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

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DECLARATION

I, CHIZA MAISHA Augustin owner of the registration number S21B32/059, hereby declare that this research project is my original work, and has not been submitted to any other institution or university for any academic award or examination.

Signature of student...

Date...

APPROVAL

This is to certify that this research and design project by CHIZA MAISHA Augustin has been conducted under my supervision and has been approved for submission to the university.

Signature………………………………………………

Date…………………………………………………….

Dr. Miria AGUNYO Frances

Academic supervisor

DEDICATION

I dedicate this report to my parents, Mr. Maisha Jean-Pierre & Mrs. Bushubweka Honorine for their tireless effort they have placed in my education, comfort and wellbeing.

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ABSTRACT

The growing accumulation of polyethylene plastic waste in urban centers like Kikuubo Market, Kampala, Uganda presents severe environmental and public health challenges, exacerbated by ineffective traditional waste management strategies. This study addresses these challenges by assessing the suitability of kaolin, a naturally abundant clay mineral sourced from Buwambo deposit in Wakiso District, as a catalyst for the pyrolysis of polyethylene plastic waste. X-Ray Fluorescence (XRF) analysis confirmed the kaolin's catalytic potential, with high levels of silicon dioxide (53.67%) and aluminium oxide (24.47%). Controlled pyrolysis experiments were conducted at 420°C and a heating rate of 10°C/min using varying kaolin-to-polyethylene mix ratios (0-20 wt%). The 16 wt% kaolin-to-plastic ratio achieved the highest oil yield of 75.67%, a notable improvement from 65.67% in non-catalytic pyrolysis. Additionally, the reaction time decreased from 91minutes (control) to 74minutes at this optimal loading, enhancing overall process efficiency. A cost-benefit analysis showed a net profit of 1,365 UGX/kg with kaolin, compared to 789 UGX/kg without, confirming the economic feasibility of the approach. Compared to synthetic zeolite and bagasse ash, kaolin offers superior performance due to its local availability and minimal processing needs. These findings highlight kaolin's potential to enhance the pyrolysis process, offering a scalable and sustainable approach to plastic waste management and energy recovery in developing regions.

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Al_2O_3 - Aluminium Oxide

ASTM - American Society for Testing and Materials

C_2H_4 - Ethylene

C_4H_8 - Butene

CaO - Calcium Oxide

CBA- Cost Benefit Analysis

CH_4 - Methane

CO_2 - Carbon Dioxide

EPA - Environmental Protection Agency

Fe_2O_3 - Iron (III) Oxide

H_2 - Hydrogen Gas

H-C - Hydrocarbons

HDPE - High-Density Polyethylene

ISO - International Organization for Standardization

K_2O - Potassium Oxide

KCCA - Kampala Capital City Authority

LDPE - Low-Density Polyethylene

MnO - Manganese (II) Oxide

Na_2O - Sodium Oxide

NEMA - National Environment Management Authority

OSHA - Occupational Safety and Health Administration

P_2O_5 - Phosphorous Pentoxide

PAHs - Polycyclic Aromatic Hydrocarbons

PE - Polyethylene

PET - Polyethylene Terephthalate

PP - Polypropylene

PS - Polystyrene

SiO_2 - Silicon Dioxide

TiO_2 - Titanium Dioxide

UNEP - United Nations Environment Programme

XRF - X-Ray Fluorescence

CHAPTER ONE: GENERAL INTRODUCTION

1.0 BRIEF BACKGROUND & INTRODUCTION

1.0.1 Brief background

Plastic waste pollution has emerged as one of the most pressing environmental challenges of the 21st century. With the global production of plastics reaching over 368 million tons annually, the accumulation of plastic waste poses significant threats to ecosystems, wildlife, and human health (Parker, 2024). Plastics are widely used due to their durability, lightweight nature, and cost-effectiveness, but their non-biodegradable properties results in persistent pollution that can last for centuries (Jambeck et al., 2015).

In Uganda, urban settings such as Kikuubo market in Kampala generate substantial volumes of plastic waste, primary composed by polyethylene products used for packaging and containers. Improper disposal methods such as open burning and legal and illegal dumping exacerbate environmental degradation and pose severe risks to the public health (Mahajan, 2023). During open burning toxic pollutants like dioxins and furans are released into the atmosphere, contributing to air quality deterioration and respiratory issues (Evode et al., 2021). Additionally blocked drainage systems, often caused by accumulation of plastic waste, worsen seasonal flooding in cities, underscoring the critical demand for sustainable waste practices (NEMA, 2024). In Uganda's urban areas, such as Kampala's Kikuubo market, rising plastic pollution (driven by heavy reliance on polyethylene products) has intensified environmental and public health risks. Open dumping and burning of plastics further degrade ecosystems and threaten community well-being (Mahajan, 2023).

Traditional waste management methods like landfills and incineration face significant drawbacks. Landfills are nearing capacity, while incineration demands high energy inputs and releases harmful gases (mostly greenhouse gases) into the environment (Evode et al., 2021). Recycling, though promoted, struggles with low adoption due to inadequate infrastructure and contamination during processing (Kabeyi & Akanni, 2023). These challenges have spurred interest in pyrolysis, a process that convert plastic waste into usable fuels with minimal environmental harm.

1.0.2 Introduction

Pyrolysis which is a thermal-chemical process, offers a promising alternative for managing plastic waste properly. This process breaks down plastics at high elevated temperatures without oxygen, yielding fuel oil, gas, and char (Devi et al., 2021). Pyrolysis offers a dual benefit, minimizing plastic waste while producing energy-rich fuels with properties similar to diesel (Miandad et al., 2019). In developed regions like Europe and North America. It has become part of circular economy systems, with plants converting large volume of plastic waste into industrial products such as naphtha (Roland Berger, 2023). Some facilities process as much as 200 kilotons of mixed plastics each year, lowering reliance on landfill, open dumping and incineration, In contrast, countries in the Global South often face challenges such as limited funding and inadequate infrastructure.

In Africa especially, rising urban populations and increasing plastic use make pyrolysis a promising decentralized solution for managing plastic waste. Countries like Kenya, for example, operates small-scale plants converting plastics into liquid fuel for local use (Kabeyi & Akanni, 2023). However, challenges like high operational cost and reliance on informal collection systems persist across Sub-Saharan Africa. Uganda's Kampala Metropolitan Area generates over 135,000 tons of plastic yearly, with less than 10% of this being recycled effectively due to systemic gaps (NEMA, 2024).

The use of catalyst can significantly enhance the pyrolysis efficiency. Catalysts accelerate chemical reactions without being consumed in the process and improve reaction rates, product yields, and the reduction of harmful by-products during pyrolysis (Zhang et al., 2023). Different type of catalyst have been used for this purpose, including zeolite and bagasse ash; however, kaolin which is a naturally occurring clay mineral, has shown particular promise due to its stability at very high temperature and catalytic properties (Anam et al., 2023). Kaolin is widely used in petroleum industry (in process like refining) and biomass pyrolysis (as catalyst) but remains underexplored as a catalyst for polyethylene pyrolysis particularly in Ugandan context (using kaolin from Buwambo deposit). Assessing the potential role of kaolin as a catalyst in PE plastic waste pyrolysis could unlock new opportunities for enhancing PE conversion efficiency while producing cleaner fuels.

This study explores the potential of kaolin as a catalyst in pyrolysis of polyethylene plastic waste. It focuses on how kaolin influences reaction time, product output, and the overall cost-effectiveness, while also determining the various metal oxide that compose the kaolin from Buwambo deposit. The goal is to support more practical and sustainable approaches to plastic waste management, both locally and globally.

1.1 PROBLEM STATEMENT

Managing plastic waste effectively requires approaches that reduce on its environmental harm, recover usable resources, and stay economically practical. Pyrolysis, a process that breaks down plastic waste into fuel oils, gases, and char by heating it without oxygen, stands out as a potential solution. And when optimized, it can reduce on the waste volumes and produce valuable outputs, supporting the idea of a circular economy. Yet, the reality is that standard pyrolysis setups struggle to get good yields (oil yields) and emissions like CO and CO_2 can be released (and they are toxic), even the end products alone often don't meet quantity and quality expectations. Researchers have suggested adding catalysts like bagasse ash, zeolite, or kaolin to tackle these issues, aiming to boost efficiency, improve the end product quality, and minimize harmful byproducts. Kaolin, in particular, looks promising because of its natural adsorbent and catalytic traits, but its full potential isn't clear yet (Dai et al., 2022).

In Uganda, especially in busy urban spots such as Kikuubo Market in Kampala, the management of plastic waste (especially polyethylene) remains a significant challenge. The large volume of generated plastic waste ends up in open dumping sites or even burned leading to public health and environment concerns. Traditional pyrolysis could turn this waste into something useful, but it still provides low yield end products, harmful emissions, and low process efficiency. Without affordable, effective catalysts, it is tough to see pyrolysis as a real answer for sustainable waste management here.

This research assesses the use of kaolin, a natural clay mineral, as a catalyst in pyrolysis of polyethylene plastic waste. To achieve this, the study will first analyze the metal oxide composition of kaolin (like CaO, SiO2, Al_2O_3, and Fe2O3) to understand how this can affect the pyrolysis process. And then it will determine the best ratios of kaolin to plastic, to understand kaolin impacts on the reaction time, and overall pyrolysis efficiency. This will ultimately contribute to better, more eco-friendly plastic waste management in urban areas.

1.2 OBJECTIVES

1.2.1 Main objective

To assess the suitability of kaolin as a catalyst for polyethylene plastic waste pyrolysis.

1.2.2 Specific objectives

1. To analyze metal oxide composition of kaolin sample from Buwambo deposit
2. To determine the optimal mix ratio of kaolin and polyethylene plastic waste for pyrolysis.
3. To assess the impact of kaolin on the reaction time.
4. To conduct a cost-benefit analysis of using kaolin from Buwambo as a catalyst in polyethylene plastic waste pyrolysis.

1.3 RESEARCH QUESTIONS

- What are the specific metal oxides present in kaolin sample from the Buwambo deposit, and how do their concentrations influence its catalytic properties in pyrolysis?
- What is the optimal ratio of kaolin to polyethylene plastic waste that maximizes product yield and improves the quality of pyrolysis products?
- How does the addition of kaolin affect the reaction time and overall efficiency of the pyrolysis process for polyethylene plastic waste?
- What are the economic benefits of using Buwambo kaolin as a catalyst compared to common used catalysts like zeolite and bagasse ash?

1.4 RESEARCH SCOPE

1.4.1 Geographic scope

The study is centered in Kikuubo Market, located in the central business district of Kampala, Uganda.

1.4.2 Time scope

The study was conducted for a period of 8 months starting from September 2024 to April 2025.

1.4.3 Content scope

This study assessed the suitability of kaolin as a catalyst for polyethylene plastic waste pyrolysis.

