

**ASSESSING THE SUITABILITY OF KAOLIN AS A CATALYST FOR
POLYETHYLENE PLASTIC WASTE PYROLYSIS : A CASE STUDY KIKUUBO
UGANDA**

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ABSTRACT.

In the Kampala Metropolitan Area, including Mbuya, approximately 135,804 tons of plastic waste are generated annually, of this, 42% remains uncollected, 15% is collected through value chain approaches, and 43% is collected by service providers. Significant amounts of plastic waste are either burned (21,728 tons), landfilled (47,457 tons), or end up in water systems (13,580 tons) (I. Tumuhimbise, 2023). Despite multiple bans on plastics since 2009, plastic use has not decreased, with over half of the waste ending up in open land and waterways (Ugandan Environmental Authorities, 2020). Recycling rates are alarmingly low at only 1%, and few companies recycle or repurpose plastic (S. Naluyima, 2022).

Traditional methods such as landfilling, open dumping, and incineration are unsustainable due to environmental degradation and public health risks. Pyrolysis, a thermochemical process that decomposes plastic waste into fuel and chemical feedstocks in the absence of oxygen, offers a promising alternative (Sharma et al., 2020). However, conventional pyrolysis faces challenges such as high energy demands, prolonged reaction times, and low-quality outputs due to incomplete hydrocarbon breakdown (Kizito, 2022). Catalytic pyrolysis addresses these limitations by using catalysts to lower reaction temperatures, improve efficiency, and enhance product yield.

This study investigates the suitability of kaolin, a locally abundant and cost-effective aluminosilicate clay, as a catalyst for polyethylene (PE) plastic waste pyrolysis. Kaolin's high silica (SiO_2) and alumina (Al_2O_3) content (53.67% and 24.47%, respectively) provides acidic sites that facilitate hydrocarbon cracking, while its thermal stability ensures durability under high temperatures (Wang et al., 2021).

The research evaluates kaolin's impact on pyrolysis efficiency, optimizing the kaolin-to-PE ratio, reaction time, and product yield. Experiments conducted using a fixed-bed reactor demonstrated that a 16% kaolin-to-PE ratio maximized liquid yield (75.67%), minimized char (4.08%) and gas (20.24%) production, and reduced reaction time by 18% compared to non-catalytic pyrolysis.

APPROVAL.

This report was approved for submission and examination by my supervisor as part of the academic requirements by the Faculty of Engineering, Design, and Technology of Uganda Christian University for the degree of Bachelor of Science in Civil and Environmental Engineering.

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Final Year Research Project Supervisor

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Date:.....

DECLARATION.

I Tagoola Prince hereby declare that this is my original work, is not plagiarised and has not been submitted any other institution for any award.

Signature:.....
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Date:.....

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DEDICATION.

This report is dedicated to my beloved family and supportive university, and their unwavering encouragement and guidance have been the foundation of my journey. This is a token of my gratitude for your endless support and belief in my potential. Thank you for being my pillars of strength.

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List of acronyms.

1. **PE** - Polyethylene
2. **LDPE** - Low-Density Polyethylene
3. **HDPE** - High-Density Polyethylene
4. **PP** - Polypropylene
5. **PS** - Polystyrene
6. **PET** - Polyethylene Terephthalate
7. **XRF** - X-Ray Fluorescence
8. **NEMA** - National Environment Management Authority
9. **KCCA** - Kampala Capital City Authority
10. **PAHs** - Polycyclic Aromatic Hydrocarbons
11. **ASTM** - American Society for Testing and Materials
12. **ISO** - International Organization for Standardization
13. **OSHA** - Occupational Safety and Health Administration
14. **H-C** - Hydrocarbons
15. **CH₄** - Methane
16. **C₂H₄** - Ethylene
17. **C₄H₈** - Butene
18. **Al₂O₃** - Aluminium Oxide
19. **SiO₂** - Silicon Dioxide

20. **Fe₂O₃** - Iron (III) Oxide

21. **CaO** - Calcium Oxide

22. **K₂O** - Potassium Oxide

23. **Na₂O** - Sodium Oxide

24. **TiO₂** - Titanium Dioxide

25. **MnO** - Manganese (II) Oxide

26. **P₂O₅** - Phosphorous Pentoxide

27. **CO₂** - Carbon Dioxide

28. **H₂** - Hydrogen Gas

29. **UNEP** - United Nations Environment Programme

30. **EPA** - Environmental Protection Agency

1 CHAPTER ONE: GENERAL INTRODUCTION.

1.1 Background of the study.

Plastic waste pollution is a growing concern globally especially in urban areas and developing countries like Uganda are facing the same vice of plastic waste pollution in its urban areas such as Kikuubo Market, a go to are by many urban dwellers in Uganda for shopping. Improper disposal methods have resulted into the environment being degraded as a result of the plastic waste and traditional waste management techniques, including landfilling, open dumping and open burning together with mechanical recycling (NEMA, 2021), are not sufficient to address the volume of waste generated and as a result a lot of plastic is ending up in drainage channels, river, lakes and so on.

In Uganda, plastic waste poses a significant environmental challenge, with over 600 tons produced daily, according to the National Environment Management Authority (NEMA). Despite only 40% of this waste being collected and properly disposed of, the remaining 60% pollutes the environment. Plastics, composed of toxic chemicals, are ubiquitous due to their use in packaging and poor disposal practices, leading to widespread environmental contamination (Ministry of Water and Environment, 2022). Each person generates about 43 kg of plastic waste annually, with plastics constituting 73% of municipal waste. During rainy seasons, plastic waste obstructs drainage systems, causing flooding and accumulating in dumpsites (B. Kizito, 2022). NEMA reports that 51% of plastic waste in cities like Kampala ends up in drainage channels, wetlands, and other natural areas, as less than 5% is recycled. Plastic waste takes over 450 years to decompose fully.

Based on the fact that other traditional methods for plastic waste management have not really been efficient, it is important that other methods are looked at and in this case pyrolysis of the plastic waste. Pyrolysis, a thermochemical process that decomposes organic material at elevated temperatures in the absence of oxygen (Sharma et al., 2020). Pyrolysis involves recycling waste into chemical and fuel feedstock and compared to other methods, pyrolysis is more versatile in managing plastic waste as will be explained further in the report. However, pyrolysis often lacks efficiency, producing lower-quality outputs in terms of oil and harmful emissions as a result of incomplete combustion of the hydrocarbons.

There are several factors that come into play for a pyrolysis process to operate successfully, including the quality and quantity of feedstock, residence time, temperature and catalytic requirements (ScienceDirect, 2023). Various research has been carried out in which a variety of catalysts such as zeolites, bagasse ash and so on have been used in the pyrolysis process. The catalytic pyrolysis process is superior to the thermal catalytic process in terms of product quality, reaction time and energy needed for the entire process.

This report looks at using kaolin, an aluminosilicate clay mineral as a catalyst for the enhancement of polyethylene plastic waste pyrolysis and the research aims to improve the yield, quality of pyrolysis while reducing the emission of harmful gases (Eldashory, 2023).

1.2 Problem Statement.

Plastic waste accumulation in Uganda, particularly polyethylene (PE), poses severe environmental and public health challenges. Kampala generates 1,500 tons of solid waste daily, 20-30% of which is plastic (NEMA, 2021). Only 40% is collected, leaving the rest to pollute drainage systems, wetlands, and natural habitats (Ministry of Water and Environment, 2022). Each Ugandan produces ~43 kg of plastic waste annually, with plastics constituting 73% of municipal waste (B. Kizito, 2022). During rains, clogged drains cause flooding, while open burning releases toxic emissions like polycyclic aromatic hydrocarbons (PAHs) (UNEP, 2022). Alarmingly, 21,728 tons are burned, 47,457 tons are landfilled, and 13,580 tons end up in water systems (Tumuhimbise, 2023). Despite multiple bans on plastics since 2009, consumption has not decreased, and over half of the waste contaminates open land and waterways (Ugandan Environmental Authorities, 2020). Recycling rates are critically low at 1%, with few companies engaged in plastic repurposing (Naluyima, 2022). Uganda's waste collection rate of 39% exacerbates pollution, underscoring the urgent need for alternative waste management solutions (NEMA, 2021).

Current waste management methods, landfilling, incineration, and mechanical recycling are inadequate. Landfills leach toxins into soil and water, incineration emits greenhouse gases, and Uganda's 1% recycling rate is insufficient (NEMA, 2021). Pyrolysis, which converts plastic waste into fuel oil, gas, and char, is a viable alternative but suffers from inefficiencies ranging from high energy demand given that thermal pyrolysis requires temperatures exceeding 500°C, increasing operational costs (Al-Rumaihi et al., 2022). The other constraint is low yield and quality as the non-catalytic pyrolysis produces unstable oil with high sulfur content and low fuel value (Rajendran et al., 2020) and lastly is the fear of harmful emissions

where incomplete cracking generates volatile organic compounds (VOCs) and heavy hydrocarbons (Zhang et al., 2020).

Catalytic pyrolysis mitigates these issues by lowering activation energy and improving product selectivity. However, conventional catalysts like zeolites are expensive and prone to coking (Tewari et al., 2020), while bagasse ash contains impurities that degrade oil quality (Saini et al., 2020). Kaolin, a low-cost locally available clay, offers a sustainable alternative to the issues posed by the other catalysts when used. Its metal oxides (e.g., Al_2O_3 , SiO_2) enhance cracking and provide for thermal stability, hence improving oil yield while ensuring that it stays highly economical.

1.3 Objectives of the Study.

Main Objective.

To assess the use of kaolin as a catalyst in enhancing the pyrolysis of polyethylene plastic waste in Kikuubo, Uganda.

Specific Objectives.

1. To analyse the metal oxides composition of Kaolin.
2. To determine the optimal mix ratio of kaolin and PE for pyrolysis and impact of kaolin on reaction time.
3. To assess the economic viability of using Kaolin as a catalyst in PE pyrolysis.

1.4 Research questions.

How does the presence of metal oxides in kaolin (such as SiO_2 and Al_2O_3) influence the catalytic cracking of polyethylene during pyrolysis?

What is the optimal kaolin-to-polyethylene ratio for maximizing the yield of liquid hydrocarbons during pyrolysis?

What effect does the addition of kaolin as a catalyst have on the pyrolysis in terms of reaction time and product yield?

What is the economic feasibility of using kaolin as a catalyst in PE pyrolysis?

1.5 Justification of the research.

The integration of kaolin as a catalyst in the pyrolysis of polyethylene plastic waste offers a promising solution to the issue of plastic pollution in Kampala, Kikuubo Market. Given its local abundance, low cost, and proven catalytic properties (Vijayakumar, 2018), kaolin can enhance the efficiency pyrolysis while reducing harmful emissions. This research not only aims to improve the yield and quality of pyrolysis products but also seeks to make pyrolysis technology environmentally and economically viable for sustainable waste management practices in communities like Kikuubo Market.

Kaolin is composed of aluminum oxide (Al_2O_3) and silicon dioxide (SiO_2), which help in the breakdown of long chain hydrocarbons into shorter ones. These oxides have an acidic characteristic that promotes efficient decomposition of the PE plastics suitable for low-cost PE plastic waste pyrolysis due to its cracking mechanism that involves the abstraction of hydride ions from the polymer structure of plastic and C-C receives an addition of protons. Also the small pore structure of Kaolin serves as a heat sink allowing the absorption of heat by the feedstock molecules hence reducing the reaction time by allowing hydrogen transfer. (Nalluri.P, 2021).

1.6 Scope of the study.

The scope of this research is limited to Kikuubo Market that is located in the central business district of Kampala, the capital city of Uganda. It is located at 26 Ben Kiwanuka St. Geographically, it lies within the area known as Kampala Central Division, one of the divisions of the city. The approximate coordinates of Kikuubo Market are, Latitude: 0.3130° N and Longitude: 32.5725° E. This section of the city is a significant point for generation and accumulation of polyethylene plastic waste.

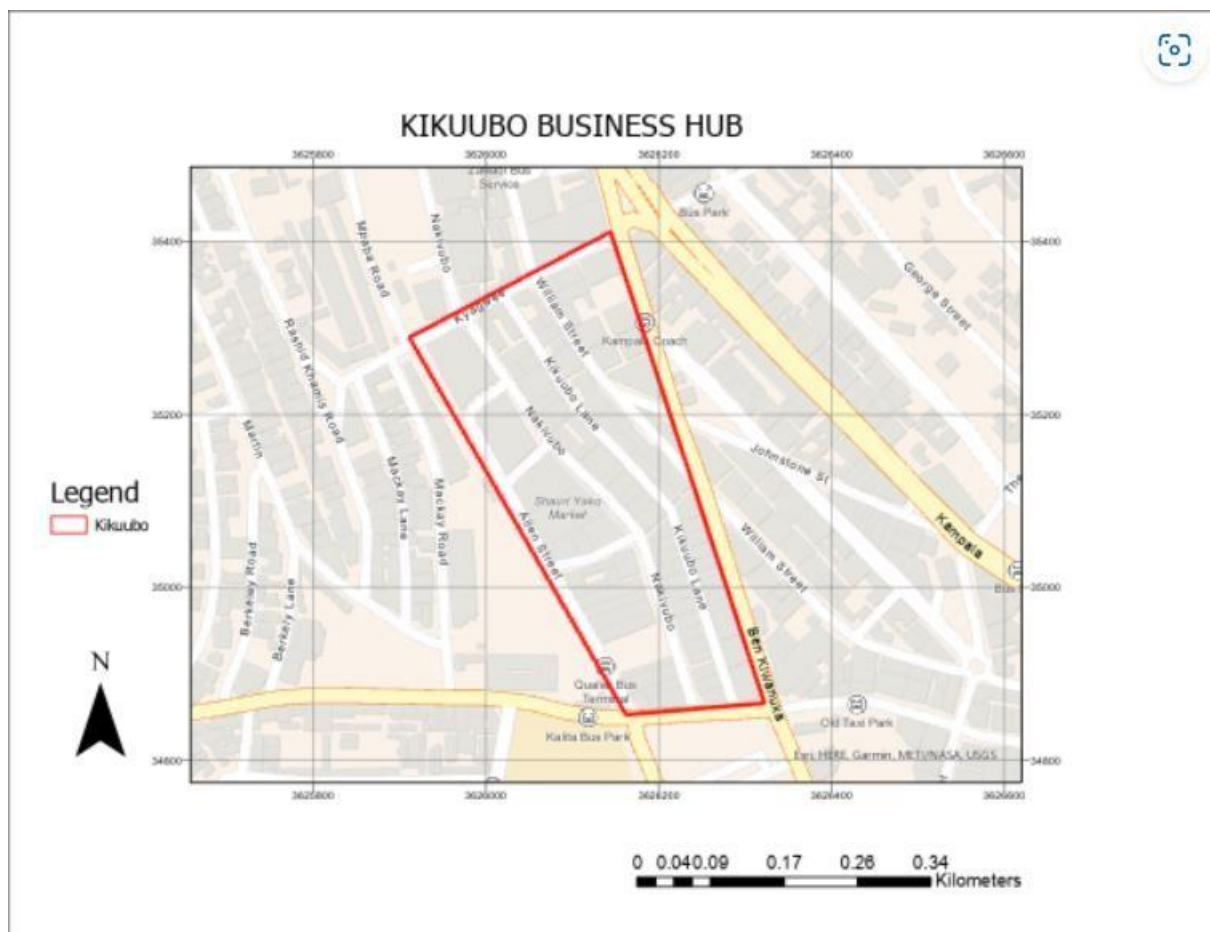


Figure 1 Location of Kikuubo Market

The research lies in the field of study of civil and environmental engineering, mainly focussing on plastic waste management of polyethylene plastic. The research borrows knowledge of environmental science, materials and chemical science which all when integrated together will aid in filling the knowledge gap focussed on. The specific aim of the research is to assess the catalytic effects of kaolin on PE pyrolysis giving focus to reaction time, oil yield, energy required and emission reduction.

