 98.38% was similar to R^2 but it took into account the sample size and so it was a more reliable statistics than R^2 . The P-Value = 0.000 implies that the cubic relationship between mass of melt drops and the percentage (amount) of clay in the solid fuel was statistically significance ($P < 0.01$) at 99% confidence level. Therefore, solving equation (6) for zero value of M_{MD} gives three values of $PC = 29.15\%$, $PC_2 = 45.43\%$ and $PC_3 = 45.43\%$. Also from Figure 4.1, at $PC = 30.00\%$ $M_{MD} = 0$. Thus the lower values of clay that would stop melting dropping of the solid fuel in the stove during combustion were found to be 29.15%, 30.00% and 45.43% with 29.15% being the minimum. The corresponding masses of clay for $PC = 29.15\%$, 30.00% and 45.43% were 123.43 g, 128.57 g and 249.75 g respectively in 300 g of plastic. The Clay to Plastic Ratio values was **1:2.43**, **1:2.33** and **1:1.20** respectively.

4.4 The Mass Combustion Rate of the Solid Fuel

The study was to determine the mass combustion rates of the developed solid fuel in the constructed stove. The average mass combustion rates of the solid fuel obtained from actual measured values (Appendix B) was presented together with the percentage of the clay in Table 4.3.

Table 4.3: Average Mass Combustion Rate.

Samples	Percentage of clay in solid fuel	Average $M_{\text{CBR}}/\pm 0.01 \text{ g min}^{-1}$
PET10	3.23	3.055
PET20	6.26	3.003
PET30	9.09	3.155
PET40	11.77	2.961
PET50	14.29	2.955
PET60	16.68	2.738
PET70	18.92	2.703
PET80	21.05	2.622
PET90	23.03	2.737
PET100	25.01	2.683
PET110	26.82	2.563
PET120	28.57	2.538
PET130	30.24	2.415
PET140	31.83	2.438
PET150	33.33	2.387
PET160	34.79	2.243
PET170	36.17	2.280
PET180	37.51	2.102
PET190	38.78	2.248
PET200	39.99	2.102
PET210	41.17	2.035
PET220	42.31	2.060
PET230	43.39	2.030
PET240	44.44	1.970
PET250	45.45	1.958
PET260	46.42	1.950
PET270	47.36	1.900
PET280	48.28	1.897
PET290	49.15	1.865
PET300	50.00	1.862

MCBR = Mass Combustion Rate

The values in Table 4.3 suggest that the mass combustion rates decreased as the percentage of clay in the solid fuel increased.

A graph of mass combustion rates against the percentage of clay was plotted as shown in Figure 4.2.

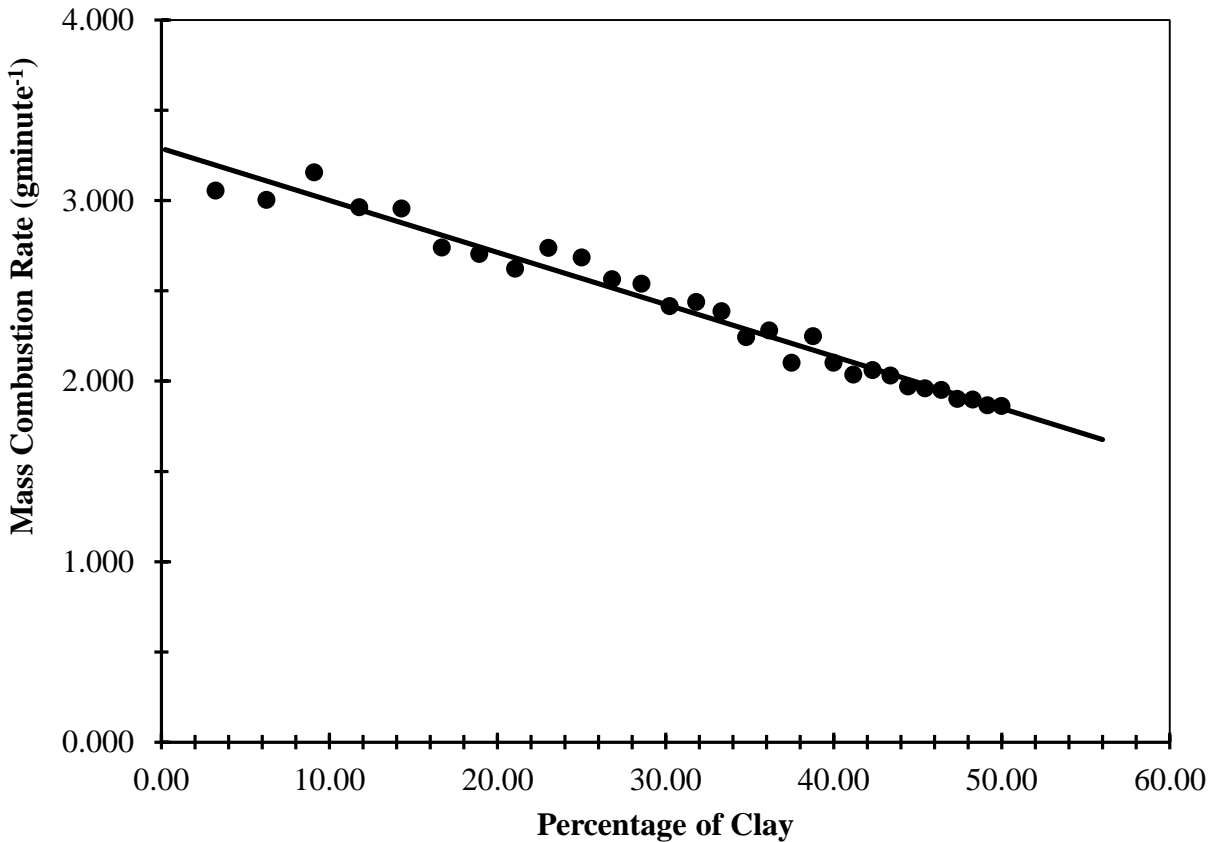


Figure 4.2: Variation of Mass Combustion Rate with Percentage of Clay.

From the graph in Figure 4.2, the average mass combustion rate of the solid fuel decreased linearly with increased percentage of clay.