1.5 JUSTIFICATION

The project aimed at assessing the suitability of using kaolin as a catalyst for enhanced polyethylene plastic waste pyrolysis is justified by the urgent need to address the significant environmental challenge posed by plastic waste pollution, particularly in urban areas like Kikuubo Market in Kampala, Uganda. The accumulation of plastic waste in this region poses serious environmental and public health risks (Kizito, 2022). Conventional waste management methods (such as landfilling, open dumping and burning) have proven both ineffective and environmentally damaging, underlining the urgent need for alternative approaches (NEMA, 2021).

Pyrolysis offers a promising route for transforming plastic waste into useful products. However, the efficiency of conventional pyrolysis methods remains a key limitation (Sharma at al., 2020). This project explores the use of kaolin (an abundant and low-cost natural clay mineral) as a catalyst to improve pyrolysis performance. By incorporating kaolin, the process can potentially achieve higher product yields, better outputs quality, shorter reaction time and reduced harmful emission (Vijayakumar, 2018).

Enhanced process efficiency can also improve the economic viability of the pyrolysis process, creating new opportunities for local entrepreneurs and contributing to job creation within the waste management sector (NEMA, 2024). Beyond addressing a technical knowledge gap in the use of kaolin for polyethylene plastic pyrolysis, this research supports broader environmental goals by promoting cleaner waste disposal method and advancing circular economy principles (Kizito, 2022). Ultimately, the project aims to help build healthier communities by reducing the impacts of plastic pollution and supporting sustainable development.

CHAPTER TWO: LITERATURE REVIEW

2.0 INTRODUCTION

This chapter reviews existing literature on plastic waste management issues and strategies, pyrolysis as a possible solution for waste management, and the catalytic properties of kaolin, with a focus on its potential to enhance polyethylene (PE) pyrolysis.

2.1 PLASTIC WASTE

2.1.1 Overview on plastic management

Plastic waste poses a significant global environmental challenge. According to UNEP (2023) and OECD (2023), over 368 million tons of plastic are produced annually, with approximately 85% ending up as waste. Among plastic types polyethylene (PE) dominates, accounting for 30-40% of total plastic waste. Its widespread use stems from its durability, flexibility, and affordability, making it a top choice for packaging, containers and simgle-use products (EPA, 2024). Despite these interesting properties, it is a persistent pollutant that can take over 500 years to decompose and contribute to long-term environmental degradation (Jambeck et al., 2015; Parker, 2024).

Developed countries have implemented waste management strategies such as Extended Producer Responsibility (EPR) policies, advanced recycling technologies, and plastic circularity initiatives to mitigate this crisis. In contrast, developing nations face significant challenges in plastic waste handling due to limited infrastructure, inadequate policy enforcement, and high waste collection costs. Taking the case of

Uganda, approximately 600 tons of plastic waste are generated daily, simultaneously Kampala Metropolitan Area alone generates 135,804 tons of plastic waste annually, with less than 10% recycled and the majority improperly disposed of through open burning and open dumping (NEMA, 2024). This mismanagement exacerbates microplastic pollution, clogs urban drainage systems, and increases flooding risks, particularly during rainy seasons (Zhang et al., 2020; NEMA, 2024).

The reliance on informal waste collectors, who manage up to 80% of recyclables, highlights the gaps in Uganda's formal waste management system (NEMA, 2024). While national initiatives such as the National Strategy for Promoting Plastics Circularity (2023–2028) and corporate partnerships, like those between Coca-Cola Beverages Uganda and Ecoplastile, aim to enhance recycling efforts, systemic barriers persist. Weak enforcement and implementation of plastic regulations, insufficient public awareness, and financial limitations hinder large-scale recycling advancements (Coca-Cola Beverages Africa, 2024; Monitor, 2025). Addressing these issues requires a combination of improved waste collection systems, investment in recycling technologies like pyrolysis (which convert plastic waste into valuable fuels and by-products), and stronger policy enforcement to reduce plastic leakage into the environment.

2.1.2 *Chemical structure and properties of polyethylene (PE)*

Polyethylene is a thermoplastic made up of long chains of ethylene units (C_2H_4). It categorized in two main forms depending on its density: low-density polyethylene (LDPE) and high-density polyethylene (HDPE). LDPE, with its branched setup (structure), stays flexible, mostly used in fabrication of plastic bags and films (wraps).

HDPE, on the other hand, has a linear structure with minimal branching, resulting in higher strength and rigidity, making it perfect for bottles and containers (Geyer et al., 2017). Knowing the basic characteristics of polyethylene, it is now important or pertinent to contextualize its properties and applications by examining how it compares to other commonly used plastics, as detailed in section 2.1.3 below.

2.1.3 Comparison of PE with other common plastics

PE is highly suitable for pyrolysis due to its hydrocarbon-rich composition, but other common plastics show varying degrees of suitability based on their chemical structure and thermal degradation behavior. So here are some of them;

a) Polypropylene (PP):

PP is similar to PE but it is a polyolefin with a hydrocarbon backbone. Its structure includes a methyl group ($-CH_3$) attached to every carbon atom, enhancing its thermal stability and mechanical properties (Jain et al., 2022; Al-Salem et al., 2017). PP is highly suitable for pyrolysis, as it decomposes into valuable hydrocarbons like propylene and other lighter alkanes.

b) Polyvinyl Chloride (PVC):

PVC differ to PE as it contains chlorine atoms in its structure, which release hazardous hydrochloric acid (HCl) during pyrolysis, posing environmental and equipment corrosion challenges (Miandad et al., 2019). Due to these different issues, PVC is considered less suitable for pyrolysis compared to PE and PP.

c) Polystyrene (PS):

PS decomposes into styrene monomers and aromatic hydrocarbons during pyrolysis, which can be valuable but require additional refining (Singh et al., 2021). While PS is suitable for pyrolysis, its product distribution is less favorable compared to PE and PP.

d) Polyethylene Terephthalate (PET):

In its structure, PET contains oxygen atoms, leading to the formation of non-condensable gases and carbonaceous residues during pyrolysis rather than liquid fuels. PET is less suitable for pyrolysis as compared to PE and PP. The table below summarizes this comparison well.

Table 2-1. Comparison of pyrolysis suitability and product distribution for common plastics (Jain et al., 2022)

Plastic type	**Chemical structure**	**Pyrolysis suitability**	**Product distribution**	**Challenges**
PE	Hydrocarbon backbone	Highly suitable	Liquid oil, gases	Low char production
PP	Hydrocarbon backbone with methyl groups	Highly suitable	Valuable hydrocarbons (e.g., propylene)	Similar to PE, high gas production

PS	Aromatic rings	Suitable but less favorable	Styrene monomers, aromatic hydrocarbons	Requires additional refining
PVC	Chlorine atoms	Less suitable	Hazardous HCl release	Environmental and equipment corrosion issues
PET	Oxygen atoms	Less suitable	Carbonaceous residues, non-condensable gases	Not ideal for liquid fuel production

Figure 2-1 bellow illustrates the common types of plastics, highlighting their distinct properties and applications in various industries.

Figure 2-1: Various types of plastics (Plastics For Change, 2021)

2.2 PYROLYSIS AS A PLASTIC WASTE MANAGEMENT SOLUTION

2.2.1 Definition and principles of pyrolysis

Pyrolysis is a thermochemical process for organic and nonorganic material breakdown, for instance, plastic waste, utilizing heating in an oxygen-free system to produce oil and other by-products (Adhikari et al., 2016). In this system, the gas content is more controlled, usually a reactor, prevents burning and, instead, provides breakdown (due to high temperatures) producing three primary end-products which are liquid (oil), gas, and solid leftover called char. The whole mechanism depends on temperature utilization for dissociation of covalent bonds in chains of polymers, turning them into smaller hydrocarbon pieces (Bryan et al., 2019). Figure 2-2 below represents a basic on pyrolysis process. This process provide an effective way to recycle or to minimize plastic waste and produce products such as fuel, chemicals, and solid char, hence supporting efforts in a circular economy.

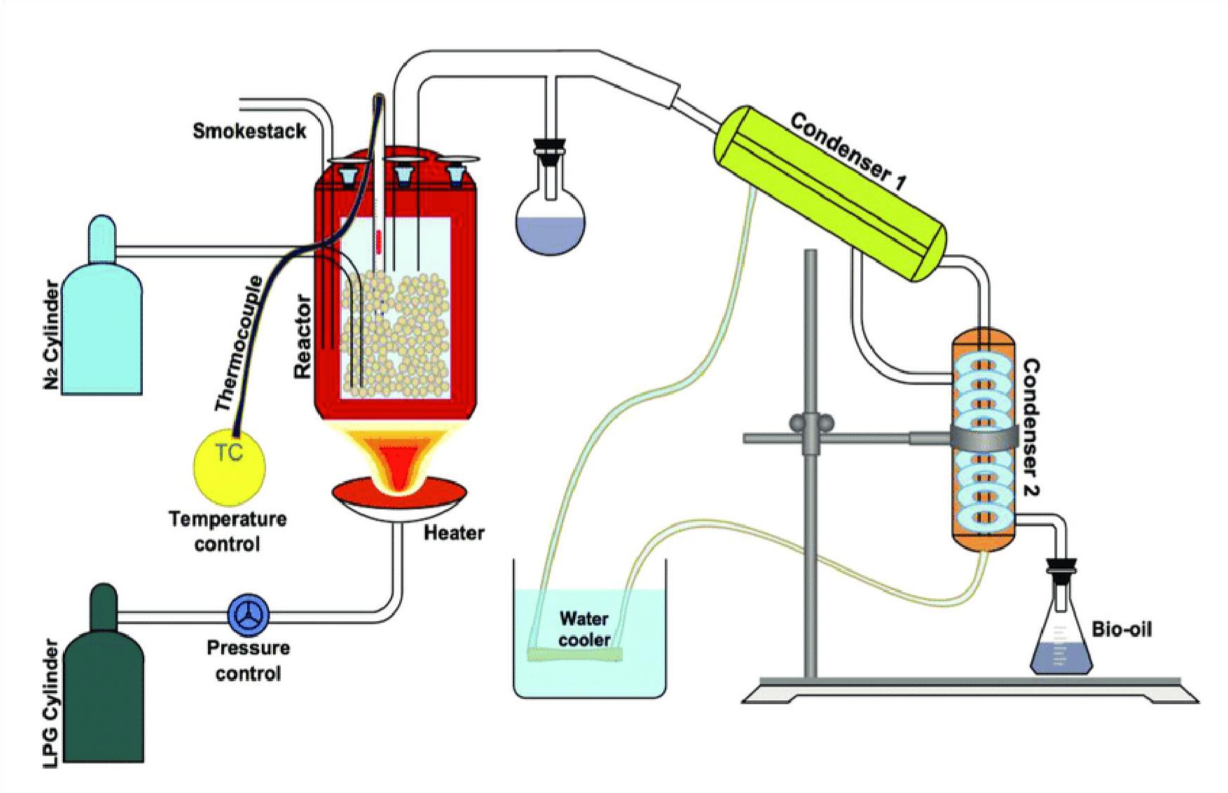


Figure 2-2: The schematic diagram of the pyrolysis system (Bryan et al., 2019)

Plastic pyrolysis consists of series of several key reactions. The process begins with thermal decomposition, where long polymer chains break down into smaller hydrocarbon molecules. Then during the cracking reactions these molecules split into lighter hydrocarbons like alkanes, alkenes, and aromatics. So it is known that polyethylene can degrade into ethylene (C_2H_4) and other hydrocarbons (Wang et al., 2021; Yardim et al., 2005). In addition, some molecules may rearrange into different isomers or cyclic compounds, which can enhance the quality of the end products (especially liquid oil). Meanwhile, condensation reactions contribute to the formation of heavier liquid fractions from certain gaseous products. The composition of the final pyrolysis oil depends on the type of plastic and catalyst used but also the specific reaction conditions.