The research is to span from October 2024 to March 2025 and in this period activities like data collection, laboratory experiments, literature review, kaolin and plastic sourcing, results analysis, report writing and project defence will be carried out.

2 CHAPTER TWO: LITERATURE REVIEW

2.1 Brief Introduction.

Plastic is a polymer that on the application of heat and pressure can be shaped into any desired shape based on the purpose of which it is to be used. This property is called plasticity and explains why plastics are used as much as they are on top of their low density, low thermal conductivity and generally the toughness some form after they harden. Plasticity as well describes if a polymer would survive the temperature and pressure during the formation process (Payal ,B. 2025). Plastics could be PE (Polyethylene), PP (Polypropylene), (PVC) Polyvinyl Chloride and so on which all serve various purposes in the community. There are two types of plastics, thermoplastics like PE and thermosetting plastics (Rodriguez ,F. 2021), which are classified based on their response to heat (American Chemistry Council, 2023).

2.2 Plastic types.

Thermoplastics have a feature that allows mobility and hence they can be shaped into various shapes when heat is applied because of their inability to chemically bond. The reshaping of these plastics has no negative effects on the physical properties of the plastics. The rate of mobility depends on which plastic it is and how much temperature is in place. The molecular weight of thermoplastics tends to be high, and their solidification happens as they cool down.

Thermosetting plastics, however, cannot be reprocessed upon heating as they have an insoluble and infusible network (Rodriguez, F., 2021). These types of plastics as they cure, become so as polymers crosslink each other and form a chemical bond that cannot be reshaped (Garcia et al., 2022).

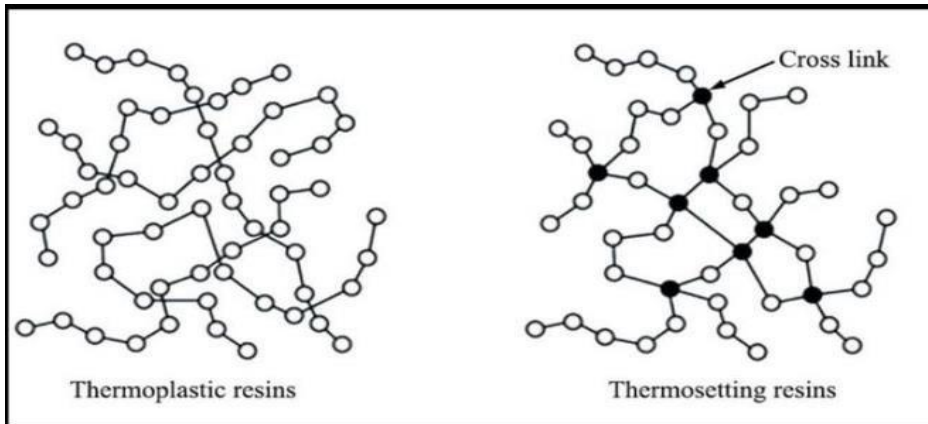


Figure 2: Structure of thermoplastic and thermosetting plastic

(Source: Polymer Science Journal, 2022)

2.2.1 Differences between thermoplastics and thermosetting plastics.

Parameter	Thermoplastic	Thermosetting plastic
Formation	Formed by addition polymerization	Formed by condensation polymerization
Molecular weight	Lower molecular weight that does not exceed 500,000g/mol	High molecular weight that could go up to about 1,000,000 g/mol
Bonding	Molecules held together by secondary bonds	Molecules held together by primary chemical bonds
Melting Points	Lower melting points which make reshaping easier	High melting points that could go up to 3000C
Tensile Strength	Low tensile strength due to weak intermolecular forces	High tensile strength because of strong crosslinked bonds

Table 1 : Differences between thermoplastics and thermosetting plastics

(Source: Garcia et al., 2022)

2.2.1 Production process of plastics.

Raw materials extraction.

The main raw materials in this process are crude oil and natural gas which are a mixture of thousands of hydrocarbons which are organic compounds made up of carbon and hydrogen. Crude oil when heated in a furnace is separated into different

components based on their boiling points in a process called fractional distillation (Kumar et al., 2022), and natural gas can be processed to obtain ethylene and propylene as a result of naphtha from which plastic is created (American Chemical Society, 2023).

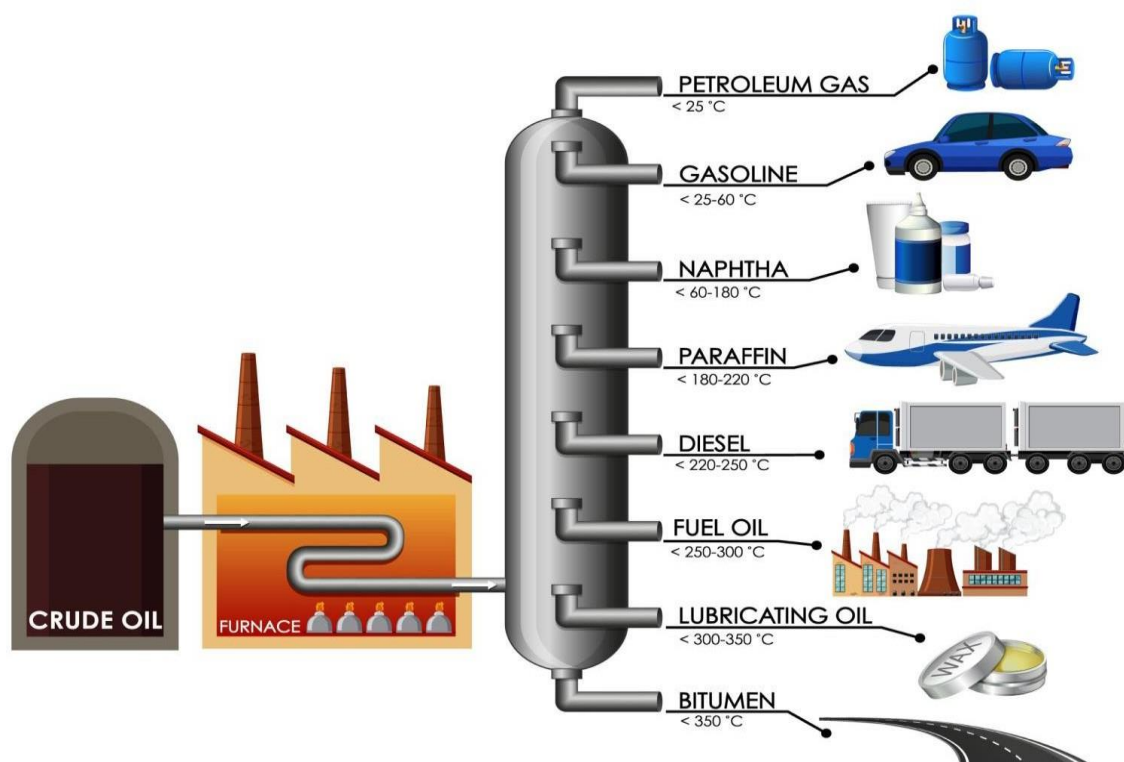


Figure 3: Fractional distillation of crude oil.

(Source: American Chemistry Society, 2023)

Refining process.

This is for monomer production and the process involves transforming crude oil into various petroleum products which are later converted into useful monomers that build up polymers. In this process, hydrocarbons are subjected to temperatures of between 800-9000C separating the heavy crude oil into smaller molecules like ethylene and propylene and after this the monomers are used in the polymerization process (Kumar et al., 2022).

2.2.2 Converting monomers to polymers.

Is the process by which short chain molecules called monomers like ethylene and propylene are transformed into long chain molecules called polymers of higher molecular weight. There are two different types of polymerization:

Addition polymerization - This is also called chain growth polymerization as it adds one monomer unit at a time and here, one monomer connects to the next called a dimer and then to the next called and it to a trimer and the process continues. Usually, a catalyst is used to fasten the reaction and as a result form polymer chains (R. Jones, 2024) . Common addition polymers are polyethylene that's used in plastic bags, bottle, another is polystyrene and polyvinyl chloride used mainly in pipe manufacture.

Condensation polymerization - Also called step growth polymerization involves 2 or more different monomers are joined together by the removal of smaller molecules and by products like water or methanol and is mainly used in the production of high-performance plastics and examples include nylon, polyesters and so on (Wiley, 2024).

2.2.3 Plastic waste management.

In the last 4 decades, the demand for plastic has grown due to the increasing population. The life cycles of plastic do not go past waste disposal sites like landfills and due to their lack of bio-degradability aspect, they cannot be readily recycled (Narayan, 2022). Waste management faces various challenges but the main one being how to properly handle it, despite having methods like landfilling, regeneration and incineration in place (Chen et al., 2021).

Over the last 20 years, the annual global production of plastic as a result of the demand has doubled and in Uganda, 42% of plastic is improperly disposed, 10% end up in water bodies and 20% burned leading to water, land and air pollution. In Uganda, sorting of waste to remove plastics is still low and only done by both informal and formal recycling industries that deal with plastic waste from homes, markets, industries and so on and all these methods haven't been as efficient over time (Draft National Strategy to prevent plastic pollution EPA, 2023).

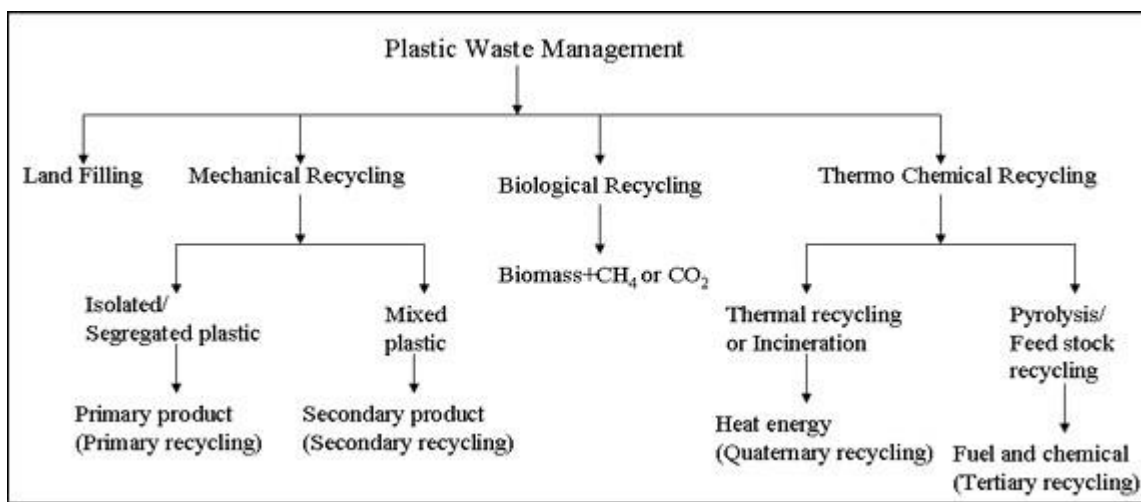


Figure 4: Different plastic waste management methods

(Source: Draft National Strategy to Prevent Plastic Pollution, EPA, 2023)

2.2.4 Statistics on plastic usage and plastic waste management.

Overtime, disposing of plastics in landfills, which has been the main method of disposal used is no longer urged owing to government policies, increased green house emissions and the failure of plastics to be biodegradable (Khan et al., 2022). Based on this, alternative methods as in the figure above must be considered as an alternative to landfilling, incineration and so on.

Plastic waste pollution is a growing concern globally especially in urban areas and developing countries like Uganda are facing the same vice of plastic waste pollution

in its urban areas such as Kikuubo Market, a go to are by many urban dwellers in Uganda for shopping. Improper disposal methods have resulted into the environment being degraded as a result of the plastic waste and traditional waste management techniques, including landfilling, open dumping and open burning together with mechanical recycling (NEMA, 2021), are not sufficient to address the volume of waste generated and as a result a lot of plastic is ending up in drainage channels, river, lakes and so on.

In Uganda, plastic waste poses a significant environmental challenge, with over 600 tons produced daily, according to the National Environment Management Authority (NEMA, 2021). Despite only 40% of this waste being collected and properly disposed of, the remaining 60% pollutes the environment. Plastics, composed of toxic chemicals, are ubiquitous due to their use in packaging and poor disposal practices, leading to widespread environmental contamination (Ministry of Water and Environment, 2022). Each person generates about 43 kg of plastic waste annually, with plastics constituting 73% of municipal waste. During rainy seasons, plastic waste obstructs drainage systems, causing flooding and accumulating in dumpsites (B. Kizito, 2022). NEMA reports that 51% of plastic waste in cities like Kampala ends up in drainage channels, wetlands, and other natural areas, as less than 5% is recycled. Plastic waste takes over 450 years to decompose fully.

For pyrolysis to produce efficient results, there are several factors that are considered, ranging from the quality and quantity of feedstock, residence time, temperature and catalyst presence (ScienceDirect, 2023). Overtime, several catalysts like fly ash, bagasse ash, zeolites have been employed in the catalyst process but have not produced efficient results, based on operation.

This report looks at using kaolin, an aluminosilicate clay mineral as a catalyst for the enhancement of polyethylene plastic waste pyrolysis and the research aims to improve the yield, quality of pyrolysis while reducing the emission of harmful gases (Eldashory, 2023).

There are over 30 corporations registered as plastic recycling agencies in Uganda (KCCA Cost Chain Mapping Record, 2022). However, these agencies have not fully addressed the issue of plastic waste pollution. Integrating catalytic pyrolysis technology offers a sustainable solution by converting waste plastics into valuable resources such as fuel oil, gas, and char. This approach not only mitigates environmental pollution but also generates economic opportunities through the production of alternative fuels and raw materials.

In 2020, Kampala generated approximately 1,500 tons of solid waste daily, with an estimated 20-30% being plastic waste (NEMA, 2021). Most of this plastic waste is either disposed of in landfills, dump sites or openly burned, leading to significant environmental and health impacts. Catalytic pyrolysis is proposed as a viable method for converting plastic waste into fuel, addressing both waste and energy challenges. This research aims to evaluate the feasibility of adopting catalytic pyrolysis technology and to provide insights into sustainable waste management practices in Kikuubo, Uganda. Successful implementation could reduce greenhouse gas emissions and offer economic benefits through the production of alternative fuels (UNEP, 2022).

2.3 Pyrolysis.

It involves heating plastics in the absence of oxygen at temperatures of 300-8000C, and the process converts long chain polymers into oligomers and the process is influenced by several factors ranging from feedstock, temperature, catalyst, residence time and so on. In comparison to other plastic waste management methods like incineration, landfilling and so on, pyrolysis poses to be more environmentally friendly while reducing waste plastics while providing fuel to be used for energy (Rajendran et al., 2020). Plastic waste can go under pyrolysis through 3 processes namely, thermal pyrolysis, catalysed pyrolysis and hydrocracking.

2.3.1 Thermal pyrolysis.

This process involves the breaking down of polymers by application of heat at a temperature range of 3000C to 8500C in the absence of Oxygen (Wu et al., 2022). As a result of this process, a solid residue also known as solid char, hydrocarbons that are highly combustible are produced which are made up of condensable liquid fuels or non-condensable gases and the type of plastic used, temperatures, residence time all affect these products (Al-Rumaihi et al., 2022).

However, this process left to itself requires very high temperatures and residence time so as to be able to breakdown the long chain polymers into shorter ones and catalytic pyrolysis provides a solution to this problem.

2.3.2 Catalytic pyrolysis.

Here, a catalyst is used in the pyrolysis methodology to initiate the cracking process, it decreases the reaction time, temperatures and improves the overall liquid yield while reducing emission of gases. Looking at the economic side, catalytic pyrolysis in regard to operation costs is cheaper than thermal pyrolysis, making it a more

desirable alternative, and this method is more efficient given that the catalyst can be reused and hence poses a more appealing and practical solution to addressing the environmental issues that have resulted from plastic waste disposal (O. Ayodeji, 2022).