A linear relationship between the mass combustion rates and the percentage of clay in the solid fuels was thus obtained and it is defined by the equation (7).

$$M_{\text{CBR}} = -0.0288\text{PC} + 3.2895 \quad (7)$$

Where, M_{CBR} is mass combustion rate of the solid fuel and PC is the percentage of clay in the solid fuel. The negative slope in equation (7) physically means that a 1% increase in amount of clay, the mass combustion rate of the solid fuel decrease by 0.0288 g in 1 minute.

To find out if there is a significant relationship between mass combustion rates and the percentage of clay, a simple linear regression analysis was carried out. The results of the statistical (linear regression analysis) were shown in Table 4.4.

Table 4.4: Regression Statistics of Mass Combustion Rate of the Solid Fuels.

Regression Statistics								
Multiple R		0.9859						
R Square		0.9719						
Adjusted R Square		0.9709						
Standard Error		0.0691						
Observations		30						
ANOVA								
		DF	SS	MS	F	Significance F		
Regression		1	4.6274	4.6274	969.7633	0.0000		
Residual		28	0.1336	0.0048				
Total		29	4.7610			CONFIDENCE INTERVALS		
TERMS	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 99.0%	Upper 99.0%
Intercept	3.2895	0.0318	103.5826	0.0000	3.2245	3.3546	3.2017	3.3773
Percentage of Clay	-0.0288	0.00092	-31.1410	0.0000	-0.0307	-0.0269	-0.0314	-0.0263

DF = Degree of freedom, SS = Sum of Squares, MS = Mean Squares, F = F –Statistics

Multiple R (or simply R) is the correlation coefficient and it measures how the two variables dependent variable (mass combustion rate) and the independent variable (percentage of clay) move in relation to each other.

From Table 4.4 above, there was very high positive correlation ($R = 0.9859$) between mass combustion rate and the percentage of clay in the solid fuel. It was also established that there was a statistically significance linear relationship between mass combustion rate and the percentage of clay in the solid fuel at 99% confidence level since $P < 0.01$. Also 97.19% ($R^2 = 0.9719$) of the variability in the mass combustion rate of the solid fuel was explained by the percentage of clay in the solid fuel. The linear relationship between M_{CBR} and PC was used to determine mass combustion rate of the solid fuel at 29.15%, 30.00% and 45.43% (or CPR = 1:2.43, 1: 2.33 & 1:1.20) of clay shown in Table 4.9.

4.5 Mass of Ash of the Solid Fuel

The mass of ash of the solid fuel samples produced was determined in the combustion stove. The average mass of ash of each of the solid fuel samples in Table 4.5 was calculated from experimental values found in Appendix D.

Table 4. 5: Average Mass of the Ash of the Solid Fuel.

Samples	Percentage of clay in solid fuel	Average $M_A/\pm 0.01$ g
PET10	3.23	18.35
PET20	6.26	19.90
PET30	9.09	15.35
PET40	11.77	21.15
PET50	14.29	21.35
PET60	16.68	27.85
PET70	18.92	28.90
PET80	21.05	31.35
PET90	23.03	27.90
PET100	25.01	29.50
PET110	26.82	33.10
PET120	28.57	33.85
PET130	30.24	37.55
PET140	31.83	36.85
PET160	34.79	42.70
PET170	36.17	41.60
PET180	37.51	46.95
PET190	38.78	42.55
PET200	39.99	46.95
PET210	41.17	48.95
PET220	42.31	48.20
PET230	43.39	49.10
PET240	44.44	50.90
PET250	45.45	51.25
PET260	46.42	51.50
PET270	47.36	53.00
PET280	48.28	53.10
PET290	49.15	54.05
PET300	50.00	54.15

M_A = Mass of Ash.

A graph of mass of ash against the percentage of clay was plotted as shown in Figure 4.3.

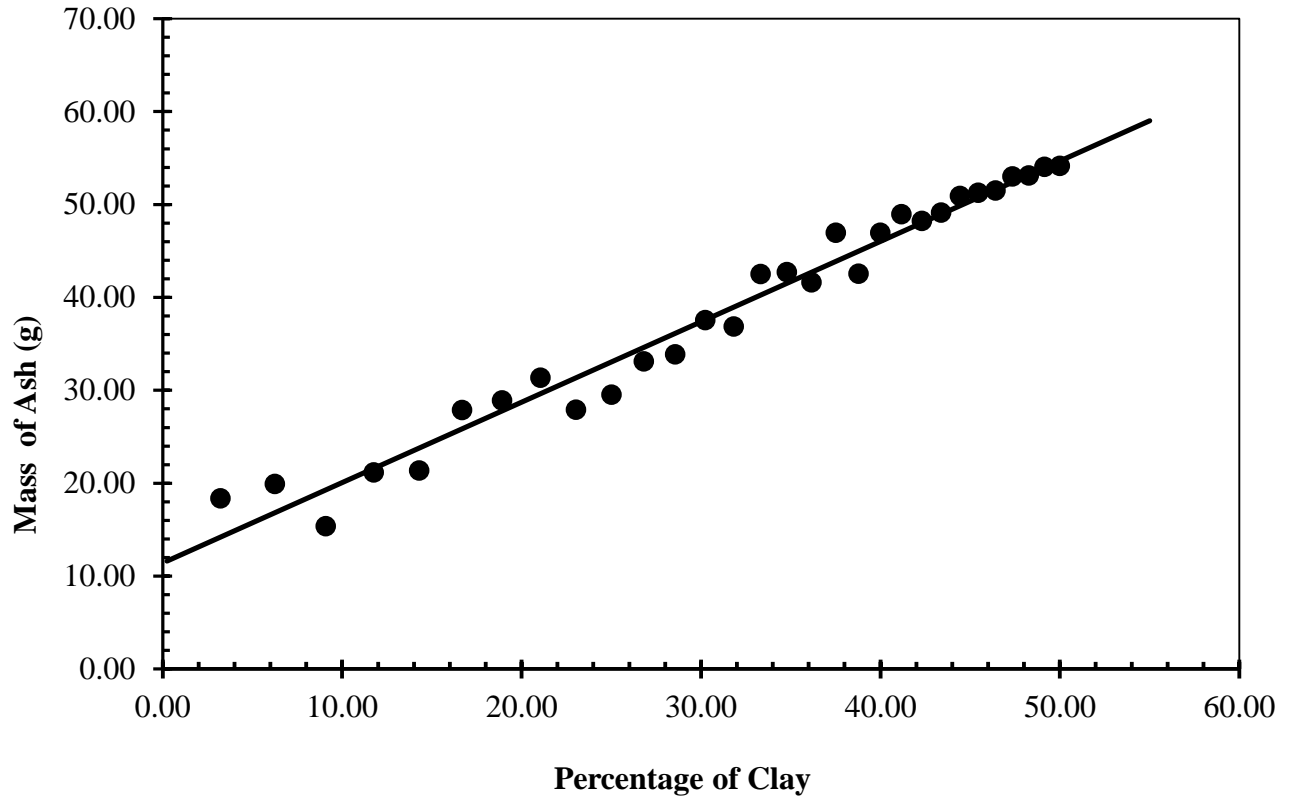


Figure 4.3: Variation of mass of ash with percentage of clay.