To illustrate this, Equation 2-1 below represents the general reaction of the pyrolysis of polyethylene plastics

$(C_2H_4)_n \rightarrow C_nH_{2n} + C_mH_{2m} + gases$ **Equation 2-1** *(Wang et al.,2021)*

Where n and m represent the number of carbon atoms in the resulting hydrocarbons.

2.2.2 Types of pyrolysis

Pyrolysis can be categorized into two primary types: thermal and catalytic. Thermal pyrolysis relies solely on heat, typically 300°C to 900°C, to break down plastic waste into smaller molecular compounds. While this method is straightforward and adaptable, it demands significant energy input, produces a broad range of products with lower selectivity, and generates by-products such as tar and char.

In contrast, catalytic pyrolysis, incorporates catalyst such as zeolite, bagasse ash, and kaolin for example to enhance the pyrolysis process. These different catalysts reduce the required temperature, and reaction time, improve efficiency, and lead to higher liquid fuel yields. However, this method has certain challenges, such as the cost of the catalysts, potential deactivation over time if used repeatedly and the need for regeneration. This study focuses on catalytic pyrolysis using kaolin as a catalyst in converting PE plastic waste into valuable end-products.

2.2.3 Limitation of thermal pyrolysis in waste management

Thermal pyrolysis offers a potential approach to managing plastic waste but is hindered by notable drawbacks affecting its efficiency. The process often produces oil of low quality and quantity, with sulfur content up to 1.5% and chlorine levels reaching 0.8%, rendering it unfit for direct fuel use without significant refining (Miandad et al.,2016). Requiring temperatures of 300-900°C, it is energy-intensive, raising operation costs by about 20-30% compared to alternative methods. It also adds to the carbon footprint, emitting 0.7-1.0 kg of CO_2 and 0.1-0.3 kg of carbon monoxide per kilogram of plastic processed, amplifying environmental harm (Miandadnet al., 2016). Futher complications arise from uncontrolled reactions and the mixed nature of plastic waste, such as PVC and PET, which release corrosive hydrogen chloride (HCl) gas at up to 0.5% concentration. This necessitates purification systems, increasing costs by 10-20% (Chen et al., 2014). These issues highlight the need for technological advancements to enhance the feasibility of conventional pyrolysis.

2.2.4 Role of Catalysts in Pyrolysis

While thermal pyrolysis has some limitations, catalysts play a pivotal role here by enhancing pyrolysis costs, efficiency and product quality and quantity. They facilitate key reactions such as cracking, isomerization, and deoxygenation, which lower activation energy and improve the selectivity of desirable hydrocarbons (Dai et al., 2022). Using the study of Zhang et al. (2021), zeolites, a class of synthetic microporous catalysts, boost the cracking of heavy hydrocarbons into lighter fractions, increasing the yield of high-value gasoline-range aromatics by 15–25%. Catalytic pyrolysis also curbs harmful emissions, reducing secondary reactions that produce CO and CO_2 by about 30–50% compared to non-catalytic processes (Zhang et al., 2021). Recent research underscores the benefits of synthetic versus natural catalysts: synthetic options like ZSM-5 zeolites, with acidity levels reaching 0.5–1.0 mmol/g and stable pore structures, enable precise reaction control, achieving hydrocarbon yields up to 70% (Dai et al., 2022). However, their high cost (often 5–10 times that of natural alternatives) limits scalability. Conversely, natural catalysts like clays, kaolin, and bagasse ash, which cost less than the previous one and are widely available in some areas, offer viable options for low-income regions, though they typically achieve 5–10% lower yields due to less structural consistency (Desai et al., 2024). The choice between synthetic and natural catalysts depends on factors like cost, availability, and efficiency. Table 2 below provides a comparison of these catalysts, highlighting their key attributes

Table 2-2: Synthetic vs. Natural Catalysts (Shaw et al., 2021)

Feature	**Synthetic Catalysts (Zeolites)**	**Natural catalysts (Kaolin, Bagasse Ash)**
Cost	High	Low
Accessibility	Limited	Abundant (in some areas)
Modification Needs	Extensive	Minimal

Environmental Impact	Higher(energy-intensive synthesis and if not clean energy source used)	Lower (minimal processing)

The table above shows that natural catalysts like kaolin or bagasse ash offer cost and sustainability advantages but require optimization to match synthetic catalysts' efficiency (Patel & Gupta, 2018; Wang et al., 2021).

2.3 KAOLIN AS A CATALYST IN PLASTIC PYROLYSIS

2.3.1 Composition and properties

Kaolin, a naturally occurring clay, contains various metal oxides that play crucial roles for its catalytic activity during pyrolysis. Here are the main metal oxides in kaolin:

- **Silicon dioxide ($\mathbf{SiO_2}$) and aluminium oxide (Al_2O_3)**: these oxides generate acidity, critical for cracking reactions in pyrolysis. The ratio influences surface acidity, directly affecting hydrocarbon breakdown.

- **Ferric Oxide (Fe_2O_3):** while enables redox reactions, its presences raises risks of excessive coke formation and catalytic deactivation if above 1.5% of the catalyst composition (Chen et al., 2021).

- **Calcium Oxide (CaO):** Acts as a structural stabilizer, enhancing thermal resistance during high-temperature processes (Luo et al.,2018)

- **Others oxides:** Nickel oxide (NiO) enhances hydrogenation reactions, leading to higher proportion of valuable fuel components and manganese oxide ($Mn0_2$) improve thermal conductivity of kaolin, ensuring uniform heat distribution during pyrolysis.

2.3.2 *Physical and chemical properties vs. catalytic activities*

Kaolin's performance hinges on its physical and chemical attributes:

- **Specific surface area and porosity:** Modified kaolin exhibits increased mesopores and surface area, leading to improvement in adsorption and catalytic efficiency (Wang et al., 2021).
- **Thermal Stability:** Kaolin retains structural integrity up to 1200°C, making it ideal for pyrolysis (Rajput et al., 2020)
- **Acidity:** Acidic sites from SiO_2 / Al_2O_3 accelerate cracking, reducing char formation (Bryan et al.2019)

2.3.3 *Previous Applications in Pyrolysis*

Kaolin has been widely investigated as a sustainable catalyst in plastic and biomass pyrolysis due to its cost-effectiveness, abundance (in some areas), and tunable acidity. Studies demonstrate that kaolin significantly improves bio-oil yield while reducing char formation. For instance, Uddin et al. 2019 reported 15-20% increase in liquid hydrocarbon yield during the pyrolysis of mixed plastic waste (here PP,PS and PE) when kaolin was used as a catalyst, attributing this to its ability to crack long-chain polymers into lighter hydrocarbon fractions. Similarly, in biomass pyrolysis, kaolin's acidic sites effectively deoxygenate bio-oil, reducing its viscosity and enhancing its stability (Uddin et al., 2019; Chen et al., 2021).

Despite its application in plastic and biomass pyrolysis, a critical gap persists in understanding how variability in its metal oxide composition (dictated by its geological source) affects its catalytic performance.

2.4 OPTIMIZATION OF PYROLYSIS PARAMETERS

2.4.1 Catalyst-to-plastic ratios

The efficiency of catalytic pyrolysis is governed by the catalyst-to-plastic ratio, which directly influences reaction time, product distribution, and economic viability. An optimal ratio maximizes catalytic surface area for polymer chain cracking while minimizing material costs and energy input. Studies typically recommend 4–20 wt. % catalyst-to-feedstock ratios for plastic pyrolysis. This range balances two competing factors:

- Lower ratios (<4 wt.%) risk insufficient catalytic activity, leading to incomplete decomposition of long-chain hydrocarbons, lower oil yields, and higher char/tar formation.
- Higher ratios (>20 wt.%) may saturate the reaction system, causing agglomeration (reducing active sites and increasing char accumulation) or excessive heat absorption, which elevates energy demands and process costs without proportional yield improvements.

For instance, in medical plastic waste pyrolysis, 5–20 wt.% natural zeolite or silica-alumina catalysts achieved peak oil yields between 75% and 82% by enhancing secondary cracking of volatile vapors. Higher ratios (e.g., 25 wt.%) marginally improved gas yields but raised catalyst recovery costs by 30% (Maqsood et al., 2024). Similarly, in biomass-plastic co-pyrolysis, a 60% plastic-to-biomass ratio optimized synergy, yielding 70.42 wt.% bio-oil with higher heating values (32.1 MJ/kg) due to plastic-derived hydrocarbons compensating for biomass's oxygenated compounds (Susastriawan et al., 2016).

In this study, series of pyrolysis experiments were conducted to evaluate the effect of varying kaolin-to-PE ratios on product distribution and yield. The results, discussed in chapter 4, provide insights into the optimal ratio for achieving high pyrolysis oil yield and efficient decomposition of PE.

2.4.2 *Reaction Time and Catalyst Impact*

Reaction time in pyrolysis (the duration feedstock undergoes thermal decomposition) typically 60–120 minutes in lab-scale setups. Catalysts like kaolin or zeolites can significantly reduce reaction time by 20-30% by lowering activation energy required for polymer cracking, thereby accelerating volatile release. For instance, natural zeolite catalysts reduced reaction time by 25% (from 90 to 67.5 minutes) while maintaining oil yield above 70% by optimizing temperature and residence time (Zhang et al., 2025). However, prolonged reaction times at elevated temperatures (>420°C) can shift product distributions, increasing gas yields by 10-15% at expense of oil yield (Rahimi et al., 2022). Heating rate also plays a key role in plastic pyrolysis. For instance, a heating rate of 10°C/min reduces reaction time by 15% and raised oil yield by 4% form the study done by Miandad et al. (2019). These findings highlights the trade-offs between reaction time, heating rate, and energy efficiency, emphasizing the need for catalyst-specific optimization.

2.5 ECONOMIC VIABILITY OF KAOLIN AS A CATALYST

2.5.1 Cost-benefit analysis of natural catalysts

Kaolin's economic viability stems from its low production costs and widespread availability. For instance, geopolymer catalysts derived from kaolin (eg. Pd-GNK) eliminate carbon-intensive synthesis steps reducing costs by ~30–50% compared to synthetic alternatives like ZSM-5 zeolites (Hazra et al., 2025).