The use of a catalyst in pyrolysis as well improves the quality of the liquid oil together with the conversion time as it reduces it, as well as reducing temperature decreases and the overall reaction time (Ong et al., 2019) and also reduces the distribution of H-C products in HDPE pyrolysis. The use of catalysts also improves the selection of H-C in the fuel range, that is C5 to C12 (Olivera et al., 2020; Nasution et al., 2022) and the fuels obtained from this catalytic pyrolysis have a greater proportion of branched H-C (Liu et al., 2020).

According to (Hou et al., 2021), catalytic pyrolysis has the best potential for pyrolysis even in terms of commercialization or on a large scale as explained in the literature above, and all the reasons as explained have played a role in informing this research. The table below highlights the differences between thermal pyrolysis and catalytic pyrolysis.

Catalytic Pyrolysis	Thermal Pyrolysis
The bio-fuel produces is of higher quality and has improved stability.	The quality of the bio-fuel produced is lower than that in catalytic pyrolysis
Lower overall operational costs as the bio-fuel might not need extra processing	Higher operational costs due to more processing that's needed for bio-fuel
Less reaction time, faster fuel production	More reaction time, slower fuel production
Reduces gaseous emission as more H-C are broken down	Less H-C are broken down, meaning more gaseous emissions
Operates at temperatures of 300-600 °C	Operates at higher temperatures of 400-800 °C

Table 2 : Differences between catalytic and thermal pyrolysis

(Source: Rajendran et al., 2020)

2.3.3 Plastic Pyrolysis Feedstock.

As explained earlier in this chapter, there are several types of plastic based on their formation thermoplastics and thermosetting plastics and also based on functional groups. The functional groups of various plastics determine their selectivity and distribution of products that they form as a result of pyrolysis. Functional groups also encourage depolymerization of long chain molecules called polymers into short chain molecules called monomers (Chen et al., 2021) and plastics like polyethylene yield high-molecular weight compounds under normal pyrolysis.

Polyethylene (PE).

PE can either be low-density (LDPE) or high-density (HDPE) and due to its long linear chains with limited branching, PE has a crystalline structure that is stronger than that of other synthetic polymers, and the strong inter-molecular interactions make it necessary to have temperatures of not less than 4000C in place for successful PE pyrolysis (Kumar et al., 2020). PE lacks aromatic compound, which makes it suitable for high fuel yield from pyrolysis.

An increase in the residence time improves the quality of the liquid fuel produced and at relatively low temperatures, the incorporation of a catalyst like kaolin allows for high quality (Miandad et al., 2017), quantity of the fuel minus necessarily having high temperatures that increase the formation of gaseous products, which are not our aim but would rather even go on to pollute the environment (Uzoejinwa et al., 2018).

2.3.4 Justification for using PE and not other plastics.

Polypropylene (PP)

PP as compared to PE has a higher melting temperature and thermal stability as a result of it being more heat resistant and generally tougher (Jain et al., 2022). The methyl group (-CH₃), present in PP cause a difference in reactivity between PE and PP because of the presence of carbon in the structure of PP that is tertiary in existence. This explains why PE is being used for the pyrolysis and not PP, though PP is the most extensively manufactured on the global market.

Polystyrene (PS)

PS is mainly made up of styrene monomers, that are formed by the movement of bonding electrons, and in appearance it is translucent and many times fragile. On undergoing pyrolysis, PS produces a major product of styrene, followed by ethylbenzene and as a result, its product distribution is less than that of PE (Zhu et al., 2021).

Polyethylene Terephthalate (PET).

PET makes up about 18% of the total plastic production globally, majorly because of its broad use in the industrial sector ranging from electronic industries to packaging industries. From research, pyrolysis of PET has yielded more of the gaseous product than the liquid fuel which is essentially needed (Du et al., 2016), and this all deems PE as a better option for pyrolysis.

2.3.5 Parameters of Plastic Pyrolysis.

Various factors affect the effectiveness of plastic pyrolysis as they may influence not only the quantity but also the quality of the liquid fuel produced and may as well influence the overall costs of the process, there by affecting the efficiency either

positively or negatively. However, all these factors can be mitigated and managed to suite best the product that is to be obtained.

- **Temperature:** This is the most important factor when it comes to pyrolysis. Thermal cracking of the polymers happens when the energy applied exceeds the binding enthalpies of the various bonds (C-C, C-H) (Mhaske et al., 2022). The temperatures have to be optimized as higher temperatures above 500 °C would end up increasing the gas and black char production and the lower temperatures between 350 and 500 °C favour the liquid fuel formation (Peng et al., 2022; Al-Rumaihi et al., 2022).
- **Reactor Type:** There are various types of reactors, that is to say; fluidized beds, fixed-bed reactors, or conical spouted beds, which all can contain up to a given temperature which overall influences the way plastics combine with or without catalysts, reaction time, quantity and quality of the yield and eventually affect the efficiency (Gebre et al., 2021).
- **Pressure:** At high pressures, the main product is the gases and lighter hydrocarbons at lower temperature below 300 °C, however the influence of high pressures is less affected at high temperatures above 400 °C especially in vacuum pyrolysis (Papari et al., 2021; Al-Rumaihi et al., 2022).
- **Catalyst Use:** Catalysts are essential in reducing the reaction time, improving the quality of liquid products, lowering activation energy without distorting the chemical composition of the plastics. There are two types of catalysts, heterogeneous and homogeneous catalysts which are essential in breaking down of polymers into monomers (Karnjanakom et al., 2020; Goh et al., 2022).

- **Reaction Time:** The time the pyrolysis process takes influences the polymer breakdown to monomers and eventually the formation of liquids, solids and gases. Shorter reaction times lead to reduced coke and gas production and improve the overall liquid yields (Ali et al., 2021), whereas longer times increase gas production that is not environmentally friendly.

2.4 Kaolin as a Catalyst in PE Pyrolysis

2.4.1 Introduction

As explained and discussed earlier, plastic waste has become a global issue that requires urgency when it comes to managing it mainly because it cannot be naturally degraded once in the environment. Overtime, mitigation measures like use of dump sites, recycling have all been incorporated but have not yielded results as expected, hence the need to come up with other technologies like pyrolysis that is a thermal decomposition process that involve the depolymerization of long chain hydrocarbons into short chain hydrocarbons that is however enhanced by the use of catalysts that could either be natural like kaolin or synthetic like zeolites.

In this specific research, kaolin is being incorporated in the pyrolysis to lower reaction temperature, reduce reaction time and improve product yield while reducing toxic gaseous emissions as will be justified below. Kolin is naturally occurring and its natural availability, abundance and cost effectiveness together

with environmental friendliness has given it a lot of attention in regard to use as a catalyst (Zhang et al., 2022).

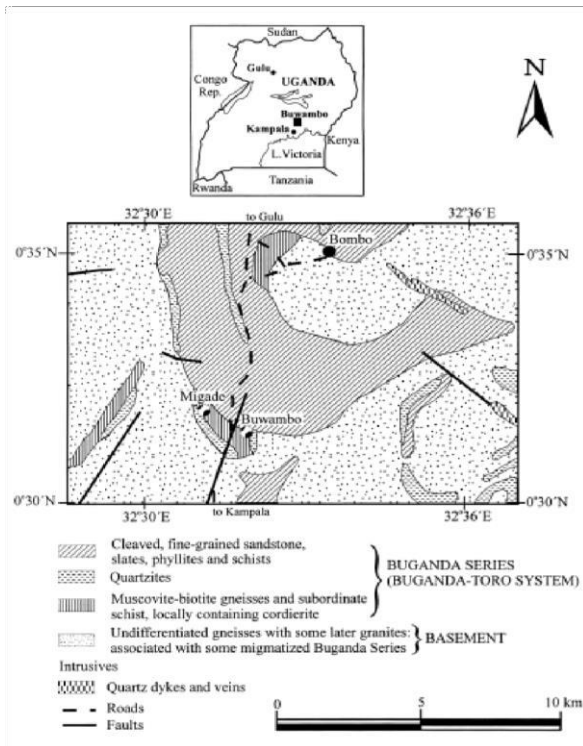


Figure 5: Location of Buwambo Kaolin Deposit

(Source: Uganda Geological Survey, 2022)

2.4.2 Structure and Properties.

Kaolin is a clay mineral that is naturally occurring, and is a soft white clay that is formed through the chemical weathering of aluminium rich feldspars in granites. It is mainly a composition of aluminium oxide (Al_2O_3) and silicon dioxide (SiO_2), with the formula $Al_2Si_2O_5(OH)_4$. It is also called kaolinite and is characterized by its layered structure that has silica sheets that are tetrahedral and octahedral alumina sheets that provide the kaolin with a large surface area hence contributing to its catalytic activity, and exists in abundance in various parts of Uganda, one of them

being the Buwambo deposit located approximately 27 km north of Kampala (Nakayiwa et al., 2021).

The figure below shows the crystal structure of kaolin as a 1:1 phyllosilicate as a result of composition of silica tetrahedral sheets and alumina octahedral sheets that are bonded together. Oxygen contributes to the bonding structure of kaolin by forming part of the silica and alumina layers. The hydroxyl that is located in the alumina octahedral sheet forms hydrogen bonds with adjacent layers, hence stabilizing the structure. Silicon forms the tetrahedral layer which consists of silicon dioxide tetrahedral linked to each other and this forms a continuous sheet and lastly the aluminium forms the octahedral layer where Al^{3+} ions are surrounded by hydroxyl groups of AlO_6 octahedral and oxygen.

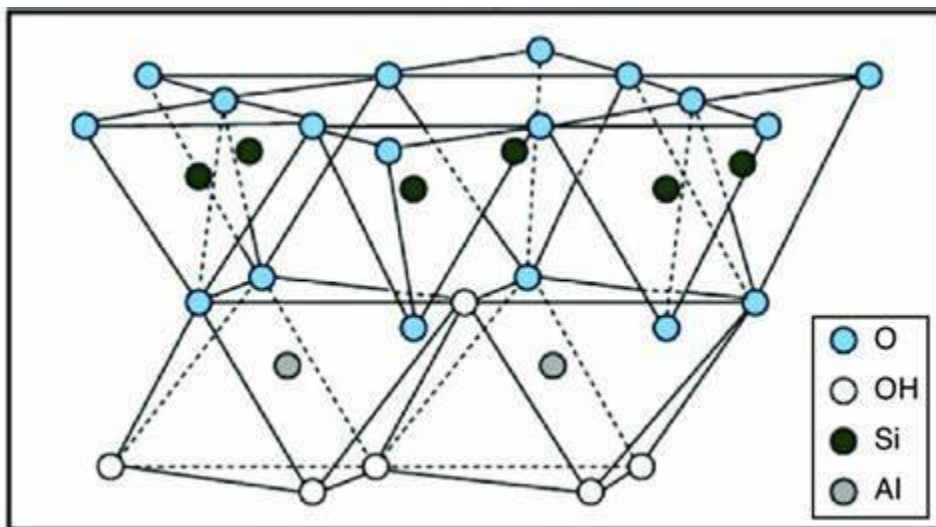


Figure 6: Kaolin Structure

(Source: Clay Minerals Society, 2021)

Summarized below are the kaolin clay properties from literature.

- Chemistry: As highlighted earlier, the chemical formula of Kaolin is $Al_2Si_2O_5(OH)_4$. It is mainly a composition of aluminium oxide (Al_2O_3) and

silicon dioxide (SiO_2), as can be seen in the formula and this is why it is called an aluminium silicate (Kumar et al., 2020).

- Structure: Kaolin has a layered structure that has silica sheets that are tetrahedral and octahedral alumina sheets that provide the kaolin with a large surface area. It also consists of hexagonal crystals that form layers that are stacked inside and these all contribute to its properties (Ahsan et al., 2020).
- pH: Kaolin has a neutral pH level, meaning that it can suitably used as a catalyst for plastic waste pyrolysis as it would not distort or influence the nature, chemistry or structure of the plastic (Ahsan et al., 2020).
- Adsorbent: Kaolin has a porous structure which allows the adsorption of other substances, including volatile organic compounds, undesirable impurities and any other foreign substances that are not desired in the process and could pollute the environment during pyrolysis (Ibrahim et al., 2020).
- Non-swelling: Kaolin between his layers has hydrogen bonds that prevent the molecules of water from entering the layers and this gives kaolin the ability to prevent water from entering is what gives kaolin this type of structure and hence does not alter the physical properties of the plastics in which they are added (Ahsan et al., 2020).

Other than other metal-based catalysts which are hazardous and expensive such as zeolites, kaolin is non-toxic and environmentally friendly and when used reduces the emission of gases that are toxic as will be explained in the later chapters. Kaolin has Al^{3+} ions that give it the acidic nature it has and eventually activates the depolymerization of polymers into monomers, hereby fulfilling one of its goals as a catalyst in enhancing breakdown (Zhang et al., 2020). Zeolites as catalysts present

a major challenge of costs as opposed to kaolin and also another to do with availability.

2.4.3 Kaolin as a Catalyst in PE Pyrolysis

Pyrolysis of PE entails the thermal decomposition of the long chain hydrocarbons into smaller ones in the absence of oxygen. The process needs high temperatures of at least not less than 400°C and long reaction times, which can be mitigated by the use of catalysts, and in this case Kaolin. Kaolin, when used as a catalyst in pyrolysis, has shown ability to increase the efficiency of pyrolysis as it reduces reaction time, lowers energy needed for breakdown of polymers.

Kaolin on its surface has acidic sites that aid the C-C bond cleavage hence leading to the formation of monomers which are the smaller H-C for example methane (CH₄), ethylene (C₂H₄), and butene (C₄H₈) (Wang et al., 2021).

Kaolin also can facilitate the removal of hydrogen atoms from the H-C chain hence leading to the formation of alkenes and hydrogen that can eventually be collected and used for other purposes as well. The alkenes eventually condense into the desired fuel and as this continues, pyrolysis is being made of higher effect and emission of heavy H-C that are toxic to the environment is reduced as there is almost total breakdown of polymers into monomers, and this is all attributed to the ability of kaolin to allow for dehydrogenation reactions (Li et al., 2020).

2.4.4 Benefits of Kaolin in PE Pyrolysis.

- Cost-effectiveness - Kaolin is cost effective as compared to synthetic catalysts like zeolite and metal based catalysts and exists naturally in abundance in the areas where it is and this availability reduces costs to do with

transportation to the processing industries and this also makes kaolin suitable for use in developing countries like Uganda, hence deeming it a better option for use on a large scale (Nakayiwa et al., 2021).

- Environmentally friendly - Unlike synthetic catalysts like metal-based catalysts and zeolites, kaolin is less toxic in terms of gases emitted like polycyclic aromatic hydrocarbons (PAHs), by promoting the breakdown of heavier hydrocarbons into lighter and more volatile compounds, mainly because of its stable structure and large surface area and its use in catalyst reduces emission of toxic gases to the environment (Zhang et al., 2020).
- Acidic properties - Kaolin has Al^{3+} ions that contribute to its natural acidity and this attribute allows for dehydrogenation reactions that lead to the formation of alkenes and hydrogen as a byproduct that can as well be used as a clean fuel (Li et al., 2020). This acidic attribute also allows for depolymerization, leading to formation of methane, butene and so on during the pyrolysis process (Wang et al., 2021).
- Reduction of reaction temperature and time - Kaolin when used as a catalyst reduces the reaction temperature required in the pyrolysis process by reducing the overall energy needed for the depolymerization process of PE and as well reduces the reaction time of the process (Zhang et al., 2020) and in the long run reduces the overall costs of production of the pyrolysis oil.
- Production of H_2 gas - Hydrogen, which is a clean and renewable gas that can be used for energy is produced in the pyrolysis process when the kaolin activates dehydrogenation reactions and as a result, the gas produced can be sold and also contributes to the economic aspect and contribution of the pyrolysis. In the equation below, the alkane undergoes dehydrogenation in

the presence of kaolin and forms an alkene and hydrogen gas that is a clean gas.