From the graph in Figure 4.3, the average mass of ash of the solid fuel increased linearly with increased percentage of clay. Thus, there is a linear relationship between the mass of ash and the percentage of clay in the solid fuel.

The linear relationship between the mass of ash and the percentage of clay in the solid fuels is defined by the equation (8).

$$M_A = 0.8655 \cdot PC + 11.408 \quad (8)$$

Where, M_A is mass of ash of the solid fuel and PC is the percentage of clay in the solid fuel.

The positive slope in equation (8) means that a 1% increase in the amount clay in the solid fuel, mass of ash increases by 0.8655 g.

Table 4.6 presents the result of the linear regression analysis of the relationship between mass of ash and the percentage of clay in the solid fuel.

Table 4.6: Regression Statistics Results for Mass of Ash.

Regression Statistics					
Multiple R	0.9857				
R Square	0.9715				
Adjusted R Square	0.9705				
Standard Error	2.0906				
Observations	30				
ANOVA					
	DF	SS	MS	F	Significance F
Regression	1	4177.744	4177.744	955.899	0.0000
Residual	28	122.3736	4.370487		
Total	29	4300.118			

					CONFIDENCE INTERVALS			
TERMS	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 99.0%	Upper 99.0%
Intercept	11.40823	0.961117	11.8698	0.0000	9.4395	13.3770	8.7524	14.0641
Percentage of Clay	0.865468	0.027993	30.9176	0.0000	0.8081	0.9228	0.7881	0.9428

DF = Degree of freedom, SS = Sum of Squares, MS = Mean Squares, F = F -Statistics

Given the correlation coefficient (multiple R) of 0.9857 in Table 4.6, there is a strong positive correlation between the dependent variable (mass of the ash) and the independent variable (percentage of clay). The R^2 and the adjusted R^2 values in Table 4.6 above are 0.9715 and 0.9705 respectively. These are the percentages of variability in the mass of the ash of the solid fuel that was explained by the percentage of clay in the solid fuel. There was a statistically significant linear relationship between the Mass of the Ash and the Percentage of Clay in the solid fuels at 99% confidence level since $P < 0.01$. This linear relationship (model) was used to determine mass of ash for the three CPR = 1:2.43, 1: 2.33 & 1:1.20 as shown in Table 4.9.

4.6 The Calorific Value of the Solid Fuel

The calorific values of the solid fuel produced were determined using C 200 Bomb Calorimeter. The average calorific values of the solid fuel samples shown in Table 4.7 were obtained from actual experimental values found in Appendix C.

Table 4.7: Average calorific value of the solid fuels and the percentage of clay in the fuels.

Solid Fuel Samples	Percentage of Clay in the Sample	Average Calorific Value (J g⁻¹)
PET10	3.23	19,652
PET20	6.26	17,410
PET30	9.09	12,996
PET40	11.77	18,925
PET50	14.29	18,254
PET60	16.68	18,224
PET70	18.92	18,706
PET80	21.05	17,965
PET90	23.03	16,979
PET100	25.01	14,807
PET110	26.82	13,842
PET120	28.57	13,496
PET130	30.24	15,273
PET140	31.83	15,927
PET150	33.33	10,567
PET160	34.79	13,221
PET170	36.17	13,082
PET180	37.51	13,232
PET190	38.78	11,253
PET200	39.99	11,607
PET210	41.17	13,412
PET220	42.31	11,631
PET230	43.39	10,742
PET240	44.44	11,174
PET250	45.45	11,821
PET260	46.42	10,388
PET270	47.36	10,621
PET280	48.28	10,095
PET290	49.15	10,610
PET300	50.00	10,420

A graph of the calorific value was plotted against the percentage of clay as shown in Figure 4.4.

The graph in Figure 4.4 has a negative slope which indicates that the calorific values decrease as the percentage of clay is increased. The straight line graph shows that there is a linear relationship between the calorific value of the fuel and the percentage of clay in the fuel.

The equation defining the straight line graph of calorific value against the percentage of clay is:

$$CV = - 193.69PC + 19981 \quad (9)$$

Where, CV = Calorific Value and PC = Percentage of Clay.

The negative slope in equation (9) means that when the percentage clay in the solid fuel is increased by 1%, the calorific value would decrease by 193.69 J for every 1 g of the solid fuel combusted.