Countries such as Indonesia and India possess extensive kaolin reserves (66 million tons in Indonesia), enabling decentralized production and reducing reliance on imported synthetic catalysts (Arnass et al., 2024).

Techno-economic assessments highlight kaolin's role in pyrolysis. Biodiesel production via kaolin-catalyzed transesterification achieves a 72.4% yield at 60% lower catalyst costs than NaOH- based methods (Hu et al., 2023). Similarly, bio-oil production via microwave-assisted pyrolysis with kaolin reduces minimum fuel selling prices to $0.82/L, competitive with fossil fuels (Arnass et al., 2024). The table below summarizes key differences in cost, processing complexity, and availability between kaolin-based and synthetic catalysts, based on findings from Hu et al. (2023) and Arnass et al. (2024)

Table 2-3. Cost and Availability Comparison of Kaolin-Based and Synthetic Catalysts (Hu et al., 2023)

Factor	Kaolin-based catalysts	Synthetic catalysts
Raw material cost	\$10-50/ton	\$500-1500/ton (zeolites)
Processing complexity	Simple acid /base activation	High-temperature synthesis
Local availability	Widely available in tropical regions	Import-dependent in most regions

2.5.2 Circular economy potential

Kaolin pyrolysis aligns with circular economy principles by converting waste into biofuels and syngas. For example, agricultural residues and sewage sludge are transformed into hydrogen-rich syngas, diverting 40-60% of organic waste from landfills (Hazra et al., 2025). Catalyst reusability further supports closed-loop systems: Pd-GNK retains ~88% activity after four cycles, while base-activated kaolin (Kd2M) achieves 92.3% recovery rates in transesterification (Arnas et al., 2024).

These systems reduce carbon footprints by avoiding emissions tied to synthetic catalyst production. Geopolymer catalysts derived from kaolin eliminate 2.1kg CO/kg associated with synthetic catalysts, aligning with U.N. Sustainable Development Goals (SDGs 7, 12) (Hu et al., 2023).

2.6 Gaps in existing literature

2.6.1 Geographic focus on industrialized regions

Over 80% of pyrolysis studies focus on Europe, America, and East Asia, neglecting the unique waste ecosystems of Sub-Saharan Africa (SSA) (Nabaho et al., 2023). Uganda's plastic waste stream differs markedly: 70% is PE (eg. Plastic bags), compared to 45% in Europe, where PET bottles dominate. Informal disposal practices (such as open burning and roadside dumping) further complicate waste management, necessitating tailored pyrolysis solutions. Despite this, only two studies (Nabaho et al. 2023; Foong et al., 2020) have explored widely catalytic pyrolysis in SSA, both limited to theoretical models rather than field trials.

2.6.2 Untapped variability of Buwambo kaolin

Buwambo kaolin's high silica content (approximately 55% SiO_2) and moderate acidity (Lewis acid sites = 0.8 mmol/g) suggest superior catalytic potential for PE pyrolysis compared to other kaolin types (Foong et al., 2020). However, no studies have experimentally tested its performance. Optimal catalyst-to-plastic ratios, remain unexplored, but similar conditions for Buwambo kaolin could yield higher efficiencies due to its unique metal oxide profile.

2.6.3 Neglect of informal socioeconomic systems

Existing techno-economic assessments (TEAs) predominantly consider structured waste collection systems, often neglecting the role of informal waste management in developing countries such as Uganda. This oversight creates a significant gap, particularly in market like Kikuubo (kampala's largest trading hub) where manual waste pickers play a crucial role in plastic recovery. Studies indicate that these informal workers collect only 30-40% of plastic waste, selling it at 0.20$/kg (Nabaho et al.,2023). However, there is limited research on how integrating these waste pickers into the pyrolysis supply chain could impact both feedstock costs and plastic collection rates. Addressing this gap could provide a more comprehensive understanding of cost-effective and scalable waste-to- energy solution in low-income settings.

2.7 CHAPTER CONCLUSION

This chapter has thoroughly examined existing literature on the composition, structure, and proprieties of plastics, identifying those suitable for pyrolysis and the role catalyst play in improving the process. It has reviewed catalyst types and their effect on pyrolysis product yields and compositions, including oil liquid yield, solid char, and gases. Kaolin's potential as a catalyst, particularly its metal oxide content and benefit, has been emphasized. However, gaps remain in determining the ideal kaolin-to-plastic ratio for the Buwambo kaolin and its impact on reaction time. These findings pave the way for chapter three, which outlines the methodology for evaluating kaolin's effectiveness and optimizing its use in PE plastic pyrolysis.

CHAPTER THREE METHODOLOGY

3.0 INTRODUCTION

This study aims to evaluate kaolin as a catalyst for polyethylene plastic waste pyrolysis. Its specific goals: (1) to analyze the metal oxide composition of kaolin from Buwambo deposit, (2) to determine the optimal kaolin-to-plastic ratio for pyrolysis, (3) to assess the impact of kaolin on reaction time and (4) to conduct a cost-benefit analysis of using kaolin from Buwambo as a catalyst in polyethylene plastic waste pyrolysis. This chapter details the experimental design, materials, equipment, and procedures employed to meet the different specific goals. The chosen methods prioritize reliability, reproducibility, and compliance with global standards like ASTM and ISO to thoroughly assess kaolin's catalytic effectiveness.

3.1 RESEARCH DESIGN

This study adopts an experimental research design to investigate the catalytic performance of kaolin in the pyrolysis of polyethylene plastic waste. An experimental design involves manipulating independent variables to observe their effects on dependent variables while controlling extraneous factors, enabling the establishment of cause-and effect relationships. This approach was selected to ensure precise control over variables, ensuring reliable and producible results critical for optimizing catalytic impacts. Here are the different variables used in this study:

a) Independent variable

The study independent variables are:

- Kaolin-to-PE ratio: 0%, 5%, 10%, 15%, and 20% (by weight).
- Kaolin composition: Metal oxides including SiO_2, Al_2O_3, Fe_2O_3, and CaO.

b) Dependent variables

The dependent variables measured were:

- Pyrolysis oil yield (in %): Quantifying catalytic efficiency.
- Reaction time (in minutes): Assessing process duration.

c) Controlled variables

To ensure consistency, the following parameters were controlled:

- Temperature: Maintained at 420°C.
- Heating rate: Fixed at 10°C/min.
- Reactor pressure: Held constant at 1 atm.

3.2 METAL OXIDE ANALYSIS OF KAOLIN

The analysis of metal oxide composition in kaolin from the Buwambo deposit in Wakiso District, Uganda, was conducted to quantify major oxides such as SiO_2, Al_2O_3, Fe_2O_3, CaO, and others. This study utilized X-ray Fluorescence (XRF) spectrometry following standardized methods for silicate analysis (ASTM D4326-21) and chemical composition determination (ISO 12677:2011).

3.2.1 *Tools Used*

- **X-ray Fluorescence (XRF) spectrometer**: For quantitative analysis of kaolin's metal oxides.
- **Hydraulic press**: For pellet preparation.
- **Muffle furnace**: For calcination of the sample at 1000°C.
- **Mechanical grinder and sieves**: For sample preparation.

3.2.2 *Procedure*

a) **Sample preparation**:

  - Raw kaolin was dried at 105°C to eliminate moisture but also to remove impurities (such as organic matter, hydroxyl groups, carbonates) and improve structural properties.
  - The dried material was ground into fine powder and sieved to achieve a uniform particle size (75–150 µm).

b) **Pellet formation**:

The powder kaolin was compressed into pellet using a hydraulic press under ~20–30 MPa pressure. This ensured a smooth surface for minimizing scattering during XRF measurements.

c) **Instrument calibration**:

The XRF spectrometer was calibrated using NIST SRM 2709 (San Joaquin Soil), a certified reference material.

d) Analysis Protocol:

- Quantitative analysis followed ASTM E1621-22 standards.
- Oxide concentrations (in wt%) were calculated using the linear regression formula: $C_i = k_i \cdot I_i + b_i$ Where:
    - C_i: Concentration of oxide i.
    - I_i: Measured XRF intensity.
    - k_i: Slope derived from calibration constants.
    - b_i: Intercept derived from calibration constants.

3.2.3 *Calculation*

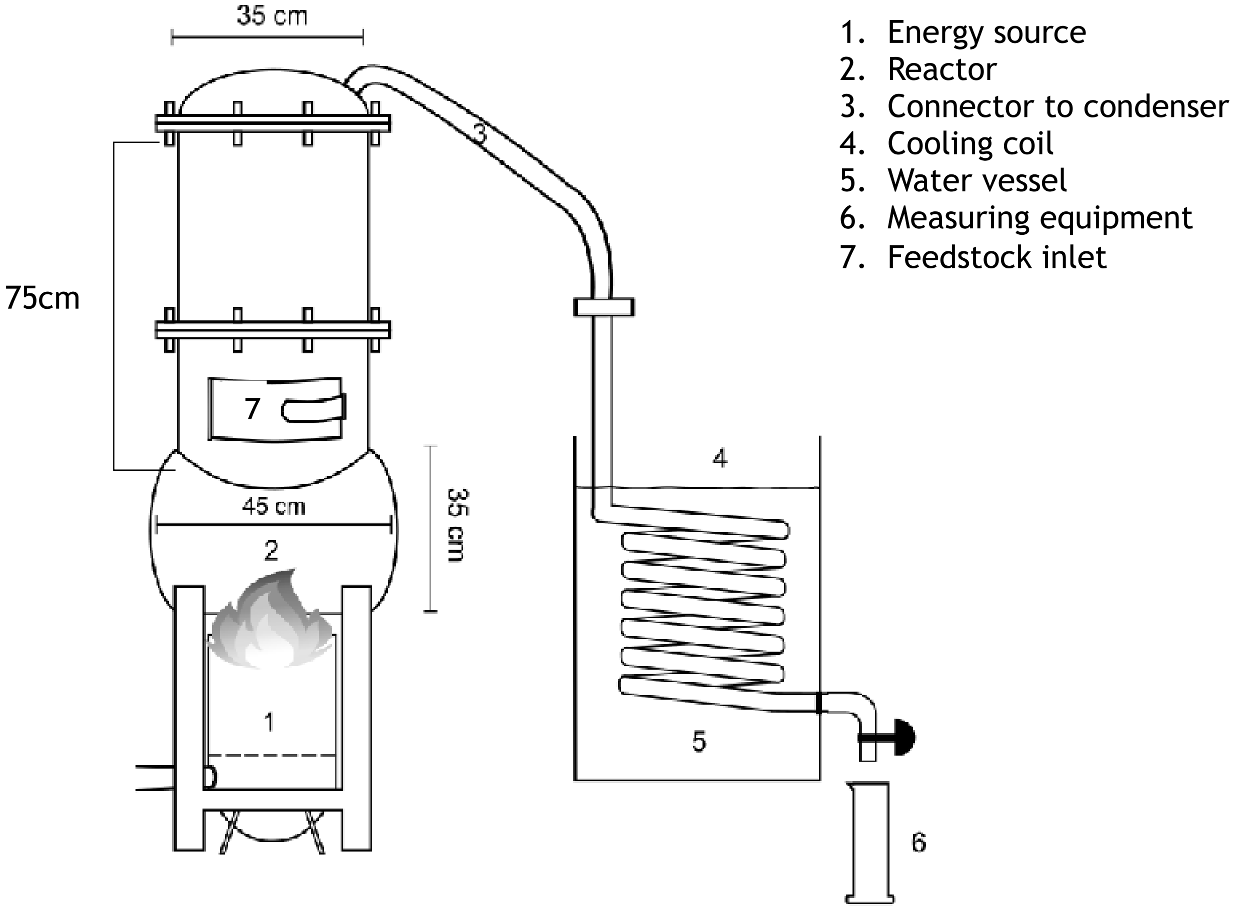
The formula used for determining oxide concentrations ensures precision by correlating measured XRF intensities with calibration constants derived from reference materials (here NIST SRM 2709). Rigorous quality control measures were implemented to ensure reliability and reproducibility of results.