- Improved quality by-products - Pyrolysis forms various by-products ranging from liquids to solids and gases as well and kaolin once used leads to the production of monomers which are more valuable hydrocarbons, hence improving the quality of pyrolysis oil, making it suitable for use as a fuel. Kaolin also reduces the production of toxic by-products like green house gases which can pollute the environment (Li et al., 2020).
- Reduction of toxic emissions - Kaolin speeds up the depolymerization process of breakdown of heavy hydrocarbons called polymers into lighter ones called monomers and since the process is faster, fewer volatile organic compounds and toxic gases like nitrogen and sulfur oxides that usually result from the combustion of the polymers (Zhang et al., 2020) are produced.
- Ability to be reused - Kaolin after being used the first time can be reused again multiple times after applying thermal treatment by calcination method to restore some of the catalytic properties it entails, hereby reducing costs involved in purchase and operation (Wang et al., 2021).

2.4.5 Challenges of using kaolin as a catalyst in PE pyrolysis.

Kaolin deactivation - According to Wang et al., 2021, there are some challenges associated with the use of kaolin as a catalyst for PE pyrolysis with the main one being the deactivation of the kaolin overtime as a result of decomposition of carbon materials on its surface, and this process known as coking reduces the catalytic activity of kaolin in the pyrolysis and calls for replacement of kaolin as its being

used, irrespective of the fact that it has the ability to be used more than once and this is one of the areas in which research should venture to solve this problem of coking, but one of the already present solutions is treating the kaolin through calcination to burn off the deposited coke.

Varying composition - Another challenge to do with the use of kaolin is the fact that its composition can generally vary based on the source as some kaolin compositions may have titanium and iron oxides that affect catalytic activity, and also results into variations in acidity, surface area and porosity of the kaolin (Nakayawa et al., 2021). The mitigation measure to this is standardization of the kaolin sources to ensure consistency in quality, together with chemical modification by calcination.

Moderate acidity - Kaolin has a moderate acidity that is lower than that of synthetic catalysts like zeolite and this might lead to incomplete depolymerization, leading to lower yields of the by-products needed (El-Sayed and Hassan, 2020). However, this can as well be mitigated by calcination and combining of kaolin with other stronger catalysts.

Compatibility with reactors - Kaolin in nature is a fine whitish powder which at times forms dust which makes uniform distribution in the reactor tricky, leading to uneven pyrolysis process hence affecting the results. The solution is to use properly sealed off reactors that don't allow the dust to escape (Ibrahim et al., 2020).

2.4.6 Comparison of kaolin with other catalysts.

Aspect	Kaolin	Zeolite	Bagasse Ash
Cost	Low cost because of natural abundance	High cost because of production process	Low cost but a by-product of bagasse combustion which is expensive
Environmental Friendliness	Non-toxic	High carbon production	Contains various heavy metals
Versatility	Can be used for several plastics ranging from PE, PP, PS etc	Narrow range of use	Inconsistent composition limits versatility
Harmful emissions	Reduces emission of harmful gases and produces hydrogen	Produces various aromatic compounds	Has impurities that result in toxic gases
Catalytic activity	Moderate acidity and less prone to coking	High acidity and prone to coking	Unstable catalytic activity because of variable composition
Thermal stability	Moderate thermal stability	High thermal stability	Low thermal stability, undergoes phase changes at high temperatures
Reusability	Can be reused multiple times	Reusing is possible but expensive because of coking	Difficult to reuse due to low thermal stability
Availability	Abundant in nature	Limited natural availability	Abundant but varies in quality

Table 3 : Kaolin comparison to other catalysts

(Source: Zhang et al., 2020 and Wang et al., 2021)

Based on the table of comparisons above, Kaolin has various attributes that give it an edge over other catalysts, its low cost, availability, reusability and so on. Other than zeolites that give off toxic gases, prone to activation and fly ash which has environmental risks and is not stable, kaolin provides a suitable solution to all these inconsistencies. Also, the ability of kaolin to give off clean hydrogen gas that can be used for energy and for it to operate effectively for various plastics, this gives it an edge over zeolites and fly ash.

2.4.7 Recent advances in kaolin catalysis for PE pyrolysis.

One of the incorporations that have been put in place is the thermal treatment of kaolin to form meta-kaolin that improves its thermal stability and as well aids in drying thereby improving acidity as well. Another method used is called calcination and this in general improves the catalytic activity of the kaolin (Wang et al., 2021).

Recent studies have focused on optimizing the catalytic performance of kaolin in HDPE pyrolysis. One approach involves the modification of kaolin through thermal or chemical treatment to enhance its surface area and acidity and the other approach is mixing ok kaolin with other metal-based catalysts at different ratios until the optimum is obtained, hereby increasing the efficiency of the pyrolysis process (Li et al., 2020). Also, calcination of kaolin at high temperatures has been shown to increase the number of active sites on its surface, thereby improving its catalytic activity (Wang et al., 2021).

In conclusion, based on the above literature, Kaolin has the capability to be used as a catalyst in PE pyrolysis based on various factors, ranging from abundance, low cost, versatility, thermal stability and environmental friendliness. It also can break down polymers and monomers, thereby obtaining the desired by-products based on

its acidic nature and the use of kaolin adds added advantage to environmental protection, given that it reduces the harmful gas emissions and also produces clean hydrogen gas that can be used as an energy source.

In the recent past, there has been modification and advancement in technology of the reactors used and this has improved on the efficiency of use of kaolin as a catalyst and this has aided in mitigation of the various challenges associated with it such as variability of the kaolin that causes it to have different compositions based on the sourcing.

3 CHAPTER THREE: METHODOLOGY.

3.1 Brief Introduction.

The main objective of this chapter is to present and discuss the research design, methods, tools and materials used in the topic of study to be able to achieve the 3 specific objectives which are; (1) to analyse the metal oxide composition of kaolin, (2) to determine the optimal mix ratio of kaolin and PE for pyrolysis and impact of kaolin on reaction time, and (3) to assess the economic viability of using kaolin as a catalyst in PE pyrolysis. This methodology is in accordance to several engineering and environmental standards to ensure accuracy, reliability and applicability of the methods and results obtained thereafter.

3.2 Research design.

The study focuses on the use of experimental and comparative design based on engineering standards. The experimental design isolates and controls each of the relevant conditions associated with the design and the comparative design focuses on comparison of relevant results that are got before, during and after the study using experimental and existing data thereby aiding proper data analysis. The research methods entailed in the research design are explained below.

3.3 To analyse the metal oxides composition of kaolin.

3.3.1 Sampling and material preparation.

The kaolin was sourced from the Buwambo kaolin deposit on longitude 32°31'54'' east and latitude 0°31'23'' north, in Namakonkome village, Wakiso district, Uganda after which it was dried at 105°C and heat treated in a laboratory furnace and then

crushed into a fine powder that could eventually be used after sieving achieve a uniform particle size 75-150 μm .

The PE plastic waste was got from Kikuubo market in Kampala, Uganda after which it was sorted to ensure that it was only PE in the mix, cleaned of any mud and dirt and then shredded into smaller pieces that could then be fed into the reactor for pyrolysis, via the inlet.

The standard used was ISO 11464:2006 which is used for pre-treatment of samples for physiochemical analysis, which aided in ensuring proper preparation of kaolin and PE to remove impurities, and as well ensuring consistency of raw materials in the mix.

3.3.2 Characterization of Kaolin.

Kaolin was characterized for its chemical composition using X-Ray Fluorescence (XRF) Spectrometry to determine the percentage of metal oxides present in the kaolin, that would either make it suitable for use as a catalyst or not. The procedure that was followed for the XRF is as below:

-First the kaolin powder was crushed, dried to remove any moisture and then sieved to remove large particles.

-The kaolin was then heated in an oven at 500-600⁰C so as to increase its thermal stability, given that pyrolysis also occurs at extreme temperatures. This Kaolin is now called meta-kaolin.

-The XRF spectrometer was calibrated using standard reference materials, and the analysis was conducted in accordance with ASTM E1621-22 and ASTM E1621-13 which is a standard guide for elemental analysis by X-Ray Fluorescence Spectrometry.

-The concentrations of key metal oxides, SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , were then quantified in composition by weight percentages.

3.4 To determine the optimal mix ratio of kaolin and PE for pyrolysis and impact of kaolin on reaction time.

To be able to achieve this specific objective, an experimental set up of pyrolysis was considered to obtain necessary values oil yield and time from which the optimal mix was got.

3.4.1 Pyrolysis reactor set up.

A fixed bed pyrolysis reactor of 35 cm by 75 cm made of stainless steel was used with an electric heating system that was connected to an ink bird temperature controller and a thermocouple for temperature monitoring. The reactor is tightly sealed off and insulated to minimize temperature losses and a small stainless steel outlet tube connected at the top and continues to the condenser tank where it forms a coil. The condenser tank has two taps, one being for fuel outlet and the other for water that would have heated up during the condensation process.

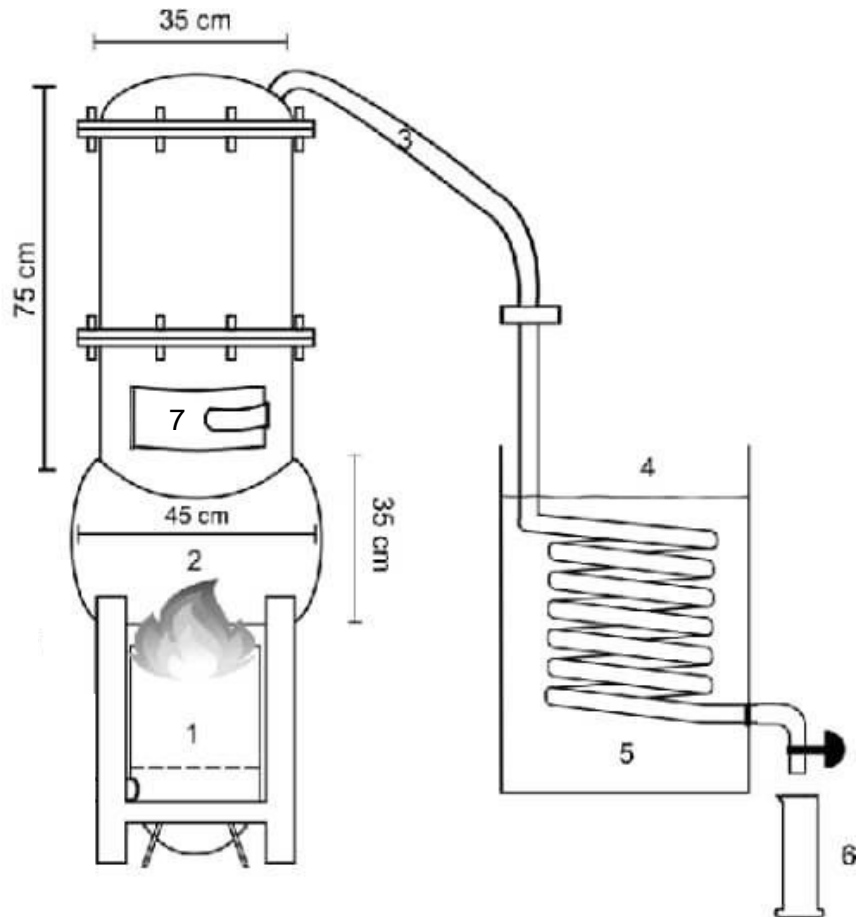


Figure 7: Pyrolysis reactor setup

Components of the pyrolysis reactor and functions.

1. Energy source - The energy source used was electricity to provide the necessary heat and temperatures for pyrolysis. This energy source is advantageous in that it allows for precise temperature control and a safer and more efficient heating system, while minimizing emissions.
2. Reactor Chamber - This is the main chamber where the polyethylene waste undergoes pyrolysis, and it is made from stainless steel for heat resistance and durability. It has a sealed lid to allow and maintain an oxygen free environment for complete pyrolysis. This chamber also has an inlet for the

feedstock, through which the polyethylene plastic was put and heated in the absence of oxygen, causing it to break down into oil, gas and char.

3. Connector to condenser - This is also a vapor transfer tube and transports pyrolysis vapors from the reactor to the condenser. It is made of heat-resistant stainless steel, well-sealed to prevent any leaks and losses and is also inclined at a small angle to allow easy flow of the vapor.
4. Cooling coil - This is the condenser system that converts the pyrolysis vapors into the pyrolysis oil. It is also made of stainless steel for high thermal conductivity and for the design, it is composed of a coiled stainless-steel tube that is inside water that provides a large surface area for complete condensation, and the condensed oil flows into a collection container below the vessel.
5. Water vessel - This, also called the cooling system provides a medium for cooling to enable condensation and it does this by holding water that absorbs water from the coils. It is connected to a thermocouple that's connected to the control box and each time the water reaches 70-800C, it is drained out and cooler water placed in the vessel.
6. Measuring equipment - This is used to collect the pyrolysis oil that has been condensed, and it has markings that aid in measurement. The equipment is sealed off to prevent any possible losses through evaporation.

3.4.2 Operation Principle of Pyrolysis Reactor Setup.

- I. Preparation of materials.

The polyethylene plastic used was obtained from Kikuubo Market in Kampala, mainly HDPE which was cleaned, washed and cut into smaller cube pieces that could fit in the pyrolysis reactor, and also allow for easy heat transfer by increasing the surface area to volume ratio for pyrolysis to occur.

The Kaolin as explained earlier was obtained from Buwambo kaolin clay deposit in Wakiso district after which it was crushed, washed, dried, sieved and calcined.

II. Placing feedstock in reactor.

For each of the pyrolysis run, approximately 1kg of plastic was placed in the reactor, each time placing the specific quantities of the kaolin in the reactor too while manually mixing to ensure the kaolin and plastic are mixed. The reactor lid was tightly closed to cut off all oxygen.

III. Heating process.

An electric source was used to mainly minimize any emissions that could result from using other fuels like wood. During the heating, a control box was used to monitor temperature from a thermocouple, and it was gradually increased from 10⁰C to 450⁰C, to allow for the breakdown of hydrocarbons in the HDPE. As temperature gradually rose, the plastic too began to decompose into smaller hydro carbons.

IV. Pyrolysis Reaction.

At 300⁰C to 450⁰C, the plastic began to constantly break down and at 450⁰C, full pyrolysis had occurred forming a mixture of pyrolysis vapours that condensed to form pyrolysis oil, and also solid char. As the kaolin was added, it was noted that it enhanced the cracking process and improved thermal stability while reducing unwanted byproducts like char and gases.

V. Vapor flow through connector.

As heating occurred, volatile gases containing hydrocarbon compounds were produced that rose up in the reactor and exited the reactor through the stainless-steel connector pipe, and these later condensed into pyrolysis fuel as they proceeded to the coil. The pipe was inclined to allow easy flow of vapor to the coil.

VI. Condensation.

The heated hydrocarbon vapours from the connector pipe moved to the coiled condenser in the water vessel containing cold water. The purpose of the water was to absorb heat hence allowing the gases to condense into the desired pyrolysis oil. This oil was collected using the measuring equipment below the tap.

VII. Removal of solid char.

After pyrolysis, the solid carbon residue that remained at the bottom of the reactor is what we called char, which contains carbon from HDPE and unreacted kaolin. The reactor was first allowed to cool before the char could be removed by manual scraping, which was collected and weighed.

3.4.3 Determination of optimal kaolin-polyethylene mix ratio.

A mix ratio of kaolin-to-plastic ratios: 0% kaolin as the control, 5% kaolin, 10% kaolin, and 15% kaolin by weight was used to obtain the optimal mix ratio.

According to Desai et al., 2024, there are variables to be controlled for this optimum mix ratio to be achieved, which we too followed and these are;

-Temperature that will be between 420-500°C.

-Heating rate of 10°C/min which is the range in which temperature increases.