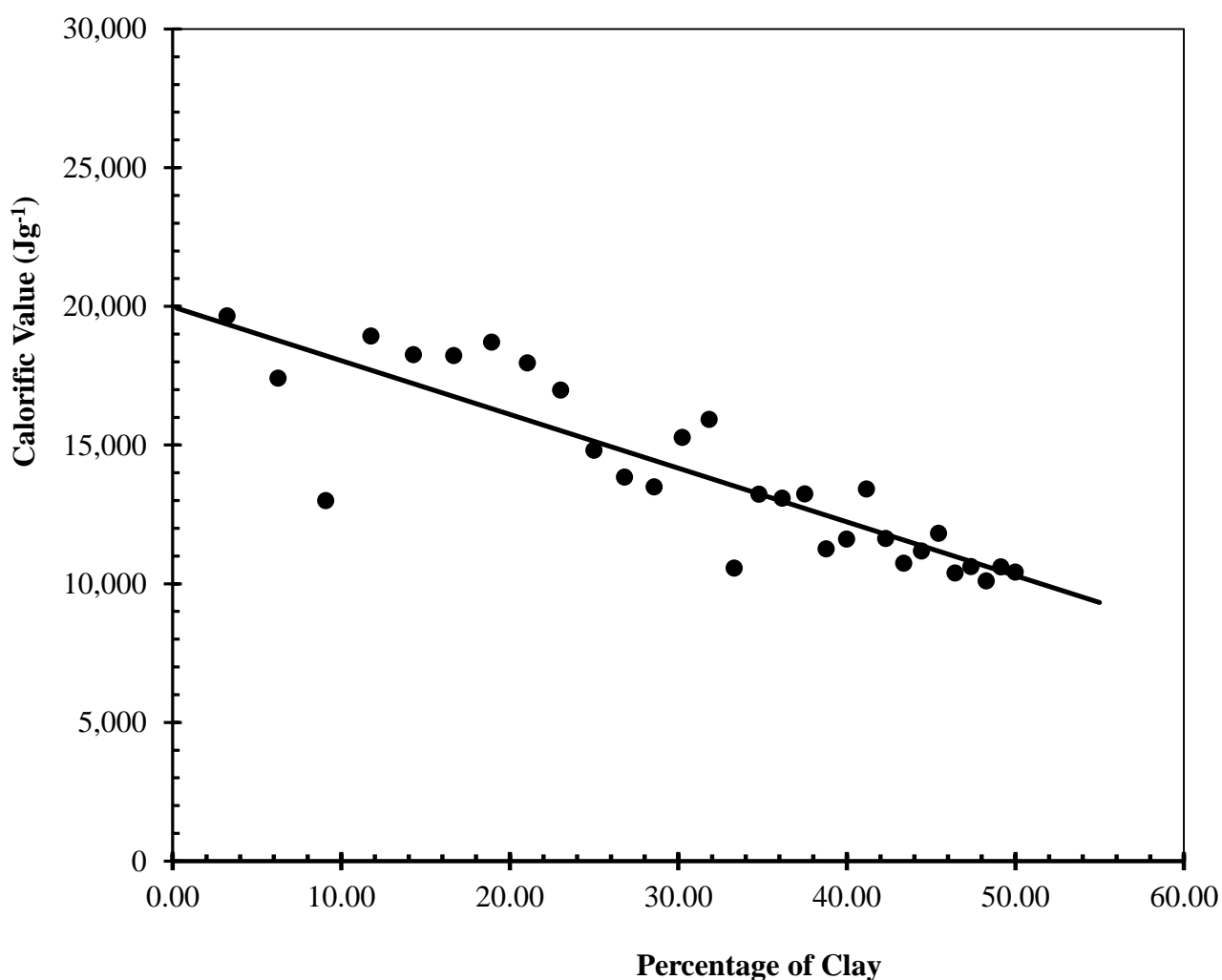


Figure 4.4: Average Calorific Value against Percentage of Clay.

The following regression statistics presented in Table 4.8 were obtained for the linear relationship between calorific value and the percentage of clay in the solid fuel.

Table 4.8: Results of the Analysis of the Average Calorific Values of the Solid Fuels.

Regression Statistics								
Multiple R	0.8679							
R Square	0.7533							
Adjusted R Square	0.7445							
Standard Error	1564.3829							
Observations	30							
ANOVA								
	DF	SS	MS	F	Significance F			
Regression	1	209234851.8837	209234851.8837	85.4964	0.0000			
Residual	28	68524231.9830	2447293.9994					
Total	29	277759083.8667						
					CONFIDENCE INTERVALS			
TERMS	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 99.0%	Upper 99.0%
Intercept	19980.9595	719.2078	27.7819	0.0000	18507.73	21454.19	17993.56	21968.32
Percentage of Clay	-193.6856	20.9471	-9.2464	0.0000	-236.59	-150.78	-251.57	-135.80

DF = Degree of freedom, SS = Sum of Squares, MS = Mean Squares, F = F -Statistics

Given the correlation coefficient (or multiple R) of 0.8679, it implies that was a very strong positive relationship between the calorific value and percentage of clay in the solid fuel.

The R^2 and adjusted R^2 values are 0.7533 and 0.7445 respectively. These values mean that up to 75.33% of the variability in the calorific of the solid fuel was explained by the percentage of clay in the solid fuel. The unexplained proportion of variability in calorific value could be due to some other factors. The linear relationship between calorific value and percentage of clay was statistically significance at 99% confidence level ($\alpha = 0.01$) since all the P – Values in Table 4.8 are zero.

Table 4.9 shows values of mass combustion rate, mass of ash and calorific value of the developed solid fuel determined at three lower CPR values.

Table 4.9: Values of the solid fuel parameters for the three CPR.

CPR	M_{CBR} (g minute⁻¹)	M_A (g)	Calorific value (J g⁻¹)
1:2.43	2.45	36.64	14,335
1:2.33	2.43	37.37	14,170
1:1.20	1.98	50.73	11,182

Table 4.10 shows the calorific values of charcoal, paper and Benzoic acid that were used as reference solid fuel materials. Charcoal is a widely used solid fuel in Uganda and it is important to compare its calorific value with that of developed solid fuel from plastic wastes.

Table 4.10 shows the calorific values of pure (not mixed with anything) PET, charcoal, Paper and Benzoic acid tablet that were used as reference solid fuel materials.

Table 4.10: Calorific value for charcoal, paper, benzoic acid and Pure PET.

Reference fuel materials	Calorific value (J g^{-1})
Charcoal	7,316
Paper	12,475
Benzoic acid tablet	24,239
Pure PET	21,254

The calorific values of the different solid fuel materials such as charcoal, paper and Benzoic acid tablet shown in Table 4.10 were compared using Bar chart with the calorific values Table 4.9 for as shown in Figure 45.