3.3 OPTIMAL KAOLIN TO PE MIX RATIO

This study aimed to determine the optimal kaolin-to-PE plastic ratio (0–20%) for maximizing oil yield while minimizing gas and char formation during pyrolysis. The experiments were conducted using polyethylene (PE) waste and kaolin as a catalyst in a fixed-bed pyrolysis reactor under controlled conditions.

3.3.1 *Tools Used*

a) **Reactor setup**: The fixed-bed pyrolysis reactor used in the experiment was a stainless-steel vessel with dimensions 35 cm by 75 cm, designed to withstand high temperatures and ensure efficient thermal decomposition of plastic waste. The reactor was equipped with an electric heating system, which was regulated using an Inkbird temperature controller and a thermocouple for precise temperature monitoring. To minimize heat losses, the reactor was tightly sealed and insulated. A small stainless-steel outlet tube was positioned at the top of the reactor, directing the pyrolysis vapors into a condenser tank. Inside the condenser, the vapors passed through a coiled tube, facilitating efficient condensation. The condenser tank featured two taps: one for collecting the condensed liquid fuel and another for draining heated water that accumulated during the cooling process. This reactor setup ensured an efficient and controlled pyrolysis process, optimizing fuel recovery while maintaining thermal stability and safety. It is shown in the figure below:



1. Energy source
2. Reactor
3. Connector to condenser
4. Cooling coil
5. Water vessel
6. Measuring equipment
7. Feedstock inlet

Figure 3-1: Reactor setup (Zhao et al., 2021)

3.3.2 *Procedure*

a) **Feedstock Preparation**:

- PE waste was manually sorted into LDPE and HDPE categories, shredded into flakes (5–10 mm), and thoroughly cleaned according to ASTM D7611M-20.
- Kaolin was dried at 105°C for 24 hours, pulverized, and sieved to a particle size of <150 µm as per ISO 13320:2020.

b) **Mixing Ratios**:

- Prepared mixtures of kaolin and PE at ratios of 0% (control), 5%, 10%, 14%, 15%, 16%, 17%, and 20% by weight.

c) **Pyrolysis Process**:

- The reactor was preheated to 420°C at a heating rate of 10°C/min.
- Each mixture was pyrolyzed under these conditions, with vapors directed into a condenser system for liquid oil collection.
- Non-condensable gases were collected in gas bags, while char was retrieved after cooling the reactor.

d) **Repetition**:

Each experiment was conducted in triplicate to ensure reproducibility as per ISO 5725-2 guidelines.

e) **Product Collection**:

- Liquid oil was collected from the condenser taps.
- Gas samples were stored in gas bags.
- Char was weighed after cooling.

3.3.3 Product yield calculations

The different equation here were used to quantify the distribution of pyrolysis products (oil, gas, and char) to assess the catalytic influence of kaolin. The yields were calculated as percentages of the initial plastic feedstock mass and followed ASTM E873-22 standard.

i. Liquid (or oil)

$$\text{Yield (\%)} = \frac{mass\ of\ oil}{Mass\ of\ the\ feedstock} \times 100$$

Equation 3-1: Oil yield (Zhao et al., 2021)

This equation calculates the percentage of the initial plastic feedstock that is converted into liquid oil during the pyrolysis process. The mass of pyrolysis oil is determined by weighing the liquid product collected after condensation. This yield is a key indicator of the effectiveness of the pyrolysis process for fuel production.

ii. Solid (or char) yield (%)

$$\text{Yield (\%)} = \frac{mass\ of\ char}{Mass\ of\ the\ feedstock} \times 100$$

Equation 3-2: Solid yield (Liaw and Wu, 2018)

The equation above quantifies the amount of solid residue (char) remaining after the pyrolysis process, expressed as a percentage of the initial plastic feedstock mass. The mass of char is determined by weighing the solid residue collected from the reactor after the experiment.

iii. Gas yield (%)

$$\text{Yield (\%)} = \frac{Mass\ of\ gas}{Mass\ of\ the\ feedstock} \times 100$$

Equation 3-3: Gas yield (Zhao et al., 2021)

This formula determines the percentage of the plastic feedstock converted into gaseous products. In this study, the mass of pyrolysis gas is calculated indirectly by subtracting the mass of the liquid product (oil) and solid residue (char) from the initial mass of the plastic feedstock.

These yield equations collectively satisfy the mass balance principle shown in equation 3-4 below:

- ⇨ Liquid yield + gas yield + solid yield = 100%

Equation 3-4: Mass balance principle

3.4 REACTION TIME

The study aims to assess the impact of kaolin on the reaction time of polyethylene pyrolysis. This involves measuring the time from the onset of heating to the appearance of the first oil droplet in the condenser system and also for the entire process.

3.4.1 Tools Used

- **Mechanical Shredder**: For shredding polyethylene waste into flakes.
- **Stopwatch**: For recording reaction time.
- **Reactor**: Preheated to 420°C with a heating rate of 10°C/min.
- **Condenser System**: For collecting liquid oil.

3.4.2 Procedure

The procedure was the same as in section 3.3.2

i. **Data Collection**:

Reaction time was recorded using a stopwatch.

3.4.3 Reaction time calculations

No specific formulas are used for this objective, as it focuses on measuring reaction time directly.

3.5 COST-BENEFIT ANALYSIS

This objective evaluates the economic feasibility of using kaolin from Buwambo as a catalyst in polyethylene pyrolysis by analyzing costs, product value, and environmental impact.

3.5.1 *Data collection*

To perform the cost benefit analysis for using kaolin as a catalyst in PE pyrolysis, both primary and secondary data sources were used

- Primary data was collected through experimental results from pyrolysis tests conducted at the laboratory in Kabanyoro, Gayaza.
- Secondary data was sourced from published literature, industrial reports and government tariff documents to estimate costs such as energy tariffs, procurement costs, and transportation expenses.

3.5.2 *Identification of cost of components*

The cost associated with kaolin-catalyzed pyrolysis were categorized as follows:

- Transport costs: the cost associated with transporting kaolin from its natural deposit site in Buwambo to the laboratory in Kabanyoro (a 20km distance assumption) was determined based the truck rental fee per trip.
- Processing costs: the expenses related to kaolin processing included drying, grinding, washing, and sieving. These cost were estimated based on industrial processing fees and laboratory-scale processing expenses.
- Energy costs: the energy consumption for both thermal pyrolysis and catalytic pyrolysis using kaolin was calculated using Uganda’s industrial electricity tariff (417.8 UGX/kWh). The energy consumption per kilogram of plastic was determined using the following formula:

Energy cost= $\frac{Energy\ consumed\ (MJ/kg)}{1kWh}$ ×Tariff

Where 1kWh= 3.6MJ

3.5.3 *Determination of benefits (revenue estimation)*

The benefits were calculated based on the revenue generated from pyrolysis oil yield

- The oil yield percentage was determined from experimental results
- The market price of pyrolysis oil (3,200 UGX/L) was obtained from industry sources;
- The revenue was computed as follows:

⇨ CBA= Total benefits-Total costs

A positive CBA value indicated economic viability, while a negative CBA value suggested that the project was not economically feasible

3.5.4 *Comparison with alternative catalysts (zeolite and bagasse Ash)*

To assess the economic feasibility of kaolin, a comparative analysis was conducted with synthetic zeolite and bagasse ash as alternative catalysts.

- Procurement costs were obtained from literature and industry reports
- Processing and transportation costs were estimated based on logistics and existing price data.
- Revenue from pyrolysis oil yield was computed using reported oil yield percentages for each catalyst

- The CBA for each catalyst was determine using the same method as for kaolin, allowing for a direct comparison of economic viability.

By following this methodology, the most cost-effective and profitable catalyst for PE pyrolysis was identified and the results are discussed in chapter four

3.6 DATA ANALYSIS

This section outlines the data processing and analytical methods used to evaluate the catalytic performance of kaolin in the pyrolysis of PE plastic waste. Data analysis involves both quantitative and qualitative techniques, with Microsoft Excel used for statistical analyses.

3.6.1 Metal oxide analysis

XRF data obtained as described in section 3.2 of this chapter, was processed to determine the weight percentages of the key metal oxides

3.6.2 Pyrolysis product yields

Yields of oil, char and gas (calculated as described in section 3.3.3) were analyzed to assess the impact of the kaolin-to-PE ratio on product distribution. Mass balance closures will be calculated to ensure data quality.

3.6.3 Cost-Benefit Analysis

The economic feasibility of using kaolin as a catalyst will be evaluated using a cost benefit analysis. The net oil revenue will be calculated as the difference between the oil revenue and total costs associated with kaolin catalyzed pyrolysis per kilogram of feedstock processed. These costs include transportation, processing, and energy expenses.

3.6.4 *Statistical analysis*

Microsoft Excel was used to analyze statistical that include product yield, catalyst composition, and reaction time. Various graphs and charts were also created to visually represent the data, allowing clear interpretation of trends and relationships among variables.

3.6.5 *Safety and environmental considerations*

3.6.5.1 *Safety precautions:*

To ensure a safe environment during the pyrolysis PE plastic waste using kaolin as a catalyst, appropriate safety measures were followed. PPE (Personal Protective Equipment) where worn during the different experiments and lab works. A well-ventilated area was required for the experiment or a fume hood to control gas emissions. To avoid burns and other problems, high-temperature equipment was handled with care.

3.6.5.2 *Environmental measures:*

Environmental measures were taken in order to manage emissions and byproducts properly. Solid residues (char) were collected and assessed for possible safe reuse or disposal. The use of kaolin (a natural and eco-friendly material) as a catalyst minimized environmental impact especially in releasing of harmful gases

- Waste products (e.g., char, non-condensable gases) were disposed properly to avoid any harm on the environment
- The use of kaolin, a natural and eco-friendly material, minimized environmental impact.