-Residence time of 30-100 minutes which is the time that the plastic spends in the reactor under pyrolysis.

3.4.4 Kaolin's impact on reaction time.

A control experiment which was the pyrolysis of 100% polyethylene plastic without kaolin catalyst was considered and experimental setups of different kaolin to plastic ratios too were considered and results for each analysed independently for the time taken from heating initiation to first oil drop formation and to the finish of entire pyrolysis process.

3.5 To assess the economic viability of using kaolin as a catalyst in PE pyrolysis.

This section explains the methodology that was used to analyse the economic viability of using kaolin as a catalyst in PE waste plastic pyrolysis, in comparison to synthetic zeolite and bagasse ash. The CBA mainly focussed on the total operation costs, mainly procurement and energy costs in comparison to benefits in terms of oil yield and reduced reaction time.

The CBA was undertaken using a complete framework and procedure involving data collection, cost and benefit identification and finally the overall evaluation. While doing this, focus was put on both direct and indirect costs related to the use of kaolin, to obtain a wholesome value for the CBA, and gauge the financial feasibility of using kaolin as a catalyst.

3.5.1 Procedure followed for CBA.

- a) Data collection.

Primary data was obtained from the pyrolysis experiment for energy use from which amount of energy used in terms of units was obtained, reaction time, product yield and costs that were involved in kaolin sample transportation and preparation.

On the other hand, secondary data was obtained mainly from published literature and reports on catalytic pyrolysis. The data was then used to establish the costs and benefits for further analysis and study.

b) Computation of cost elements.

The main costs that were considered were kaolin procurement costs that focussed on costs involved in getting the kaolin from Buwambo kaolin clay deposit, transportation costs involved in transporting kaolin from Buwambo to the laboratories, kaolin purification costs involved in crushing, washing, drying, sieving and calcinating and costs involved in energy use.

c) Computation of benefit elements.

The economic benefits were computed from the revenue obtained from elements that were directly influenced by the use of kaolin as a catalyst in the pyrolysis process which were, revenue from oil yield increase basing on oil market prices, revenue as a result of reduced reaction time since by this less energy would be consumed for pyrolysis, hence benefits from energy.

d) Economic evaluation.

The method used was the CBA method to obtain the overall benefits, which is simply a difference between the total benefits and total costs involved. Scientifically, for a project to be considered economically viable, the CBA should give a positive value, meaning that the total benefits outweigh the total costs.

CBA = Total Benefits - Total Costs

Total Costs = Operation Cost + Energy Costs + Purification Costs + Transportation Costs

Total Benefits = Pyrolysis oil Costs + Reduced Energy Costs

3.6 Data analysis.

3.6.1 Yield Calculation.

This was done using the mass balance equations, and the calculation is essential in the analysis of data as it aids in obtaining which of the kaolin to polyethylene ratios gives the best pyrolysis oil yield.

Yield of oil (%) = (Mo / Mi) x 100

Yield of char (%) = (Mc / Mi) x 100

Yield of gas (%) = 100 (Yield of oil + Yield of char)

Where; Mi = Initial mass of PE feedstock (g)

Mo = Mass of pyrolysis oil (g)

Mi = Mass of char (g)

The yield is calculated using the formula above and the standards below as a basis:

ASTM D523-14 which is the standard test method for specular gloss, and it is applied in analyzing the quality of the pyrolysis oil which is the yield based on visual properties especially of colour.

ASTM D7346-15 which is the standard test method for Noack volatility of petroleum and fuel Products and is used to evaluate the stability and volatility of the pyrolysis oil.

3.7 Data collection methods.

- One of the methods that was used is direct measurements which included weight, reaction time, temperature, and oil volume measurement using the equipment that was in place.
- Laboratory analysis was used which gave chemical composition of kaolin and pyrolysis products and the standard used was ISO 17025:2017 which gives guidelines for general requirements for competence of testing and calibration laboratories, ensuring laboratory measurements are reliable and accurate.
- Observation and recording too was used, which involves visual inspection of residue and emission control effectiveness. This method follows the ISO 17025:2017 guidelines for accuracy.

3.8 Environmental and operational safety standards.

- ISO 14001:2015 which is a standard for environmental management systems and ensures waste is handled appropriately to minimize negative environmental impacts from the pyrolysis.
- OSHA 1910.132 that provides standards for personal protective equipment.
- ASTM E741 which is the standard test method for determining air change in a single zone by tracer gas dilution and is essential in providing guidance on ventilation and toxic gas management.

In conclusion, this chapter highlights a detailed methodology for evaluating the significant effect of kaolin when used as a catalyst for polyethylene pyrolysis. It

focuses on the research design, methods used for data collection and analysis to optimize the pyrolysis process and also gives an overview of the pyrolysis experiment set up.

4 CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Brief Introduction.

This chapter presents and discusses the results obtained from the characterization of kaolin and other catalysts, as well as the pyrolysis experiments. The elemental composition of kaolin, determined using X-ray fluorescence (XRF), is compared with other catalysts such as zeolite and bagasse ash. The chapter also examines the pyrolysis product yields (liquid, gas, and char) and evaluates the performance of kaolin as a catalyst in enhancing polyethylene plastic waste pyrolysis.

4.2 Catalyst characterization results (XRF analysis).

The elemental composition of the kaolin sample, obtained from Buwambo, Wakiso District, was determined using XRF analysis. The table below presents the results of the XRF analysis of kaolin, revealing the presence of key oxides.

Metal Oxide	Results for Kaolin (% m/m)
Silicon dioxide (SiO ₂)	53.67
Aluminium Oxide (Al ₂ O ₃)	24.47
Potassium Oxide (K ₂ O)	12.63
Calcium Oxide (CaO)	8.16
Manganese (II) Oxide (MnO)	0.19
Titanium dioxide (TiO ₂)	0.17
Iron (III) Oxide (Fe ₂ O ₃)	0.65
Phosphorous pentoxide (P ₂ O ₅)	0.03

Table 4 : Kaolin XRF results

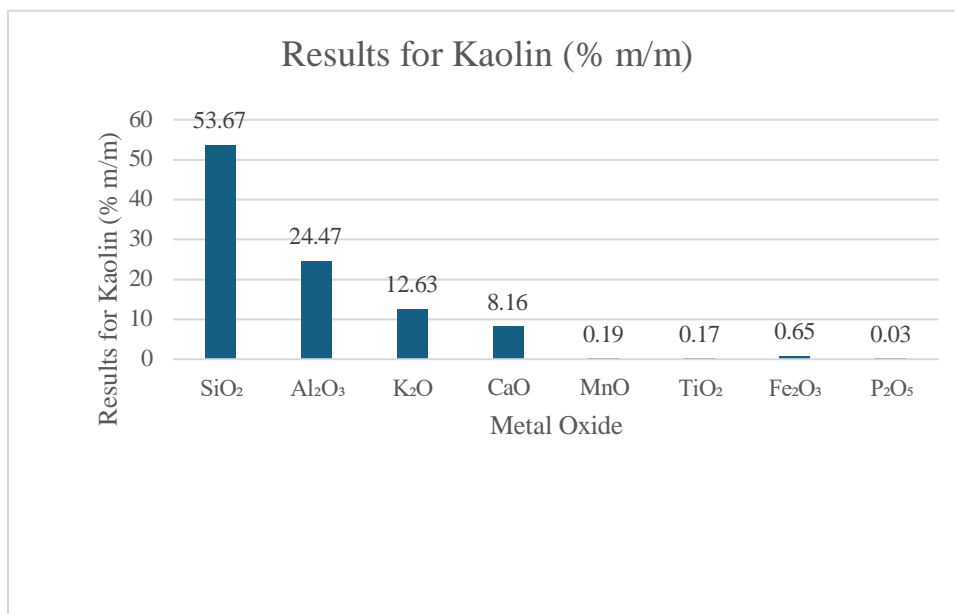


Figure 8: Bar graph showing kaolin metal oxides composition

4.2.1 Explanation of Kaolin XRF results.

I. Silicon Dioxide (SiO₂).

SiO₂ has the highest composition in kaolin at 53.67%. It is essential in contributing to the structural stability of the kaolin as a catalyst providing the capability to withstand high temperatures without necessarily having its composition changed and it also improves catalytic properties by providing a large surface area.

II. Aluminium Oxide (Al₂O₃).

Al₂O₃ with a percentage composition of 24.47% plays an important role in giving kaolin an acidic nature that contributes to the cracking of the hydrocarbons. This oxide being present also gives kaolin the ability to breakdown polymers into monomers, a process commonly known as depolymerization.

III. Calcium Oxide (CaO).

Calcium oxide at 8.16% gives kaolin its basicity nature that promotes decarboxylation reactions which remove oxygenated compound hence improving oil quality, as pyrolysis occurs in absence of oxygen.

IV. Potassium Oxide (K_2O).

Potassium oxide affects the reaction kinetics of the pyrolysis process, thereby reducing coke formation that could rather deactivate the kaolin overtime as the pyrolysis process goes on.

V. Iron (III) Oxide (Fe_2O_3).

Kaolin has a low Fe_2O_3 content of 0.65%, which reduces the excessive coke formation and catalytic deactivation, this makes kaolin a usable catalyst for prolonged polyethylene pyrolysis.

VI. Other Oxides (MnO , TiO_2 , P_2O_5).

These oxides as well exist in kaolin but in very trace compositions by percentage and have minimal chances of influencing the catalytic activity of kaolin.

4.2.2 Comparison of kaolin with other catalysts.

To assess the suitability of kaolin as a catalyst for pyrolysis, its composition was compared with other catalysts, such as zeolite and bagasse ash. Table below summarizes the major oxide compositions of these catalysts based on literature data and the XRF results.

COMPOSITION	KAOLIN (%)	BAGASSE ASH (%)	ZEOLITE (%)
SiO ₂	53.67	60.94	71.30
Al ₂ O ₃	24.47	14.83	13.10
Fe ₂ O ₃	0.05	12.81	1.90
MgO		2.05	1.20
CaO	8.16	3.05	5.20
Na ₂ O		0.51	1.30
K ₂ O	12.63	3.71	3.40
P ₂ O ₅	0.03	0.84	
TiO ₂	0.17	1.27	0.30
MnO	0.19		

Table 5 : Kaolin comparison to other catalysts

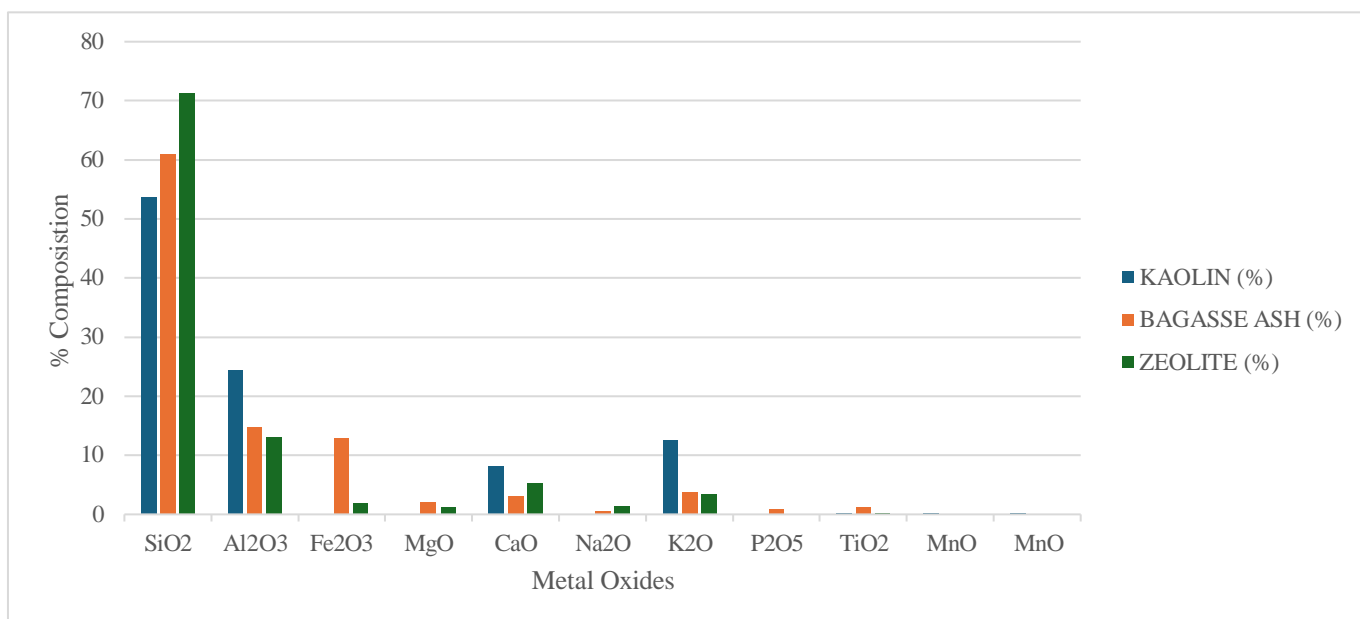


Figure 9: Bar graph showing kaoline, zeolite and bagasse ash composition

4.2.3 Discussion on why Kaolin is a better catalyst.

1. High Aluminium Oxide (Al₂O₃) content for hydrocarbon cracking.

Kaolin contains a significantly higher Al₂O₃ content (24.47%) compared to bagasse ash (14.83%) and zeolite (13.10%). Al₂O₃ is a key component in the formation of acid sites, which are essential for catalytic cracking of hydrocarbons during pyrolysis. The presence of these acid sites facilitates the breakdown of long-chain polymers into shorter, more valuable hydrocarbon chains, thereby increasing the liquid yield (Abnisa et al., 2020). Studies have shown that catalysts with high Al₂O₃ content are

more effective in enhancing the production of liquid fuels from plastic waste (Miandad et al., 2020). This makes kaolin a superior choice for improving the efficiency of pyrolysis reactions.

2. Optimal Silicon dioxide (SiO₂) content for structural stability.

While zeolite has the highest SiO₂ content (71.30%), kaolin's SiO₂ content (53.67%) is still sufficient to provide structural stability and a high surface area for catalytic reactions. Excessive SiO₂ content, as seen in zeolite, can lead to high rigid structures that may limit accessibility to active sites (Zhang et al., 2021). Kaolin vails a balance between structural stability and catalytic activity, making it more versatile for pyrolysis applications.

3. High Calcium Oxide (CaO) content for decarboxylation reactions.

Kaolin has a higher CaO content (8.16%) compared to bagasse ash (3.05%) and zeolite (5.20%). CaO is known to enhance the basicity of the catalyst, which promotes decarboxylation reactions. These reactions are crucial for removing oxygenated compounds and improving the quality of the pyrolysis oil by reducing its acidity (López et al., 2021). The presence of CaO in kaolin ensures a cleaner and more stable liquid product, which is a significant advantage over other catalysts.

4. Low Iron (III) oxide (Fe₂O₃) content for reduced unwanted reactions.

Kaolin has a very low Fe₂O₃ content (0.05%) compared to bagasse ash (12.81%) and zeolite (1.90%). High Fe₂O₃ content, as seen in bagasse ash, can lead to excessive redox reactions, which may result in the formation of undesirable by-products such as coke and tar (Chen et al., 2022). The low Fe₂O₃ content in kaolin minimizes these

unwanted reactions, ensuring a more efficient pyrolysis process with higher-quality products.

5. Potassium oxide (K₂O) for reduced coke formation.

Kaolin contains a moderate amount of K₂O (12.63%), which is higher than that in bagasse ash (3.71%) and zeolite (3.40%). K₂O is known to influence reaction kinetics and reduce coke formation during pyrolysis (Wang et al., 2021). Coke deposition is a common issue in catalytic pyrolysis, as it can deactivate the catalyst over time. The presence of K₂O in kaolin helps mitigate this issue, extending the catalyst's lifespan and improving its overall efficiency.