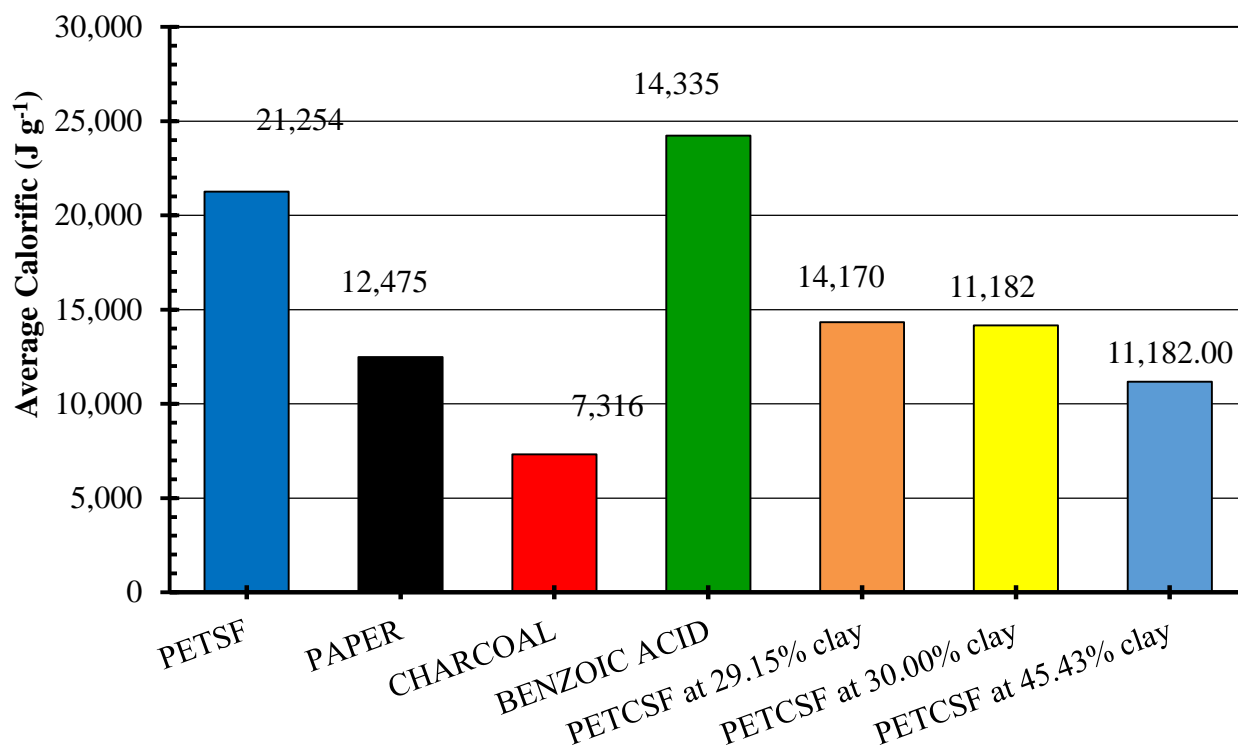


Figure 4.5: Bar graph of calorific values of selected solid fuels.

From the bar graph in Figure 4.5 the calorific values of the PETCSF for 29.15% and 30.00% of clay are higher than that of paper and charcoal of equal mass. The calorific value of PETCSF at 45.43% of clay is higher than for charcoal of equal mass but lower than for Benzoic acids and paper of

equal mass. The calorific value of the PETCSF for 29.15% and 30.00% of clay are about twice the calorific value of charcoal of equal mass. Benzoic acid tablet had the highest calorific value compared to calorific value of the developed solid fuel.

CHAPTER FIVE: SUMMARY, CONCLUSION AND RECOMMENDATION

5.1 Summary

Mass melt dropping during combustion in the stove was stopped by the inclusion of clay into the developed solid fuel. The following clay to plastic ratios 1:2.43, 1:2.33 and 1:1.20 were found to be sufficient to prevent melt flowing or dropping out of the stove of plastic based solid fuel during combustion. An exponential decay relationship was found to exist between mass of melt drop and percentage of clay added to the solid fuel. However, a cubic relationship that explained up to 98.38% ($R^2 = 98.59\%$ and Adjusted $R^2 = 98.38\%$) of the decreased in the melt dropping behavior of the solid fuel in the stove was also found to be a reliable model as it enabled the minimum amount (29.15%) of clay needed to prevent melt dropping from occurring during combustion to be calculated.

Melt dropping behavior or flowing of the plastic when combusted is undesirable because it inhibits complete combustion to take place and also draws away the fuel from the combustion zone of the stove so that the fuel would not burn. So mitigating it was the first step to be taken in to count when developing solid fuel from waste plastic material.

A very strong positive correlation ($R = 0.9859$) between the mass combustion rate and the amount (percentage) of clay added to the solid fuels. A statistically significant linear relationship was found to exist between mass combustion rates and the percentage of clay at 1% significance level ($P < 0.01$). Moreover, such a significance linear relationship between mass combustion rates and the percentage of clay explained up to 97.19% ($R^2 = 0.9719$ and adjusted $R^2 = 0.9709$) of the variability (decreased) in the Mass Combustion Rates of the solid fuel in terms of the percentage of clay in the fuel. The remaining 2.81% could be due to some other unknown factors.

The fact that there was a statistically significant linear relationship between the mass combustion rates and the percentage of clay and that the linear relationship explained up to 97% of the variability in the mass combustion rates means that Clay can be used to control the rate of burning of the fuel in the stove. This is a very useful finding to rely on when making plastic based solid fuel to use in ordinary charcoal stove. Mass combustion rate of the solid fuel can also be predicted from such a linear relationship for a desired setting of the clay to plastic ratios which in this study were those which gave zero melt dropping of the fuel in the stove.

There was also a strong positive correlation (multiple $R = 0.9857$) found to exist between the mass of ash and percentage of clay in the PETCSF that was developed.

A statistically significant linear relationship at 0.01 significance level was found to exist between; the mass of ash and percentage of clay ($P < 0.01$).

The R^2 and the adjusted R^2 values in table 4.6 are 0.9715 and 0.9705 respectively indicated that up to 97.05 % of the variability in mass of ash of the solid fuel was explained or affected by the percentage of clay in the solid fuel.

There was a very strong positive correlation ($R = 0.8679$) between the calorific values and the percentage of clay in the solid fuel. Given the R^2 and the adjusted R^2 values in table 4.8, over 74.00% of the variability in the calorific values of the solid fuels was explained by the percentage of clay in the fuels. A statistically significant linear relationship was found to exist between calorific values and the percentage of clay in the fuel at 1% significance level ($P < 0.01$). Such a relationship can be used to predict or find the calorific value of the solid fuel for a desired percentage of clay or find the settings for the percentage of clay that correspond to a desired value or range of values for the calorific value of the fuels. In this study the desired percentages of clay were 29.15%, 30.00% and 45.43% for which melt dropping was zero in the stove.

The calorific value of the PETCSF for 29.15%, 30.00% and 45.43% of clay were found to be $14,335 \text{ J g}^{-1}$, $14,170 \text{ J g}^{-1}$ and $11,182 \text{ J g}^{-1}$ respectively. These were compared with calorific value of charcoal, paper and benzoic acid tablet as reference solid fuel materials. The calorific value the developed solid fuel with 29.15% % 30.00% clay were two times higher than that of charcoal of equal mass and slightly greater than the calorific value of paper of equal mass. Benzoic acid tablet had a higher calorific value than the developed solid fuel.