3.7 CHAPTER SUMMARY

This chapter described the methodology used to assess the catalytic performance of kaolin in polyethylene waste pyrolysis. The different methods were selected to ensure accuracy, reproducibility, and compliance with international standards. The results of this study will provide valuable insights into the use of kaolin as a catalyst for enhancing plastic waste pyrolysis and they are discussed in the following chapter (Chapter four).

CHAPTER FOUR: RESULTS AND DISCUSSION

4.0 INTRODUCTION

This chapter presents the different results from the XRF analysis of kaolin and other catalysts, along with findings from the pyrolysis experiments and cost benefit analysis. This will help in assessing the catalytic performance of kaolin in PE waste pyrolysis.

4.1 CATALYST CHARACTERIZATION RESULTS (XRF ANALYSIS)

The table below presents the results of the XRF analysis done on the kaolin sample from Buwambo deposit in order to determine its elemental composition.

Table 4-1: XRF Analysis Results for Kaolin

Parameter	**Results for Kaolin (% m/m)**
Silicon dioxide (SiO_2)	53.67
Aluminium Oxide (Al_2O_3)	24.47
Potassium Oxide (K_2O)	0.23
Calcium Oxide (CaO)	8.16
Manganese (II) Oxide (MnO)	0.19
Titanium dioxide (TiO_2)	0.17
Iron (III) Oxide (Fe_2O_3)	0.65
Phosphorous pentoxide (P_2O_5)	0.03

4.1.1 *Comparison of kaolin with other catalysts*

To assess the suitability of kaolin as a catalyst for PE plastic pyrolysis, its composition was compared with other common used catalysts, in this case zeolite and bagasse ash. The table below summarizes the major oxide compositions of these three catalysts based on literature data and XRF results.

Table 4-2: Comparative XRF analysis of different catalysts

COMPOSITION	KAOLIN (%)	BAGASSE ASH (%)	ZEOLITE (%)
SiO_2	53.67	60.94	71.30
Al_2O_3	24.47	14.83	13.10
Fe_2O_3	0.05	12.81	1.90
MgO		2.05	1.20
CaO	8.16	3.05	5.20
Na_2O		0.51	1.30
K_2O	12.63	3.71	3.40
P_2O_5	0.03	0.84	
TiO_2	0.17	1.27	0.30
MnO	0.19		

4.1.2 *Discussion of catalyst composition*

Data in Table 4.1 exhibits significant differences in oxide composition of kaolin, bagasse ash, and zeolite, affecting their catalytic potential in PE plastic pyrolysis. Zeolite exhibited the highest SiO_2 content (71.30%), which enhances structural stability and provides a high surface area for catalytic reactions, followed by bagasse ash (60.94%) and kaolin (53.67%). Kaolin, however, had the highest Al_2O_3 content (24.47%), a key factor in formation of acid sites necessary for hydrocarbon cracking, whereas bagasse ash (14.83%) and zeolite (13.10%) contained lower amounts. The Fe_2O_3 content was significantly higher in bagasse ash (12.81%), suggesting a greater redox potential compared to zeolite (1.90%) and kaolin (0.05%). Kaolin also exhibited a high K_2O content (12.63%), which can influence catalytic behavior by affecting reaction kinetics and coke formation. Additionally, CaO levels were highest in kaolin (8.16%), enhancing its basicity and ability to promote decarboxylation reactions. Additionally, Na_2O was present in bagasse ash (0.51%) and zeolite (1.30%) but absent in kaolin. The Na_2O oxides may have an impact on the release of harmful gases such as sodium oxide (Na_2O) during pyrolysis.

From this comparison, kaolin exhibits favorable catalytic properties similar to bagasse ash and zeolite, making it a promising candidate for plastic waste pyrolysis.

Figure 4-1 below provides a visual comparison of the XRF results, illustrating the distribution of major oxides among the catalysts.

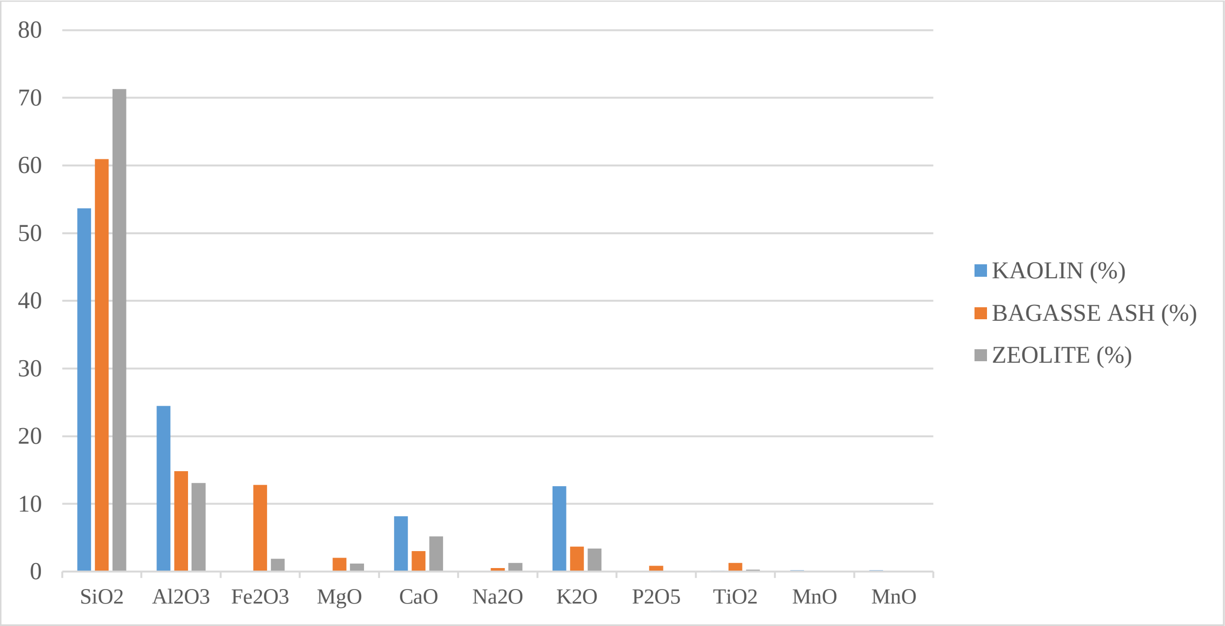


Figure 4-1: XRF Composition Comparison of Different Catalysts

4.2 PRODUCT YIELD ANALYSIS

The effect of kaolin loading on the yield of pyrolysis products (oil, char, and gas) was evaluated. The following table presents the average yields obtained for different kaolin loadings.

Table 4-3: Pyrolysis product yields with different kaolin loadings

Mix ratio	**Oil yield (%)**	**Gas yield (%)**	**Char yield (%)**
Control (0%)	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%	75.67	20.24	4.08
17%	74.3	20.81	4.89
20%	69.91	23.89	6.20

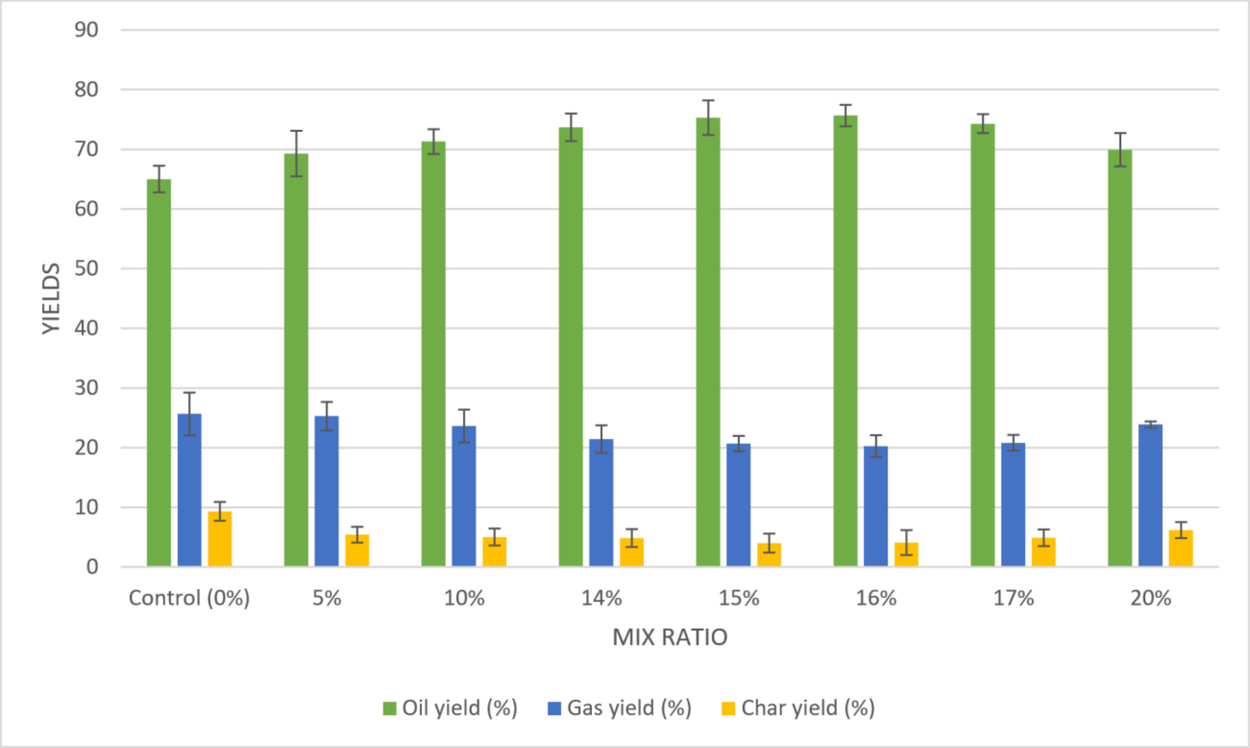


Figure 4-2: Oil, Gas, and Char yields vs. Kaolin loading

The results in Table 4-3 and Figure 4-2 above show that increasing kaolin loading improves oil yield while reducing gas and char yield. The highest oil yield (75.67%) was observed at 16% kaolin loading, after which a decline was noted at 17% and beyond. This trend suggests that kaolin effectively promotes thermal cracking, increasing the liquid fraction. The reduction in gas and char yields with kaolin addition confirms its role in enhancing oil selectivity while minimizing secondary degradation of hydrocarbons.

The declining oil yield at 20% kaolin loading suggests that excessive catalyst presence might lead to unwanted secondary reactions, which promote gas formation rather than liquid hydrocarbons. This finding aligns with literature that indicates an optimal catalyst-to-plastic ratio for maximizing oil production. The decreasing trend beyond 16% loading suggests that catalyst saturation may have been reached, leading to side reactions that favor gas formation

4.3 EFFECT OF KAOLIN LOADING ON REACTION TIME

The time taken for the first oil drop and the total retention time were recorded. The results are summarized in the table below.