6. Absence of sodium oxide (Na₂O) for safer pyrolysis.

Unlike bagasse ash (0.51%) and zeolite (1.30%), kaolin does not contain Na₂O. The presence of Na₂O in catalysts can lead to the release of harmful gases, such as sodium oxide, during pyrolysis (Liu et al., 2020). The absence of Na₂O in kaolin makes it a safer and more environmentally friendly option for pyrolysis applications.

The figure below provides a visual comparison of the XRF results, illustrating the distribution of major oxides among the catalysts.

4.3 Pyrolysis Experiment Results.

From the use of the semi-batch reactor, different mix ratios of kaolin:PE were used and the oil yield, char yield and gas yield of each noted and recorded. For each mix ratio, the experiment was conducted thrice and mean obtained for each, which was then considered and used in later parts of this report for discussion. The tables below show the results of yield obtained.

Mix ratio	Oil yield (%)	Gas yield (%)	Char yield (%)
0% (Control)	65.01	25.66	9.32
5%	69.3	25.28	5.42
10%	71.31	23.66	5.03
14%	73.69	21.45	4.86
15%	75.29	20.7	4.01
16% (Optimum)	75.67	20.24	4.08
17%	74.3	20.81	4.89
20%	69.91	23.89	6.20

Table 6: Pyrolysis Yields

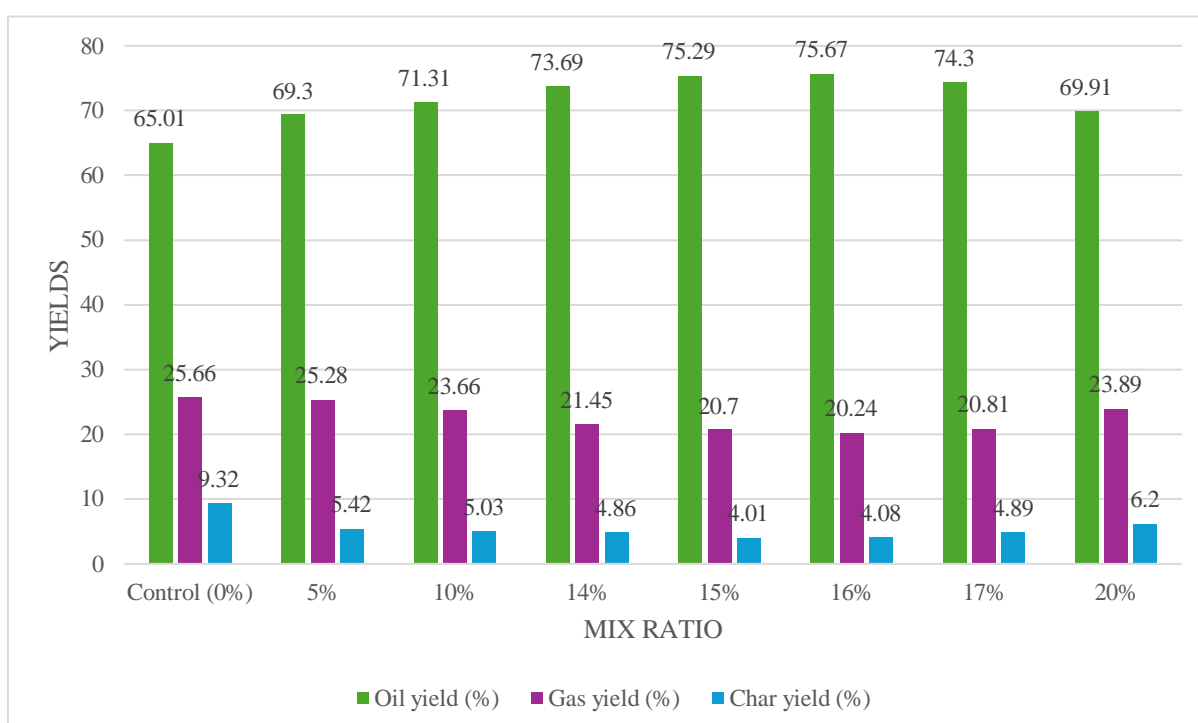


Figure 10: Bar graph showing pyrolysis yield

4.3.1 Discussion of Yield Results.

Oil Yield.

At 0% catalyst which was considered as the control experiment, the oil yield was 65.01% which turned out to be the lowest oil yield over the entire experiment. Thermal pyrolysis is what was happening at this ratio and resulted in a slower

pyrolysis process as the cracking from polymers to monomers was not as efficient and complete, hence resulting in high char and gas yield which reduced the oil yield. According to Wang et al., 2020, when pyrolysis experiment was conducted, it still produced lowest oil yield at the control as opposed to other mix ratios.

The different catalyst to HDPE ratios gave different oil yields, with 16% giving the highest oil yield of 75.67%. It should be noted however that so long as catalysts are used irrespective of the ratio, there is an increase in oil yield, which justifies kaolin use in pyrolysis. The highest oil yield at 16% ratio is due to the catalytic activity of kaolin which allowed for more breakdown of hydrocarbons while minimizing secondary reactions that contribute to char and gas formation. Kaolin's high aluminium oxide (Al_2O_3) content is the primary reason for the increase in liquid yield. Al_2O_3 is known to create acid sites on the catalyst's surface, which are essential for hydrocarbon cracking and facilitating of dehydrogenation reactions. During pyrolysis, these acid sites break down long-chain polymers in polyethylene into shorter, more valuable hydrocarbon chains, leading to a higher yield of liquid products (Abnisa et al., 2020).

At 20% kaolin, the oil yield decreased to 69.91% which is due to over cracking and high thermal degradation as a result of excessive catalyst that leads to formation of lighter hydrocarbons that are gases as opposed to liquids (Kim et al., 2020). Also, the over formation of the char on the kaolin surface could have contributed to the reduced catalytic activity, reducing the oil yield.

Char Yield.

For the char yield, it was highest at 0% mix ratio with a 9.32% composition due to incomplete degradation of polymers. The introduction of kaolin at the different

ratios keeps reducing the char formation and at 16% which is the optimum, the char yield was reduced to 4.08% due to improved breakdown of hydrocarbons. The presence of K_2O in the kaolin helps regulate reaction kinetics and prevents the buildup of carbon deposits (coke) on the catalyst surface, which can lead to char formation (Miandad et al., 2020). However, at 20% ratio, char yield again increased to 6.20%, which meant that the excessive cracking favoured for more char formation and also because of catalyst deactivation.

Gas Yield.

At 0% catalyst, the gas yield was at 25.66% which was due to thermal degradation that favours the breakdown of HC chains into more volatile gases. At the optimum mix, gas yield was at 20.24% as the presence of the catalyst aided the formation of liquid HC due to breakdown of the polymers, so the lower gas yield was mainly attributed to the high oil yield. The CaO in kaolin contributes to basicity the stabilizes the liquid HC which prevents further decomposition to gases. This reduces formation of lighter gases like methane (Wang et al., 2021).

4.3.2 Reaction Time Results and Discussion.

The reaction time for a pyrolysis experiment is essential in informing pyrolysis efficiency, energy consumption and oil yield. The reaction time is usually reduced by incorporating use of catalysts and in this case, kaolin was used and the results at different mix ratios are tabulated and discussed below.

4.3.2.1 Results.

Mix ratio	Reaction time (minutes)
0% (Control)	91
5%	81.67
10%	78.67
14%	76.67
15%	74.67
16% (Optimum)	74.33
17%	79.67
20%	87

Table 7: Pyrolysis reaction times

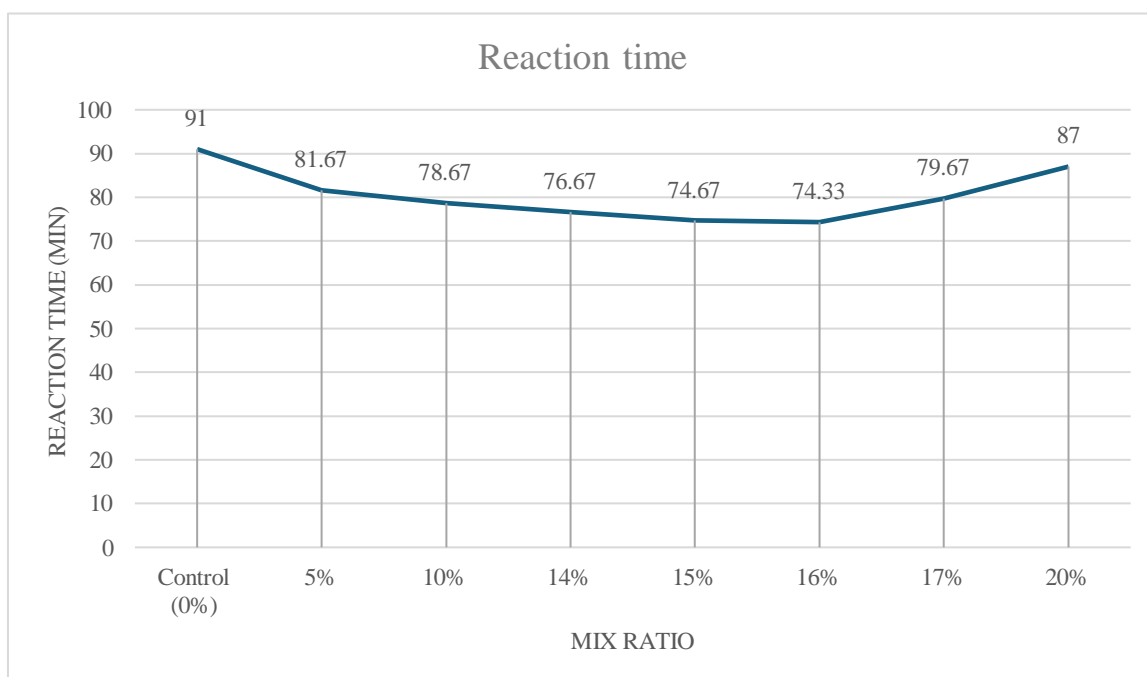


Figure 11: Line graph showing reaction time

4.3.2.2 Results Discussion.

The reaction time at 0% in the absence of kaolin was recorded as 91 minutes which was the highest among all mix ratios due to first the absence of a catalyst hence

slower depolymerization process as the thermal pyrolysis only relies on heat transfer to breakdown plastic leading to higher reaction times (Wang et al., 2020).

At 16% which is the optimum, the lowest reaction time of 74 minutes was recorded meaning that kaolin caused the speeding up of the pyrolysis process by promoting thermal cracking and reducing the overall energy needed for the pyrolysis process. The reduced reaction time can also be seen at the other kaolin concentrations, still owing to the same reasons (Wang et al., 2020).

For the highest ratio of 20%, reaction time at 87 minutes was higher than at the other ratios though lower than that of the control. This was due to the excessive kaolin in the mix that reduced the available surface area for reaction and introduced mass transfer limitations by restricting flow of volatile compounds hence slowing down the entire reaction (Zhang et al., 2020).

4.4 Cost Benefit Analysis.

4.4.1 Brief Introduction.

Cost benefit analysis is a step-by-step process used to evaluate the economic feasibility of a project by quantifying all involved costs and benefits and comparing them. Building on primary and secondary data, this analysis focusses on various costs involved in kaolin transportation, processing and so on, proceeding up to the revenue obtained when it is used in pyrolysis as a catalyst. This also focusses on comparison between kaolin and zeolite and bagasse catalysts and establishing which of the three is most economically viable and profitable when used.

4.4.2 CBA Results.

As explained in the methodology, total costs and benefits were calculated to obtain the economic feasibility of using kaolin as a catalyst in PE pyrolysis.

Costs (UGX/kg)		
Category	With Kaolin	Without Kaolin
Transport Costs (UGX/kg)	70	0
Processing Costs (UGX/kg)	500	0
Energy Costs (UGX/kg)	465	696
Total Costs (UGX/kg)	1,035	696
Revenue (UGX/kg)		
Oil Yield (%)	75	61
Oil Revenue (UGX/kg)	2,400	1,952
CBA (UGX/kg)		
CBA (UGX/kg)	1, 365	1, 256

Table 8:Kaolin lab scale CBA/kg

4.4.3 Discussion of Cost Benefit Analysis Results.

a. Transport Costs.

The transport costs were calculated based on the current materials transportation costs (B. Nuwagaba, 2021), as a truck carrying 1,000 kg of kaolin over a 20 km stretch (which is the distance from the Buwambo kaolin deposit to the laboratory in Kabanyoro, Gayaza where pyrolysis experiment took place), at a cost of 70, 000 UGX per trip, meaning that the cost/kg is 70 UGX, which remains the same in both scenarios.

b. Processing Costs.

The processing included drying, grinding, washing and sieving which all required costs. This cost was estimated based on the cost we were charged for processing 20 kg which was 10, 000 UGX, giving a value of 500 UGX/kg for cost. The value was also estimated based on industrial practices for material preparation (Kim.S, 2023).

c. Energy Cost.

Energy cost, based on the industrial tariff of Uganda is 417.8 UGX/kWh (UERA, 2024) was calculated from the formula below, considering that the pyrolysis process consumed 6 MJ/kg and the catalytic pyrolysis process consumed 4 MJ/kg, showing a significant reduction in energy consumption.

$$1 \text{ kWh} = 3.6 \text{ MJ}$$

For 5MJ/kg without kaolin.

$$\text{Energy Cost} = (\text{Pyrolysis Energy} / 1 \text{ kWh}) \times \text{Tariff}$$

$$= (6 / 3.6) \times 417.8$$

$$= 696 \text{ UGX/kg}$$

For 4MJ/kg with kaolin.

$$\text{Energy Cost} = (\text{Pyrolysis Energy} / 1 \text{ kWh}) \times \text{Tariff}$$

$$= (4 / 3.6) \times 417.8$$

$$= 465 \text{ UGX/kg}$$

d. Oil Yield Revenue.

The pyrolysis yield from the pyrolysis experiment increased from 61% to 75% for the control and optimum respectively. The cost per liter of pyrolysis oil is at 3, 200 UGX (Procurement Resource, 2023), given that it still needs to undergo some purification to meet required fuel standard.

Without kaolin.

$$\text{Oil revenue} = \text{Yield in liters} \times \text{Oil cost}$$

$$= 0.61 \text{ (L)} \times 3,200 \text{ UGX/L}$$

$$= 1,952 \text{ UGX/kg}$$

With kaolin.

Oil revenue = Yield in liters x Oil cost

$$= 0.75 \text{ (L)} \times 3,200 \text{ UGX/L}$$

$$= 2,400 \text{ UGX/kg}$$

e. CBA analysis.

For a project to be considered worthwhile, it needs to give a positive value of CBA which means that the benefits outweigh the costs, and the higher the value, the more profitable the project.

Without Kaolin.

CBA = Total Benefits - Total Costs

$$= 1,952 - 696$$

$$= 1,256 \text{ UGX/kg}$$

With kaolin.

CBA = Total Benefits - Total Costs

$$= 2,400 - 1,035$$

$$= 1,365 \text{ UGX/kg}$$

From this outcome, it can be concluded that kaolin when used as a catalyst in PE pyrolysis is economically advantageous as opposed to thermal pyrolysis since it

improves oil yield, thereby increasing oil revenue from 1,952 UGX/kg to 2,400 UGX/kg, and at the same time reduces energy consumption by 22%, leading to higher profits, and by incorporating use of kaolin as a catalyst in PE pyrolysis, the project achieves economic benefits, making it a justified alternative for waste management in Uganda, while at the same time providing energy through pyrolysis oil.

4.4.4 CBA Comparison of Kaolin to synthetic zeolite and bagasse ash.

Other than kaolin, synthetic zeolite and bagasse ash have as well been used as catalysts in PE pyrolysis and have both produced increase in oil yield, however there are constraints they possess especially in regard to economic viability (Tewari et al., 2020 and Musawwa et al., 2020), as explained in the results and discussions below.