5.2 Conclusions

A plastic based solid fuel was developed from waste PET bottles mixed with clay powder in a 1:2.43, 1:2.33 and 1:1.20 clay to PET ratio. In each of these ratios, melt dropping of the solid fuel in the stove during combustion was zero. The calorific value of the developed solid for each of these ratios was found to be greater than the calorific value of an equal mass of charcoal (Figure 4.5). Moreover, the rate combustion of the developed solid fuel can be controlled by varying the amount of clay used (Table 4.9). Therefore, plastic based solid fuel can be an alternative to charcoal and firewood which are predominant sources of fuel upon which majority of the population in Uganda depend to meet their energy demand. Plastics wastes and clay are all in abundant quantity in the environment which means sustainable production of plastic based solid fuel is guaranteed anywhere in the country. Where clay may not be available, fine soil can be used as an alternative since the

clay is only used to hold plastic melt together so that complete combustion can take place in the stove. This purpose can be achieved using fine soil particles too.

5.3 Recommendations

The population should be encouraged to use plastic based solid fuel as an alternative to firewood and charcoal since the calorific value of this type of is even higher than that of an equal mass of charcoal.

The use of plastic based solid fuel particularly in an ordinary charcoal stove should be in an oxygen rich environment (outdoors) as insufficient air supply can lead to incomplete combustion of the plastic element and produce fume/smoke which may contain carbon monoxide which is harmful if inhaled for a longer time especially during cooking.

A comprehensive combustion test needs to be carried out to analyze the smoke contents and measure compounds like SO_2 & H_2S and other harmful emissions arising from the combustion of the solid fuel in the different stoves since plastics are believed to produce toxic fumes.

Similar study should be done targeting different types of plastic wastes including polythene bags in combination with other materials such wood dusts, etc. this would help widen the scope of materials to be use.

The existing relationship between air flow characteristics (like velocity, air concentration, flow mechanism-laminar or turbulence) and the combustion characteristics of the fuel (such as smoke level, flame color, flame duration, and mass combustion rates) need to be established. Such knowledge will provide further information that would lead to improving the combustion process of the fuel and the design of an efficient stove for this type of solid fuel.

The relationship between the rate of cooling and accumulation of ash in the stove needs to fully be understood. The ash may retain some of the heat and release it over time: Heat retention may be higher in solid fuel with high ash content than in fuels with lower ash content. Such information would be very useful in the design of the stove and hence in the conservation of the energy (Heat) from the combustion of the fuel.

The stove needs to be improved particularly to minimize heat loss to the surroundings and allow all the heat released from the fuel to be sufficiently utilized.

The mass combustion rates and the melt dropping behavior of the developed solid fuel should further be investigated in the different available commercial energy saving stoves to find their efficiencies for complete combustion of the developed solid fuel.

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APPENDICES

APPENDIX A: Raw data for the mass of melt drops of the solid fuel.

Solid Fuel Sample	Percentage of clay	M _{md} / ± 0.1 g		Solid Fuel Sample	Percentage of clay	M _{md} / ± 0.1 g	
		1	2			1	2
PET ₀	0.00	11.3	11.9	PET ₁₆₀	34.78	0.0	0.0
PET ₁₀	3.23	9.6	10.3	PET ₁₇₀	36.17	0.0	0.0
PET ₂₀	6.25	7.2	6.8	PET ₁₈₀	37.50	0.0	0.0
PET ₃₀	9.09	5.4	6.0	PET ₁₉₀	38.78	0.0	0.0
PET ₄₀	11.76	4.0	3.7	PET ₂₀₀	40.00	0.0	0.0
PET ₅₀	14.29	3.7	3.3	PET ₂₁₀	41.18	0.0	0.0
PET ₆₀	16.67	2.8	3.0	PET ₂₂₀	42.31	0.0	0.0
PET ₇₀	18.92	1.7	1.9	PET ₂₃₀	43.40	0.0	0.0
PET ₈₀	21.05	0.0	0.0	PET ₂₄₀	44.44	0.0	0.0
PET ₉₀	23.08	0.0	0.0	PET ₂₅₀	45.45	0.0	0.0
PET ₁₀₀	25.00	0.0	0.0	PET ₂₆₀	46.43	0.0	0.0
PET ₁₁₀	26.83	0.0	0.0	PET ₂₇₀	47.37	0.0	0.0
PET ₁₂₀	28.57	0.0	0.0	PET ₂₈₀	48.28	0.0	0.0
PET ₁₃₀	30.23	0.0	0.0	PET ₂₉₀	49.15	0.0	0.0
PET ₁₄₀	31.82	0.0	0.0	PET ₃₀₀	50.00	0.0	0.0
PET ₁₅₀	33.33	0.0	0.0				

M_{md} = Mass of melt drops of the solid fuel samples.

APPENDIX B: Raw data for mass combustion rate of the solid fuels.