Table 4-4: Effect of kaolin loading on reaction time

Mix ratio	**Reaction time (minutes)**
Control (0%)	91
5%	82
10%	79
14%	77
15%	75
16%	74
17%	80
20%	87

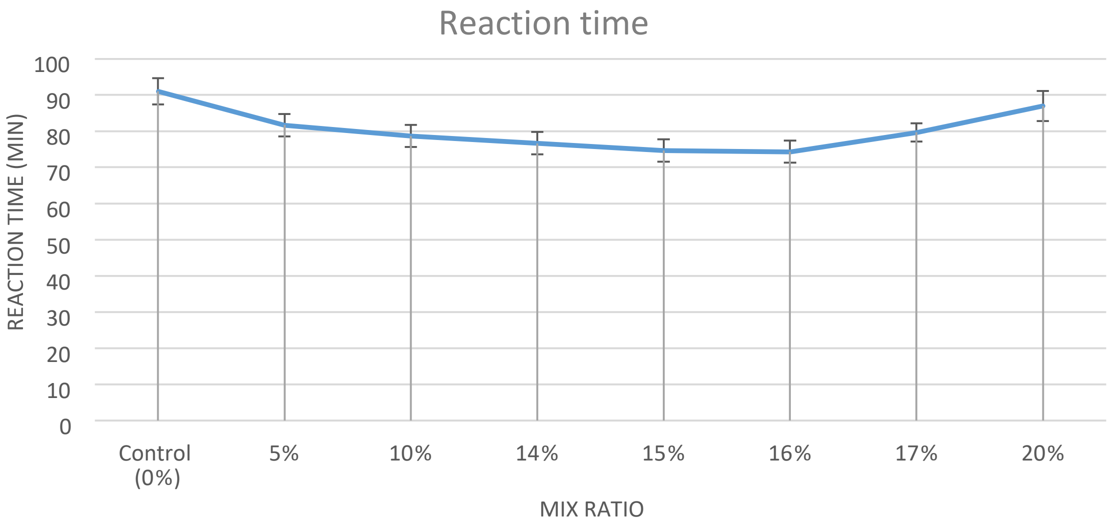


Figure 4-3: Reaction time vs. kaolin loading

Table 4-4 and Figure 4-3 indicate that reaction time decreases with increasing kaolin loading up to 16%, after which a slight increase is observed. The shortest reaction time (74 minutes) was recorded at 16% kaolin loading, which is approximately a 18.7% decrease in reaction time comparing to the control (91miutes). This trend can be attributed to the enhanced thermal conductivity and catalytic activity of kaolin, which facilitates rapid polymer degradation and accelerates oil formation.

However, beyond 16% loading, the reaction time increased, with 20% kaolin showing a notable rise (87 minutes). This could be due to excessive catalyst particles hindering effective heat distribution or leading to clogging effects that slow down the reaction. The observed trend aligns with findings from previous studies, which suggest that while catalysts enhance reaction rates, excessive amounts can introduce inefficiencies by altering the reaction environment.

4.4 COST BENEFIT ANALYSIS

This was done in order to obtain the economic feasibility of using kaolin as a catalyst in PE plastic waste pyrolysis.

4.4.1 Cost benefit analysis results

The cost benefit analysis was conducted in order to obtain the economic feasibility of using kaolin as a catalyst in PE plastic waste pyrolysis. The results are presented in the table 4-5 below.

Table 4-5: cost benefit analysis results

Costs (UGX/kg)		
Category	With Kaolin	Without Kaolin
Processing Costs (UGX/kg)	500	0
Transport Costs (UGX/kg)	70	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

4.4.2 *Discussion of Cost Benefit Analysis.*

a. **Transport Costs.**

The transport costs were computed based on transporting 1,000 kg of kaolin over a 20km distance (which is the distance from the Buwambo kaolin deposit to the laboratory in Kabanyoro, Gayaza where pyrolysis experiment was done) at a cost of 70,000 UGX per trip, resulting in a cost of 70 UGX/kg. This cost remains constant in other scenarios (where zeolite and bagasse ash were used).

b. **Processing Costs.**

The processing costs included processes like drying, washing, grinding and sieving, estimated at 500 UGX/kg based on the industrial practices and laboratory processing fees (which was 10,000 UGX for a 20kg).

c. **Energy Costs**

Energy costs were calculated using Uganda's industrial tariff of 417.8 UGX/kWh (URA, 2024). Catalytic pyrolysis reduced energy consumption from 5 MJ/kg to 4MJ/kg, resulting in a cost of 465 UGX/kg compared to 581 UGX/kg without kaolin. The computation below shows how these costs were obtained;

$$1\ kWh = 3.6\ MJ$$

For 5MJ/kg without kaolin.

Energy Cost = (Pyrolysis Energy/1 kWh) x Tariff

= (5/3.6) x 417.8

= 581 UGX/kg

For 4MJ/kg with kaolin.

Energy Cost = (Pyrolysis Energy/1 kWh) x Tariff

= (4/3.6) x 417.8 = 465
UGX/kg

d. Oil Yield Revenue

The pyrolysis yield increased from 61% to 75% with kaolin, generating revenue of 2,400 UGX/kg compared to 1,952 UGX/kg without kaolin (with a cost per pyrolysis oil of 3,200 UGX in both situations as there is need of further purification).

Without kaolin.

Oil revenue = Yield in liters x Oil cost

= 0.61 (L) x 3, 200 UGX/L

= 1, 952 UGX/kg

With kaolin.

Oil revenue = Yield in liters x Oil cost

= 0.75 (L) x 3, 200 UGX/L

= 2, 400 UGX/kg

e. CBA analysis.

The CBA indicates that using kaolin as a catalyst is economic viable, with a higher net benefit of 1,365 UGX/kg compared to 789 UGX/kg without kaolin. This is due to increased oil yield and reduced energy consumption by 22%. As demonstrated by the following computation;

Without Kaolin.

CBA = Total Benefits-Total Costs

= 1, 952-1, 151

= 789 UGX/kg

<u>With kaolin.</u>

CBA = Total Benefits-Total Costs

= 2, 400-1, 035

= 1, 365 UGX/kg

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

Synthetic zeolite and bagasse ash have been used as catalysts in PE pyrolysis and have both produced increase in oil yield, however they pose inconsistencies especially in regard to economic viability comparing to kaolin (Tewari et al., 2020 and Musawwa et al., 2020), as presented the table and discussions below.

***Table 4-6**: CBA Comparison of Kaolin to synthetic zeolite and bagasse ash*

catalyst	Kaolin	Synthetic zeolite	Bagasse ash
Procurement costs (UGX/kg)	0	9,000-15,000	800

Transport cost (UGX/kg)	70	70	70
Processing cost (UGX/kg)	500	0	0
Energy costs (UGX/kg)	465	465	465
Total costs (UGX/kg)	1,035	12,535	1,335
Total revenue (UGX/kg)	2,400	2,560	1,760
CBA (UGX/kg)	1,365	-9,975	425

a. Procurement Costs.

Kaolin has no procurement cost, while zeolite costs between 9,000 and 15,000 UGX/kg, and bagasse ash costs 800 UGX/kg (G. Fadillah, 2021; Procurement Resource, 2025).

b. Transport Costs.

The transport costs are consistent across all catalysts at 70 UGX/kg.

c. Processing Costs.

Kaolin from Buwambo deposit requires processing, whereas zeolite and bagasse ash do not.

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 was still used (UERA, 2024).

e. Oil Yield Revenue.

Synthetic zeolite yields the highest revenue of 2,560 UGX/kg as it has a large surface area and acidic properties facilitating cracking hydrocarbons in the pyrolysis process to produce pyrolysis oil (Maqbool et al., 2020) and according to literature, catalytic pyrolysis using zeolite has produced an oil yield of up to 80% (Tewari et al., 2020). On the other hand, research has shown that bagasse has produced an oil yield of 55% when used as a catalyst in PE pyrolysis (Saini et al., 2020), which is much lower than that of kaolin and zeolite.

The cost of pyrolysis oil is considered to be 3,200 UGX/L, and below is the oil revenue computation.

<u>For Zeolite.</u>

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 (L) x 3, 200 UGX/L

= 1, 760 UGX/kg

From the above computation, zeolite produces the highest revenue as compared to kaolin (2,400 UGX/kg) and bagasse ash (1,760 UGX/kg).

f. CBA analysis.

For Zeolite.

CBA = Total Benefits-Total Costs

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

= -9, 975 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.

CBA = Total Benefits-Total Costs

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

= 425 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.

In conclusion, kaolin offers the highest positive CBA among the other catalysts, making it the most economically viable option for PE plastic waste pyrolysis.

DESIGN AND DRAWINGS

The drawing presented below illustrates a conceptual design of an ideal polyethylene pyrolysis system intended for future implementation. It includes all keys components of a complete setup such as a feedstock input unit, fixed-bed reactor, temperature control system, condensation unit, oil and gas collection sections, and a char removal chamber. Though not used in the current experimental study, this design serves as a visual representation of how the process could be scaled or industrialized. It highlights the integration of kaolin as a catalyst within a controlled thermal environment to enhance product recovery, process efficiency, and environmental safety in practical pyrolysis applications.