Catalyst	Procurement Cost (UGX/kg)	Transport Cost (UGX/kg)	Processing Cost (UGX/kg)	Energy Cost (UGX/kg)	Total Costs (UGX/kg)	Total Revenue (UGX/kg)	CBA (UGX/kg)
Kaolin	0	70	500	465	1,035	2,400	1,365
Zeolite	9,000-15,000	70	0	465	12,535	2,560	-9,975
Bagasse ash	800	70	0	465	1,335	1,760	425

Table 9: CBA/kg of different catalysts

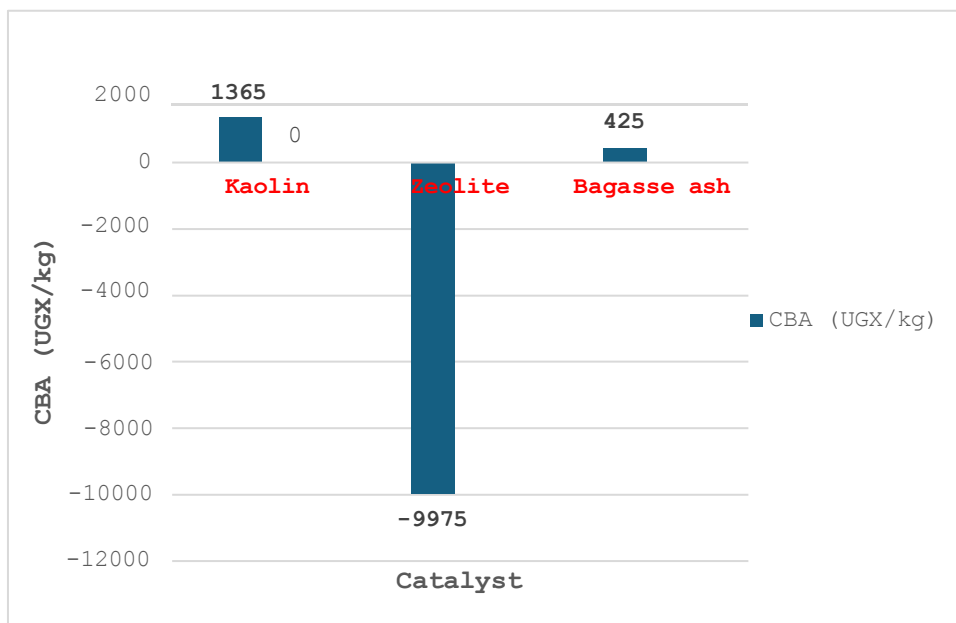


Figure 12: Bar graph showing kaolin, zeolite and bagasse ash CBA

a. Procurement Costs.

As explained earlier for kaolin its procurement is 0 UGX/kg. However, synthetic zeolite costs between 9, 000-15, 000 UGX/kg (Procurement Resource, 2025) whereas bagasse ash in terms of procurement costs 800 UGX/kg since it is more locally available (G. Fadillah, 2021).

b. Transport Costs.

The transport costs for zeolite and bagasse ash are the same as those of kaolin, given that the quantity remains the same (B. Nuwagaba, 2021).

c. Processing Costs.

The zeolite is purchased when already processed (R.D. Crangle, 2021), that's why its called synthetic zeolite which means that for processing zeolite, it is 0 UGX/kg,

which is the same case for bagasse ash that doesn't need any further processing. These costs are catered for in the overall procurement costs.

d. Energy Costs.

For the energy costs, not much literature is provided on energy consumption when zeolite or bagasse ash is used, so the cost when kaolin is used was as well considered in this case which is 5 MJ/kg for thermal pyrolysis and for the catalytic pyrolysis process 4 MJ/kg. A standard tariff of 417.8 UGX/kWh (UERA, 2024) was still used.

e. Oil Yield Revenue.

Zeolite has a large surface area and acidic properties that facilitate cracking hydrocarbons in the pyrolysis process, producing pyrolysis oil (Maqbool et al., 2020), and because of this according to literature, it has produced a yield of up to 80% when synthetic zeolite has been used (Tewari et al., 2020). On the other hand, research has shown that bagasse has produced a yield of 55% when used as a catalyst for PE pyrolysis (Saini et al., 2020), which is much lower than that of kaolin and zeolite.

The cost per liter of pyrolysis oil considered is still 3, 200 UGX, and below is the oil revenue computation.

For Zeolite.

Oil revenue = Yield in liters x Oil cost

= 0.80 (L) x 3, 200 UGX/L

= 2, 560 UGX/kg

For Bagasse ash.

Oil revenue = Yield in liters x Oil cost

$$= 0.55 \text{ (L)} \times 3,200 \text{ UGX/L}$$

$$= 1,760 \text{ UGX/kg}$$

From the computation above, it can be noted that zeolite produces the highest revenue as compared to kaolin and bagasse ash that produces the least.

f. CBA analysis.

For Zeolite.

$$\text{CBA} = \text{Total Benefits} - \text{Total Costs}$$

$$= 2,560 - (12,000 + 70 + 465)$$

$$= -9,975 \text{ UGX/kg}$$

Zeolite gives a negative CBA even though it has a high revenue as compared to kaolin and bagasse ash, mainly because of the high procurement costs it has.

For Bagasse ash.

$$\text{CBA} = \text{Total Benefits} - \text{Total Costs}$$

$$= 1,760 - (800 + 70 + 465)$$

$$= 425 \text{ UGX/kg}$$

Bagasse ash provides for a positive CBA which makes it economically viable, however it is less economical as compared to kaolin that has a higher positive CBA value.

From this analysis and comparison with other catalysts, it can be concluded that kaolin is a more economically viable option for use as a catalyst in PE pyrolysis as opposed to zeolite and bagasse ash, and this is attributed mainly to the fact that in

terms of total costs it is cheaper than zeolite, though zeolite yield a higher revenue. Kaolin though more expensive than bagasse ash, its higher revenue gives it an edge over bagasse ash and the fact that it produces a higher yield than it, and from the data above, a conclusive remark can be given and use of kaolin over the other 2 catalysts justified, owing to the highly positive CBA kaolin gives as opposed to bagasse ash and zeolite.

4.5 Expanded CBA for Implementing Kaolin as Catalyst in PE Pyrolysis.

4.5.1 Introduction.

The increasing population of plastic waste, in this case PE waste in Kampala poses a significant impact to the environment (NEMA, 2022), and though pyrolysis has emerged as a suitable solution to this problem, its economic viability that depends on maximizing oil yields while minimizing costs needs to be assessed (Miandad et al., 2019).

The expanded CBA aims to assess and evaluate the economic feasibility of using kaolin that is a locally available clay mineral as a catalyst in PE pyrolysis that is at an industrial scale, using factors obtained when it was used at laboratory scale.

4.5.2 Methodology.

Assumptions.

- It was assumed that PE plastic waste to be used is 1 tonne, with cost of 700 UGX/kg based on the local market values (UPMA, 2023).
- From the pyrolysis experiment, 16% mix-ratio was obtained as the optimum ratio for mix of kaolin to PE plastic, meaning that for one tonne of plastic, 160 kgs of kaolin would be needed.

- Price of pyrolysis oil is 3,200 UGX/L (Procurement Resource, 2023).
- Energy costs are at 417.8 UGX/kWh (UERA, 2024).
- Yield improvements at 61% without catalyst and at 75% when catalyst is used.
- Transporting 1 tonne (1000kg) of kaolin costs 70,000 UGX, given that each kg costs 70UGX (B. Nuwagaba, 2021).

4.5.3 Results.

Category	Cost per kg (UGX)	Cost per 1 tonne of plastic (UGX)
Plastic Procurement	700	For 1000 kg of plastic. (700x1000) =700,000
Transport Costs	70	For 160 kg of kaolin. (70x160) =11,200
Processing Costs	500	For 160 kg of kaolin. (500x160) = 80,000
Energy Costs	465	For 1000 kg of plastic. (465x1000) = 465,000
Total Costs	1,735	1,256,200

Table 10:Costs involved in kaolin pyrolysis when 1 tonne of plastic is used

Category	Revenue per kg (UGX)	Revenue per 1 tonne of plastic (UGX)
Oil Revenue	(0.75x3200) = 2,400	(0.75x1000x3200) = 2,400,000

Table 11:Revenue from kaolin pyrolysis when 1 tonne of plastic is used

Category	CBA per kg (UGX)	CBA per 1 tonne of plastic (UGX)
CBA	(2,400-1,735) = 665	(2,400,000-1,256,200) = 1,143,800

Table 12:CBA kaolin pyrolysis when 1 tonne of plastic is used

4.5.4 Discussion of results.

From the results and computations above, the total cost including procurement of plastic and other costs is 1,735 UGX/kg and per tonne total cost is 1,256,200 UGX

and on incorporating the revenue as well to obtain the CBA, a net profit of 1,143,800 UGX/tonne is obtained meaning that despite the processing and transportation costs of kaolin, the high oil yield of 75% at 16% catalyst optimum still ensures that the project is profitable, and scaling up to an industrial scale pyrolysis plant improves more on the profits, given that there is bulk purchase and optimized energy use.

A 5 tonne/day processing pyrolysis machine costs 162,250,000 UGX for procurement (Divya International, 2025), and based on the computations above, a 5 tonne/day processing machine could generate 5,719,000 UGX daily profit, using a factor of 1,143,800 UGX/tonne.

Category	Cost (UGX)
Fixed Costs	
Reactor purchase	162,250,000
Installation and setup	25,000,000
Permits	5,000,000 - Annual
Insurance	8,000,000 - Annual
Maintenance	15,000,000 - Annual
Total fixed costs	215,250,000 (for year 1) 28,000,000 (for years after year 1)
Variable Costs	
Costs per tonne/day	1,656,200 (including labor and waste disposal costs)
Costs for 5 tons/day	(1,656,200x5) = 8,281,000
Total annual variable costs	(8,281,000x330) = 2,732,730,000 <ul style="list-style-type: none"> Considered 330 days factoring in maintenance days
Total Annual Costs	First year = 215,250,000+2,732,730,000 = 2,947,980,000 1+ years = 28,000,000+2,732,730,000 = 2,760,730,000

Table 13: Costs in kaolin pyrolysis when 5 tons of are plastic is used

It can be observed that plastic procurement and energy contribute the biggest to the total costs, that is to say 42% and 28% respectively.

Annual revenue.

1 tonne/day = 2,400,000 UGX

5 tons/day for 330 days = 2,400,000x5x330 = 3,960,000,000 UGX

CBA.

First year

3,960,000,000-2,947,980,000 = 1,012,020,000 UGX

It can be observed that the net profit margin is at 25.6% for the first year.

1+ years

3,960,000,000-2,760,730,000 = 1,199,270,000 UGX

For subsequent years, a 30% net profit margin is noted.

4.5.5 Sensitivity Analysis.

This is a technique that is used to calculate and study how the inconsistency in output of a model, like net profit is affected by changes in the input variables (B. Venki, 2022), like for this case amount of plastic, yields and so on. It helps in identification of which variable has the most significant impacts on the output, hence aids in study of projects efficiency under various and different cases.

Case	Annual Profit (UGX)	Net Profit Margin (%)
5 tons/day	1,199,270,000	30
4 tons/day (80% capacity)	959,416,000	28
Plastic cost increases by 20%	959,416,000	27
Oil price drops by 10%	839,270,000	24

Table 14:Sensitivity Analysis table

- At 5 tons/day, the plant operates 100% efficiency and at optimal conditions and the net margin is 30%, which is high and makes the investment worthwhile.

- At 4 tons/day, profit drops by 20% but the margin is still close to the optimum 30%, meaning that even in the case of operation breakdown, there is still profit.
- Plastic procurement contributes the most to the total costs at 42% yet though its cost increases by 20%, the profit margin will still not shrink by much.
- In the scenario of oil price dropping by 10% because of market fluctuations and so on, the plant still remains highly profitable which means that it can withstand conditions in the long run.
- It can be concluded that even with worst case scenario, the project still remains profitable at above 20% net profit margin in each case.

4.6 Design.

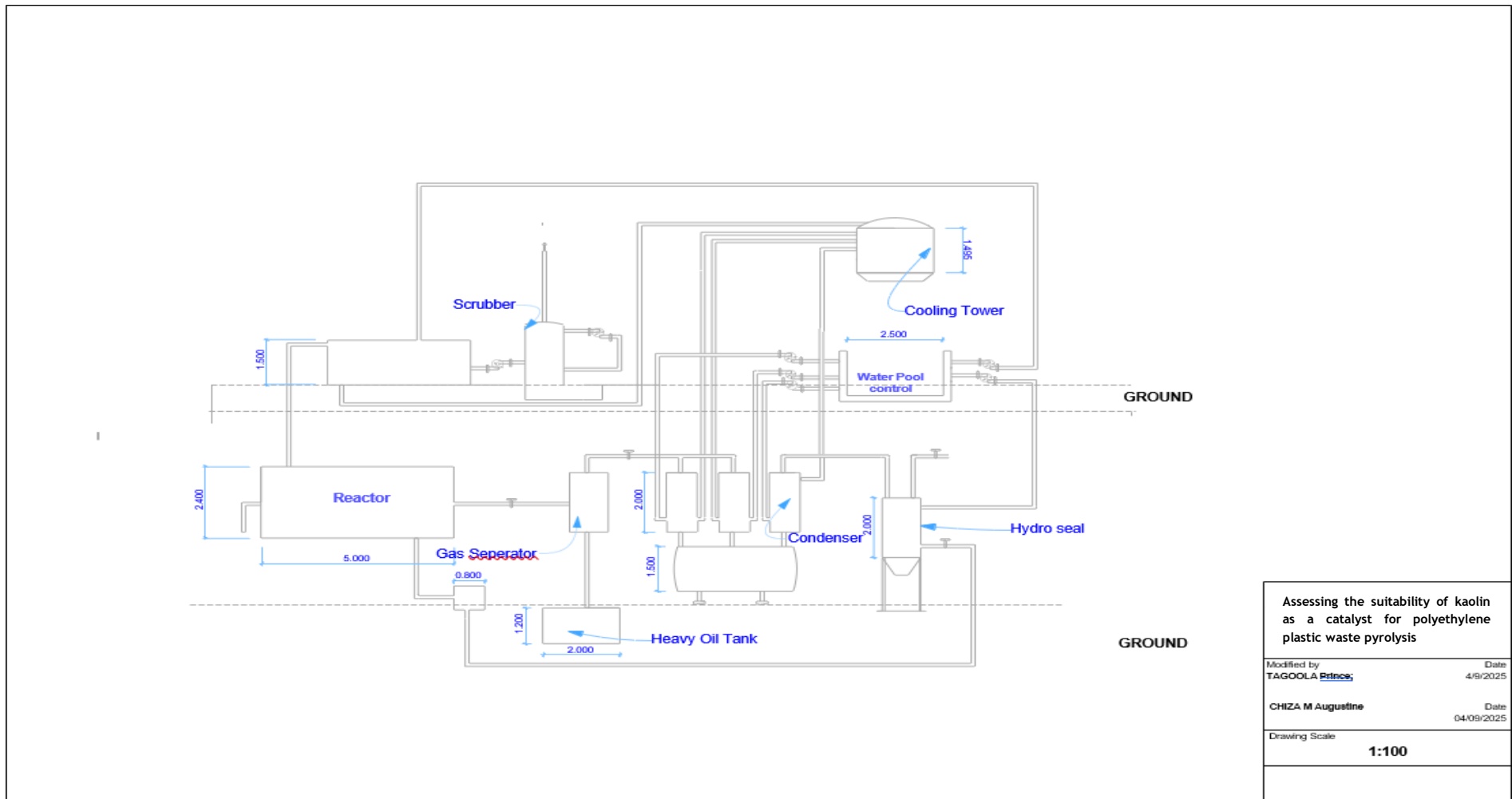


Figure 13: Design of a pyrolysis reactor

4.7 Conclusion.

This chapter presented the XRF analysis results of kaolin and discussed its potential role as a catalyst for polyethylene pyrolysis. The presence of oxides like silicon dioxide, aluminium oxide and calcium oxide enhance the possibility of using kaolin as a catalyst as they contribute to thermal stability, improve basicity and so on.