Sample	$M_{sh}/\pm 0.1 \text{ g}$		$M_S/\pm 0.1 \text{ g}$		$M_{shS}/\pm 0.1 \text{ g}$		$M_{shA}/\pm 0.1 \text{ g}$		$M_B/\pm 0.1 \text{ g}$		$M_{CBR}/\pm 0.1 \text{ g min}^{-1}$	
	EXP1	EXP2	EXP1	EXP2	EXP1	EXP2	EXP1	EXP2	EXP1	EXP2	EXP1	EXP2
PET0	340.4	337.9	110.0	110.0	450.4	447.9	353.8	353.5	96.6	94.4	3.2200	3.1467
PET10	339.4	338.0	110.0	110.0	449.4	448.0	359.5	354.6	89.9	93.4	2.9967	3.1133
PET20	339.3	338.0	110.0	110.0	449.3	448.0	361.9	355.2	87.4	92.8	2.9133	3.0933
PET30	339.4	338.2	110.0	110.0	449.4	448.2	357.3	351.0	92.1	97.2	3.0700	3.2400
PET40	339.2	338.0	110.0	110.0	449.2	448.0	359.5	360.0	89.7	88.0	2.9900	2.9333
PET50	339.0	338.1	110.0	110.0	449.0	448.1	360.6	359.2	88.4	88.9	2.9467	2.9633
PET60	339.6	337.9	110.0	110.0	449.6	447.9	367.9	365.3	81.7	82.6	2.7233	2.7533
PET70	339.2	337.7	110.0	110.0	449.2	447.7	369.9	364.8	79.3	82.9	2.6433	2.7633
PET80	339.8	337.9	110.0	110.0	449.8	447.9	371.0	369.4	78.8	78.5	2.6267	2.6167
PET90	338.1	337.9	110.0	110.0	448.1	447.9	361.5	370.3	86.6	77.6	2.8867	2.5867
PET100	338.3	337.7	110.0	110.0	448.3	447.7	363.8	371.3	84.5	76.4	2.8167	2.5467
PET110	338.2	337.4	110.0	110.0	448.2	447.4	370.4	371.4	77.8	76.0	2.5933	2.5333
PET120	338.2	336.8	110.0	110.0	448.2	446.8	371.4	371.3	76.8	75.5	2.5600	2.5167
PET130	338.4	337.6	110.0	110.0	448.4	447.6	376.5	374.6	71.9	73.0	2.3967	2.4333
PET140	338.6	337.6	110.0	110.0	448.6	447.6	375.1	374.8	73.5	72.8	2.4500	2.4267
PET150	338.8	337.6	110.0	110.0	448.8	447.6	383.5	377.9	65.3	69.7	2.1767	2.3233
PET160	338.4	337.5	110.0	110.0	447.4	447.5	383.5	377.8	64.9	69.7	2.1633	2.3233
PET170	338.3	337.4	110.0	110.0	448.3	447.4	383.1	375.8	65.2	71.6	2.1733	2.3867
PET180	338.0	337.7	110.0	110.0	448.0	447.7	384.5	385.1	63.5	62.6	2.1167	2.0867
PET190	337.9	337.9	110.0	110.0	447.9	447.9	379.3	381.6	68.6	66.3	2.2867	2.2100
PET200	337.7	337.6	110.0	110.0	447.7	447.6	384.9	384.3	62.8	63.3	2.0933	2.1100
PET210	337.7	337.6	110.0	110.0	447.7	447.6	386.5	386.7	61.2	60.9	2.0400	2.0300
PET220	337.7	337.6	110.0	110.0	447.7	447.6	386.3	385.4	61.4	62.2	2.0467	2.0733
PET230	337.9	337.6	110.0	110.0	447.9	447.6	389.6	384.1	58.1	63.5	1.9433	2.1167
PET240	337.8	337.3	110.0	110.0	447.8	447.3	389.6	387.3	58.2	60.0	1.9400	2.0000
PET250	337.8	337.4	110.0	110.0	447.8	447.4	389.6	388.1	58.2	59.3	1.9400	1.9767
PET260	337.6	337.3	110.0	110.0	447.6	447.3	390.2	387.7	57.4	59.6	1.9133	1.9867
PET270	337.6	337.5	110.0	110.0	447.6	447.5	392.0	391.1	55.6	56.4	1.9200	1.8800
PET280	337.8	337.4	110.0	110.0	447.8	447.4	390.6	390.8	57.2	56.6	1.9067	1.8867
PET290	337.6	337.8	110.0	110.0	447.6	447.8	391.5	392.0	56.1	55.8	1.8700	1.8600
PET300	337.6	337.4	110.0	110.0	447.6	447.4	391.5	391.8	56.1	55.6	1.8700	1.8533

M_S = Input mass of the solid fuel, M_{sh} = Mass of empty solid fuel holder

M_{shA} = Mass of solid fuel holder and the Ash contents, M_B = Mass of the solid fuel burnt in 30 minutes. M_{BR} = Mass burn out rate of the solid fuel. EXP₁ = Experiment 1, EXP₂ = Experiment 2.

Calculation formulae:

$$M_B = (M_{shS} - M_{shA}),$$

$$M_{CBR} = \left(\frac{M_{shS} - M_{shA}}{T} \right) = \left(\frac{M_B}{T} \right), T = 30 \text{ Minutes.}$$

APPENDIX C: Raw data for the calorific values of the solid fuel.

Solid fuel Sample	Percentage of Clay	Calorific Value (joules)			
		1	2	3	4
PET ₀	0.00	21,254	21,247	21,253	21,248
PET ₁₀	3.23	19,652	19,649	19,654	19,652
PET ₂₀	6.26	17,406	17,409	17,411	17,414
PET ₃₀	9.09	12,998	12,995	12,993	12,997
PET ₄₀	11.77	18,929	18,918	18,929	18,925
PET ₅₀	14.29	18,270	18,274	18,199	18,273
PET ₆₀	16.68	18,226	18,219	18,229	18,220
PET ₇₀	18.92	18,702	18,704	18,706	18,711
PET ₈₀	21.05	17,988	17,899	17,986	17,988
PET ₉₀	23.03	16,983	16,979	16,984	16,969
PET ₁₀₀	25.01	14,801	14,809	14,810	14,806
PET ₁₁₀	26.82	13,840	13,844	13,841	13,842
PET ₁₂₀	28.57	13,499	13,501	13,504	13,479
PET ₁₃₀	30.24	15,272	15,269	15,274	15,275
PET ₁₄₀	31.83	17,436	17,426	14,428	14,419
PET ₁₅₀	33.33	10,571	10,569	10,559	10,568
PET ₁₆₀	34.79	13,217	13,224	13,223	13,219
PET ₁₇₀	36.17	13,082	13,093	13,076	13,078
PET ₁₈₀	37.51	13,231	13,232	13,232	13,231
PET ₁₉₀	38.78	11,258	11,249	11,248	11,258
PET ₂₀₀	39.99	11,606	11,608	11,604	11,608
PET ₂₁₀	41.17	13,410	13,411	13,409	13,419
PET ₂₂₀	42.31	11,633	11,629	11,632	11,628
PET ₂₃₀	43.39	10,742	10,743	10,741	10,742
PET ₂₄₀	44.44	11,174	11,176	11,173	11,174
PET ₂₅₀	45.45	11,823	11,819	11,820	11,821
PET ₂₆₀	46.42	10,397	10,388	10,367	10,399
PET ₂₇₀	47.36	10,619	10,620	10,621	10,623
PET ₂₈₀	48.28	9,971	10,210	10,211	9,988
PET ₂₉₀	49.15	10,610	10,611	10,610	10,610
PET ₃₀₀	50.00	10,423	10,418	10,415	10,424