From the pyrolysis results, 16% was chosen as the optimum mix because it gave the highest oil yield of 75% while reducing char formation and gas formation, and it also gave the lowest reaction time of 74 minutes, proving that if it is incorporated in further experiments, the ratio to be used is known.

It can also be concluded from the CBA that kaolin when used as a catalyst in PE pyrolysis is a low risk yet a highly profitable investment even when done on a large scale and could provide a suitable solution to Uganda's waste management crisis while boosting the energy sector.

The next chapter will provide conclusions and recommendations based on the results that were obtained.

5 CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION.

1. To analyse the metal oxides composition of kaolin.

The composition of Kaolin in terms of metal oxides showed that it has a high composition of SiO_2 and Al_2O_3 at 53.67% and 24.47% respectively, which together contributed to the thermal stability of the kaolin that made it possible for it not to dissociate at high temperatures used in the pyrolysis process. The Al_2O_3 contributed to the thermal cracking of the polyethylene plastics by contribution of its acidic property, which allowed easier breaking down of the long chain hydrocarbons. The presence of CaO as well at 8.16% gave kaolin its basicity nature that promoted decarboxylation reactions which removed oxygenated compounds hence improving oil quality, as pyrolysis occurs in absence of oxygen. Potassium oxide at 12.63% contributed to the effects to the reaction kinetics hence reducing the coke formation that could rather affect the pyrolysis oil yield as the process went on. The kaolin used had a low Fe_2O_3 content of 0.65%, which reduced the excessive coke and harmful emissions formation together with catalytic deactivation, which made kaolin a usable catalyst for prolonged polyethylene pyrolysis.

2. To determine the optimum mix ratio of kaolin and PE for pyrolysis and impact of kaolin on reaction time.

Pyrolysis of polyethylene plastic at 0% mix-ratio, without catalyst produced an oil yield of 65.01% of the total polyethylene feedstock that was loaded in the pyrolysis reactor mainly because of inefficient thermal cracking as the pyrolysis typically relied on heat for the breakdown, and as a result there was incomplete cracking of the long chain hydrocarbons. This was also due to the lack of acidic sites necessary

for improving cracking. Without catalyst, a char yield of 9.32% was obtained as there were more unreacted polymer chains which increased char yield at the expense of oil yield. At 0% catalyst, a gas yield of 25.66% was obtained, which also owes to the incomplete combustion of the polymers to monomers, which in turn would generate an environmental concern regarding air pollution. The reaction time at 0% kaolin usage was obtained as 91 minutes because the cracking of the polymers to monomers in the absence of a catalyst took a long time and the fact that thermal pyrolysis left to itself has no acidic sites present, hence increasing overall time taken for pyrolysis.

3. To assess the economic viability of using kaolin as a catalyst in PE pyrolysis.

Regarding cost benefit analysis, kaolin when used as a catalyst on lab scale produced a positive CBA of 1,365 UGX/kg, which means it is profitable as the benefits are higher than the total costs. In comparison of thermal pyrolysis to catalytic pyrolysis, catalytic pyrolysis with a CBA of 1,365 UGX/kg proved higher than that of thermal pyrolysis of 1,256 UGX/kg, meaning that even beyond catalytic pyrolysis just being profitable, it is still more profitable in comparison to thermal pyrolysis, mainly owing to the improved oil yield from 61% to 75%. When compared to other catalysts like zeolite and bagasse ash that have been used in pyrolysis as well, the CBA calculated was -9,975 UGX/kg and 425 UGX/kg respectively and in this case, kaolin still proves to be a better catalyst when looked at in the aspect of financial feasibility. For the expanded CBA when using kaolin at industrial scale pyrolysis, even under the worst case scenarios, the project produced more than 20% net profit with a pay back period of less than 5 months.

5.2 RECOMMENDATIONS.

First and foremost, kaolin-catalyzed pyrolysis should be integrated into Uganda's waste management systems, particularly in urban areas with high plastic waste generation like Kampala. Municipal authorities and private waste management companies should establish pilot pyrolysis plants with capacities of 1-5 tons per day to demonstrate the technology's viability. These plants should utilize the optimal 16% kaolin-to-plastic ratio identified in this study, which maximizes oil yield at 75% while minimizing unwanted byproducts. The fixed-bed reactor design with precise temperature control between 400-500°C has proven most effective and should be adopted as the standard configuration.

Government support will be crucial for widespread adoption. Policy measures should include financial incentives such as tax breaks for companies investing in pyrolysis technology and subsidies for kaolin procurement to keep operational costs low. Existing plastic waste regulations need stronger enforcement, with pyrolysis recognized as an approved recycling method. The Uganda National Bureau of Standards should establish quality specifications for pyrolysis oil to ensure its suitability as an alternative fuel, while environmental agencies must monitor emissions to maintain air quality standards.

Continued research and development will further enhance the technology's effectiveness. Studies should explore methods to improve kaolin's catalytic properties through acid treatment or higher-temperature calcination. The potential for using kaolin with other types of plastic waste beyond polyethylene should also be investigated. Investment in waste sorting infrastructure will improve the quality

of plastic feedstock, while community education programs can increase public participation in waste collection efforts.

Building local capacity is essential for sustainable implementation. Vocational training programs should be developed to equip workers with skills in pyrolysis plant operation and maintenance. Entrepreneurship initiatives could help create small businesses focused on collecting plastic waste and marketing pyrolysis byproducts. Partnerships with kaolin miners in Buwambo will ensure a reliable, low-cost supply of catalyst material.

Use of renewable energy sources like biogas and solar so as to reduce the costs invested in energy purchase, there by making the project more profitable and having these costs diverted to expansion of facilities and plastic purchase.

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APPENDIX.



Figure 14 : Buwambo Kaolin deposit

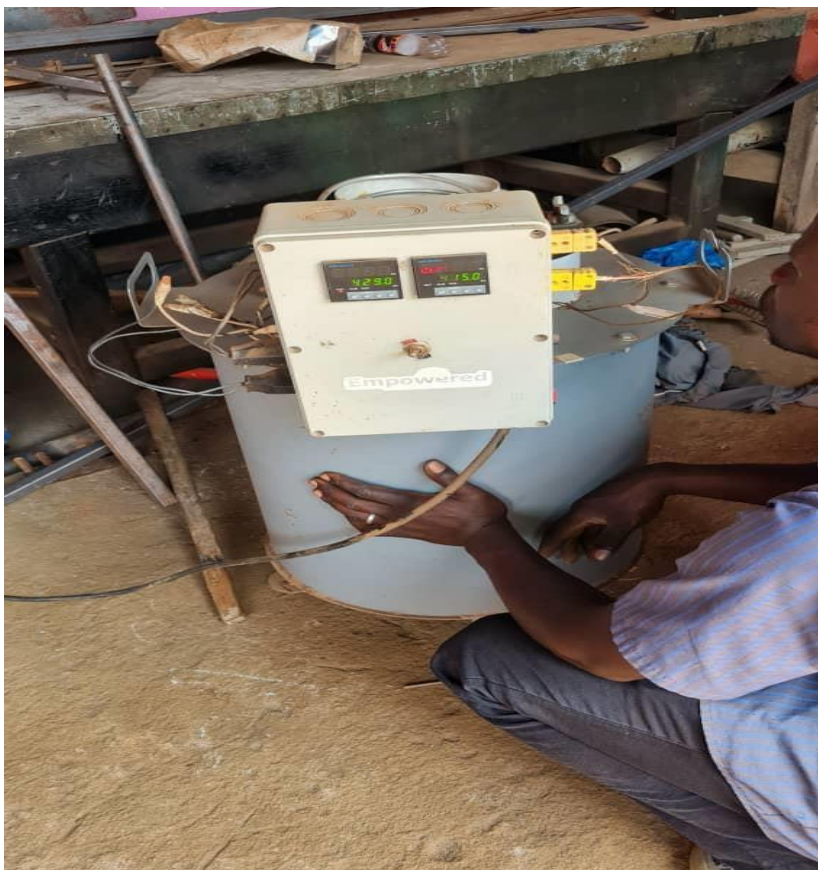


Figure 15 : Pyrolysis reactor



Figure 16 : Shredded plastic

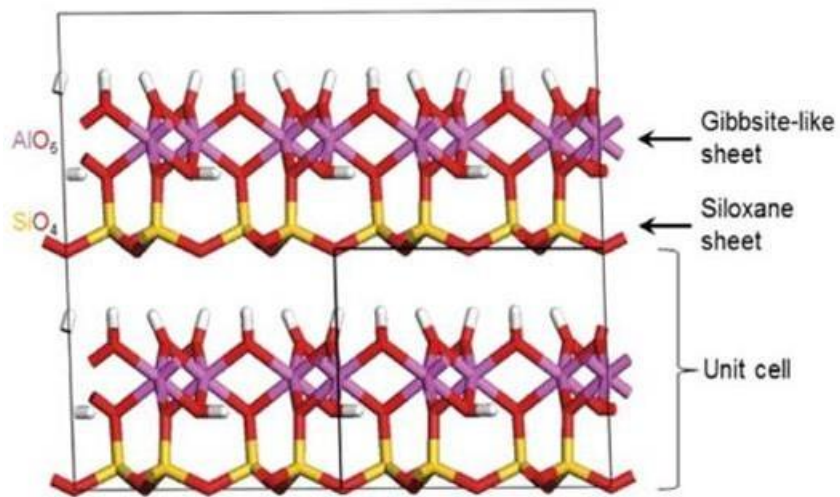


Figure 17 : Elemental structure of Kaolin



Figure 18 : Kaolin sample ready for XRF analysis



Figure 19:Pyrolysis oil



Figure 20:Char from pyrolysis

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DEPARTMENT OF AGRICULTURAL AND BIOSYSTEMS ENGINEERING

TITLE	Assessing the suitability of kaolin as a catalyst for polyethylene plastic waste pyrolysis
CLIENTS	Tagoola Prince And Chiza Maisha Augustin
EXPERIMENT	Catalytic Pyrolysis of HDPE plastic
MATERIAL SOURCE OF LOCATION	Buwambo
MATERIALS	Kaolin HDPE Plastic (shredded)

1ST RUN OF PYROLYSIS OF HDPE PLASTIC (0%/CONTROL)

	Sample 1	Sample 2	Sample 3
Weight of sample	989.8g	1001.1g	999.5g
Temp start	10	10	10
Amount of oil produced	645.8g	650.3g	648g
Weight of black carbon	91.2g	95.9g	91.7g
Time taken for the 1 st drop	32mins	39mins	37mins
Observed sample	Yellowish substance	Yellowish substance	Yellowish substance
Time taken	1hr 28mins	1hr 34mins	1hr 31mins

2ND RUN OF PYROLYSIS OF HDPE PLASTIC (5%)

	Sample 1	Sample 2	Sample 3
Weight of sample	991.8g	981.5g	987.1g
Temp start	10	10	10
Amount of oil produced	685.9g	679.5g	686.3g
Weight of black carbon	55.4g	50.9g	54.1g
Time taken for the 1 st drop	35mins	29mins	33mins
Observed sample	Yellowish substance	Yellowish substance	Yellowish substance
Time taken	1hr 24mins	1hr 19mins	1hr 22mins

3RD RUN OF PYROLYSIS OF HDPE PLASTIC (10%)

	Sample 1	Sample 2	Sample 3
Weight of sample	991.8g	1001.5g	987.1g
Temp start	10	10	10
Amount of oil produced	705.8g	715.4g	704.2g
Weight of black carbon	47.6g	55.1g	47.3g
Time taken for the 1 st drop	37mins	39mins	33mins
Observed sample	Yellowish substance	Yellowish substance	Yellowish substance
Time taken	1hr 18mins	1hr 22mins	1hr 16mins

4TH RUN OF PYROLYSIS OF HDPE PLASTIC (14%)

	Sample 1	Sample 2	Sample 3
Weight of sample	996g	994.2g	993.8g
Temp start	10	10	10
Amount of oil produced	735.4g	732.7g	730.8g
Weight of black carbon	44.8g	48.4g	51.8g
Time taken for the 1 st drop	36mins	38mins	32mins
Observed sample	Yellowish substance	Yellowish substance	Yellowish substance
Time taken	1hr 19mins	1hr 23mins	1hr 17mins

5TH RUN OF PYROLYSIS OF HDPE PLASTIC (15%)

	Sample 1	Sample 2	Sample 3
Weight of sample	990.6g	980.2g	978.3g
Temp start	10	10	10
Amount of oil produced	746.6g	738.7g	735.1g
Weight of black carbon	41.2g	38.8g	38.2g
Time taken for the 1 st drop	31mins	29mins	25mins
Observed sample	Yellowish substance	Yellowish substance	Yellowish substance
Time taken	1hr 18mins	1hr 14mins	1hr 12mins

6TH RUN OF PYROLYSIS OF HDPE PLASTIC (16%)

	Sample 1	Sample 2	Sample 3
Weight of sample	1000g	998.2g	997.1g
Temp start	10	10	10
Amount of oil produced	757.4g	755.5g	753.8g
Weight of black carbon	39.1g	40g	43.1g
Time taken for the 1 st drop	31mins	29mins	25mins
Observed sample	Yellowish substance	Yellowish substance	Yellowish substance
Time taken	1hr 21mins	1hr 80mins	1hr 18mins

7TH RUN OF PYROLYSIS OF HDPE PLASTIC (17%)

	Sample 1	Sample 2	Sample 3
Weight of sample	990.8g	991.5g	989.1g
Temp start	10	10	10
Amount of oil produced	735.9g	737.5g	734.3g
Weight of black carbon	48.4g	49.9g	47.1g
Time taken for the 1 st drop	35mins	37mins	32mins
Observed sample	Yellowish substance	Yellowish substance	Yellowish substance
Time taken	1hr 19mins	1hr 23mins	1hr 17mins

8TH RUN OF PYROLYSIS OF HDPE PLASTIC (20%)

	Sample 1	Sample 2	Sample 3
Weight of sample	995g	990.5g	983.8g
Temp start	10	10	10
Amount of oil produced	696.3g	692.7g	686.8g
Weight of black carbon	62.8g	61g	60.2g
Time taken for the 1 st drop	36mins	30mins	28mins
Observed sample	Yellowish substance	Yellowish substance	Yellowish substance
Time taken	1hr 30mins	1hr 26mins	1hr 25mins



Figure 21: Pyrolysis Results

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In any Correspondence on
 this subject please
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DFD 029/2025

07th February 2025

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REPORT OF ANALYSIS

Description of the Samples

One sample in black polythene bag containing Kaolinite clay sample was submitted by Mr. Tagoola Prince on 24th January 2025, and analysed on 30th January 2025. A summary of the sample received is shown in table below

S/N	Description	Quantity	Assigned Lab ID
1	Kaolinite clay powdered substances packed in a black polythene bag.	01	Sample "A" DFD 029/2025

Analysis Requested

Elemental analysis

Method of Analysis

Elemental analysis was done using the XRF Method

Results of Analysis

The above sample has been analyzed with the following results as below.

Parameter	Units	Results for DFD 029/2025 Kaolinite clay powder sample
Silicon dioxide	% m/m	53.67
Aluminium Oxide	% m/m	24.47
Potassium Oxide	% m/m	12.63
Calcium Oxide	% m/m	8.16
Manganese (II) Oxide	% m/m	0.19
Titanium di oxide	% m/m	0.17
Iron (III) Oxide	% m/m	0.05
Phosphorous pentaoxide	% m/m	0.03

Remarks

- Results relate to sample analyzed and are reported as on received basis.

SFW - 07/02/25
 Semalago Fredrick
 Government Analyst

"Go Scientific for a Safe and Just Society"

Figure 23: XRF Results