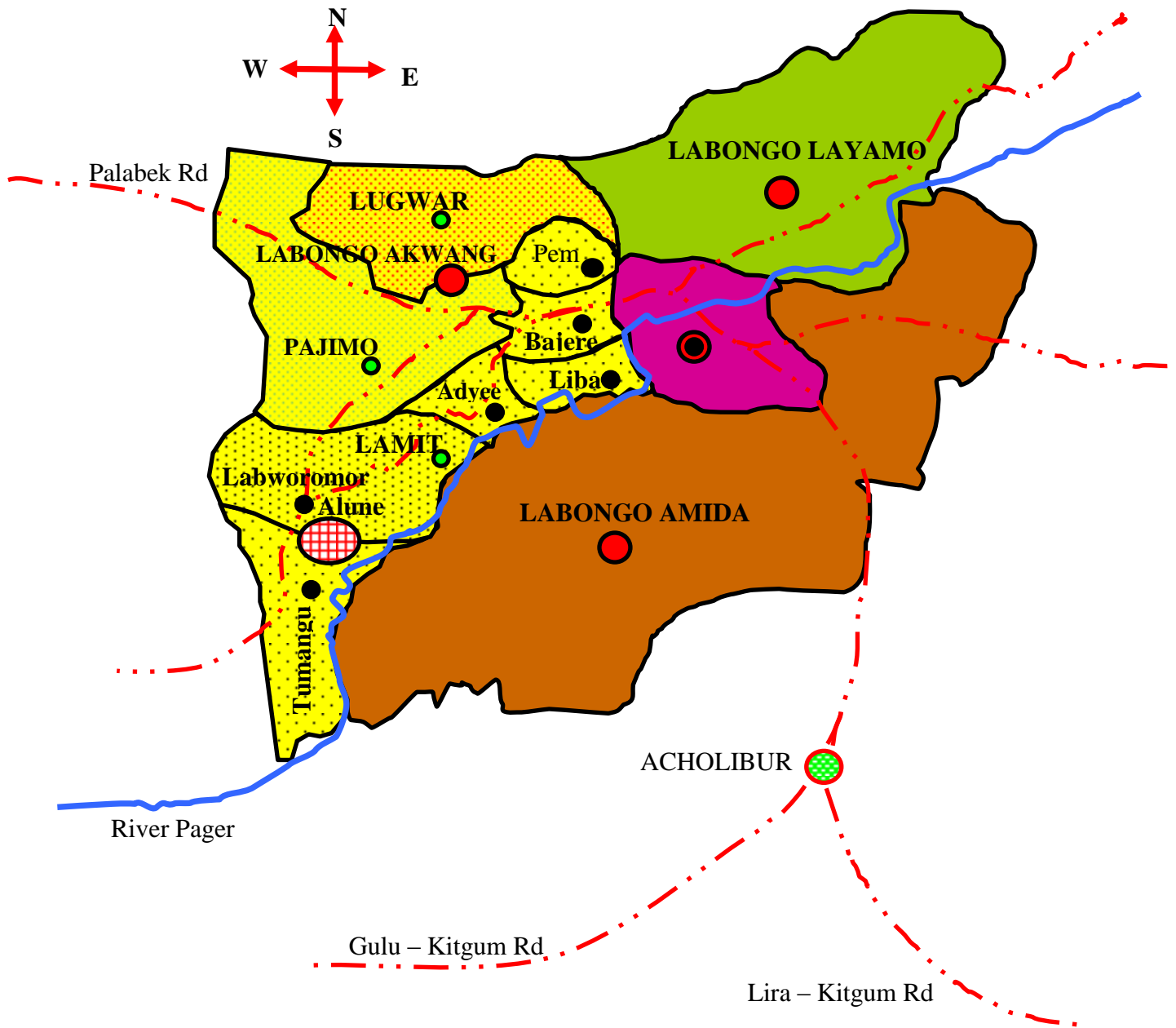
APPENDIX D: Raw data for mass of ash of the solid fuel.

Sample	M _A /±0.1 g		Sample	M _A /±0.1 g	
	1	2		1	2
PET ₀	13.4	15.6	PET ₁₆₀	45.1	40.3
PET ₁₀	20.1	16.6	PET ₁₇₀	44.8	38.4
PET ₂₀	22.6	17.2	PET ₁₈₀	46.5	47.4
PET ₃₀	17.9	12.8	PET ₁₉₀	41.4	43.7
PET ₄₀	20.3	22.0	PET ₂₀₀	47.2	46.7
PET ₅₀	21.6	21.1	PET ₂₁₀	48.8	49.1
PET ₆₀	28.3	27.4	PET ₂₂₀	48.6	47.8
PET ₇₀	30.7	27.1	PET ₂₃₀	51.7	46.5
PET ₈₀	31.2	31.5	PET ₂₄₀	51.8	50.0
PET ₉₀	23.4	32.4	PET ₂₅₀	51.8	50.7
PET ₁₀₀	25.5	33.5	PET ₂₆₀	52.6	50.4
PET ₁₁₀	32.2	34.0	PET ₂₇₀	52.4	53.6
PET ₁₂₀	33.2	34.5	PET ₂₈₀	52.8	53.4
PET ₁₃₀	38.1	37.0	PET ₂₉₀	53.9	54.2
PET ₁₄₀	36.5	37.2	PET ₃₀₀	53.9	54.4
PET ₁₅₀	44.7	40.3			










APPENDIX E: List of apparatus used.

S/N	APPARATUS	SPECIFICATIONS	Availability
01	Thermometers	Thermocouple (type K)	✓
02	Heating sources/ignition	Charcoal	✓
03	Burner/ stove	Fabricated	✓ Fabricated
04	Electronic balance	Any having unit in grams	✓
05	Bomb Calorimeter	C 200 Model	✓
06	Timer	Digital watches	✓
07	Travelling Microscope	10x eyepiece, 5x objective	✓
08	Filter	0.003mm size	✓

APPENDIX F: Map of Kitgum District showing Alune (Location of the Ball Clay)



KEY

- | | | | | | |
|---|-------------------|---|---------------------|---|------------------|
|  | Villages |  | Parishes | | |
|  | Akwang Sub County |  | Kitgum Municipality |  | Location of Ball |
|  | Amida Sub County |  | Layamo Sub County |  | Major routes |
| | | | |  | River |