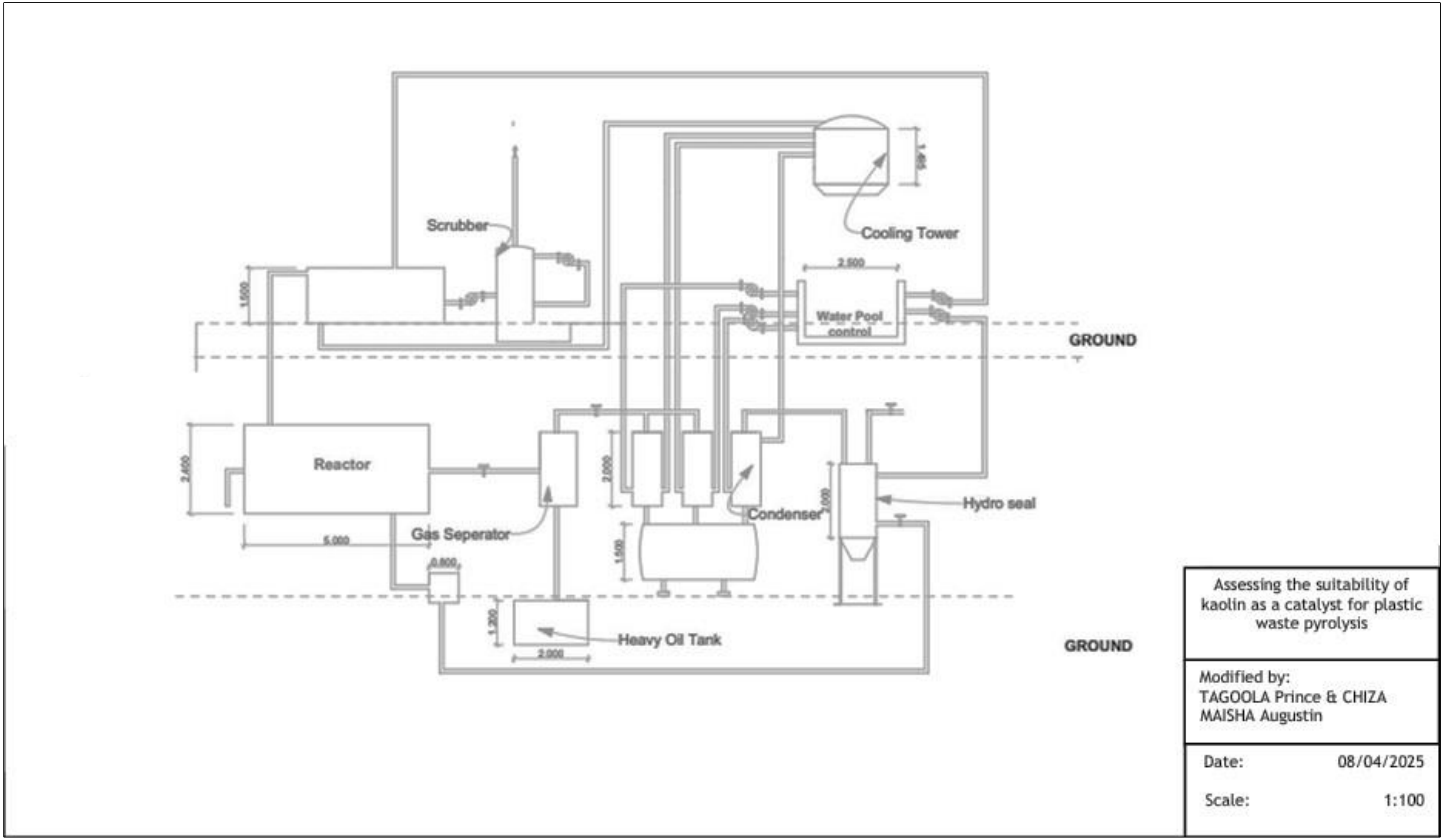


Figure 0-1: Pyrolysis setup system

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study investigated the suitability of kaolin as a catalyst for polyethylene plastic waste pyrolysis, focusing on optimizing product yields, reducing reaction time, and evaluating economic viability. Key findings demonstrated that kaolin from Buwambo deposit in Uganda processes a favorable metal oxide composition, including 53.67% SiO_2 and 24.47% Al_2O_3, which enhanced its catalytic activity by promoting hydrocarbon cracking and reducing char formation. The optimal kaolin-to-PE ratio of 16% achieved a maximum oil yield of 75.67%, significantly surpassing non-catalytic pyrolysis (65.01%). Furthermore, kaolin reduced reaction time by 18.7% (from 91 to 74 minutes), improving process efficiency. Economically, kaolin demonstrated superior cost benefit analysis outcomes (1,365 UGX/kg net benefit) compared to synthetic zeolite (-9,975 UGX/kg) and bagasse ash (425 UGX/kg), primarily due to its low procurement costs and sufficient oil yield.

These findings address the study's objectives by confirming kaolin's potential to enhance pyrolysis by-product yields while aligning with sustainable waste management goals. By converting plastic waste into valuable fuels, this approach mitigates environmental pollution in urban areas like Kikuubo market and supports Uganda's circular economy initiatives (NEMA, 2024; Zhang et al., 2023).

5.2 Recommendations

- Local governments and waste management stakeholders should promote small-scale pyrolysis plants using Buwambo kaolin as this strategy aligns with Uganda's National Strategy for Promoting Plastics Circularity (2023-2028) and leverages the catalyst's affordability and local availability
- Regulatory frameworks should incentivize the adoption of natural catalysts like kaolin through subsidies or tax exemptions to offset initial setup costs for pyrolysis facilities.
- Future research should assess kaolin's durability and regeneration potential over multiple pyrolysis cycles to optimize cost-effectiveness.
- Detailed studies on emissions (for example CO, CO2) and char toxicity are critical to ensure kaolin-based pyrolysis meets environmental safety standards
- Similar studies should evaluate kaolin deposits in other regions to verify consistency in catalytic performance and adaptability to diverse plastic waste streams.
- Conduct GC-MS (Gas Chromatography-Mass Spectrometry) and FTIR (Fourier-Transform Infrared Spectroscopy) analyses to characterize the hydrocarbon profile of pyrolysis oil. This will determine its suitability as fuel (for example compliance with ASTM D975 diesel standards) or chemical feedstock.
- Assess pollutants like polyaromatic hydrocarbons (PAHs) and sulfur content to ensure environmental safety
- Replicate the study with PP and PS plastic waste which dominate Uganda's plastic waste stream alongside PE (NEMA, 2024). PP's methyl braches and PS's

aromatic structure may require adjusted kaolin ratios or pyrolysis temperatures to optimize oil yield.

- Investigate hybrid catalysts (for example kaolin-zeolite blends) to synergize kaolin’s affordability with zeolite’s high acidity and surface area. For example, kaolin could reduce zeolite costs while improving thermal stability (Zhang et al., 2021; Ratnasari et al., 2017).
- Use TGA-FTIR (Thermogravimetric Analysis) to study real-time degradation kinetics of PP/PS with kaolin and identify intermediate compounds

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APPENDIX

Figure 6-1: Buwambo Kaolin Deposit

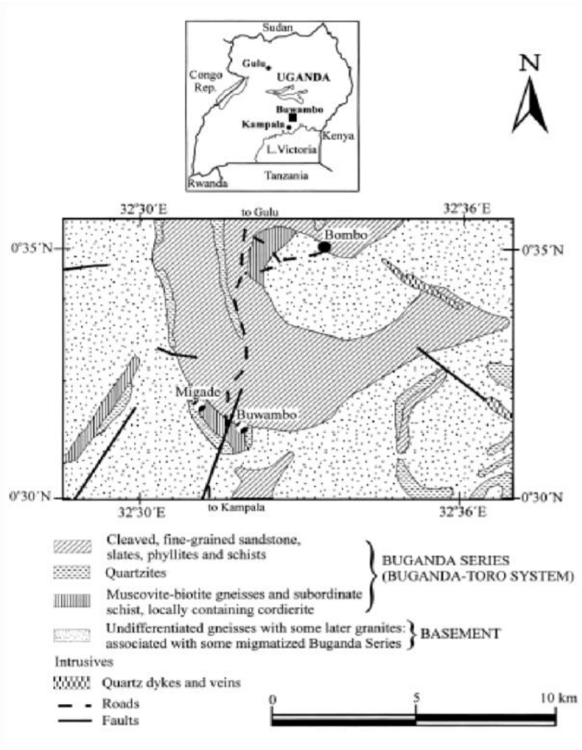


Figure 6-2: Location of Buwambo Kaolin Deposit

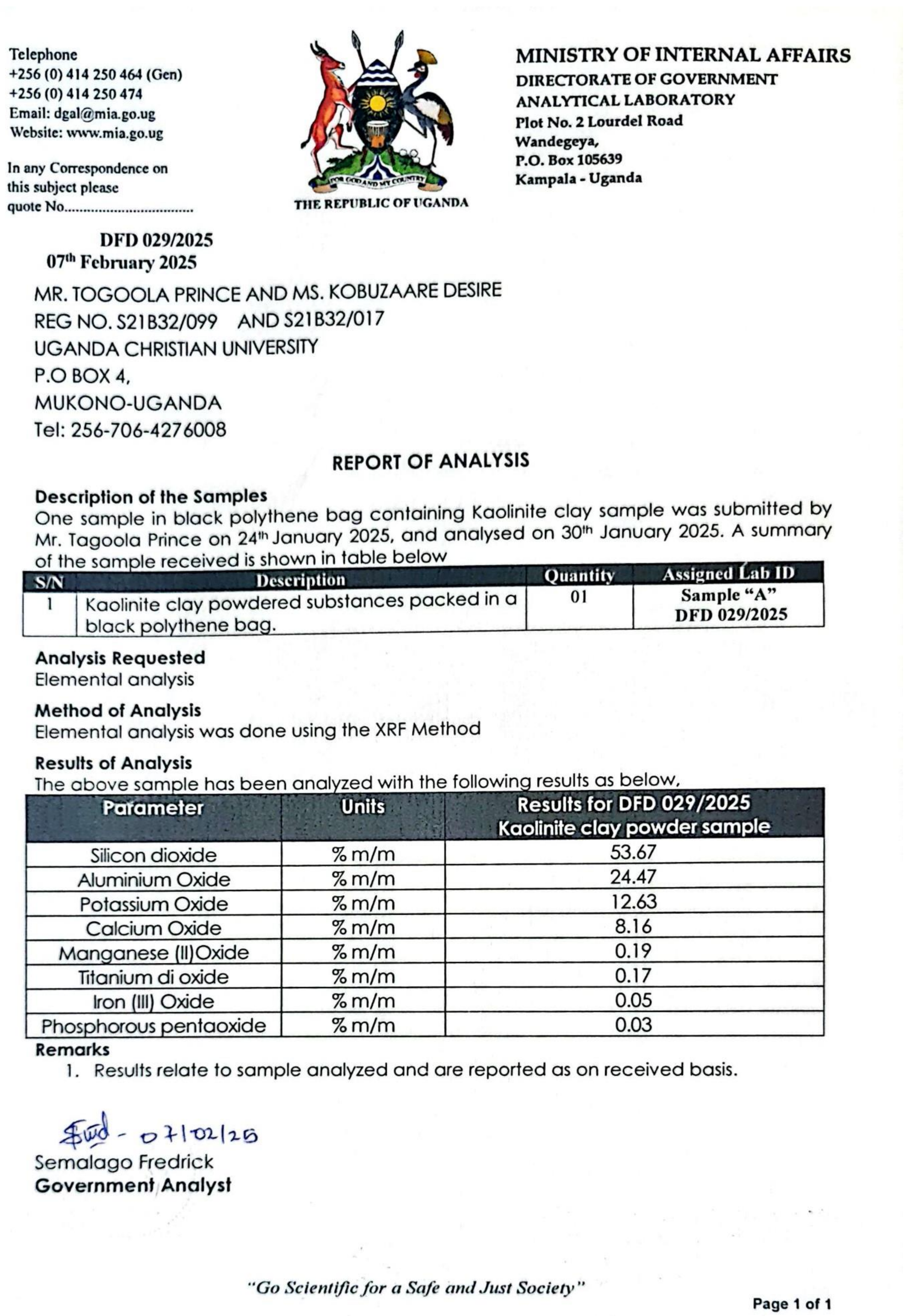
Figure 6-3: Pyrolysis reactor

Figure 6-4: Shredded PE plastic used for pyrolysis

Figure 6-5: Kaolin sample

Figure 6-6: Pyrolysis oil from pyrolysis

Figure 6-7: Black char form pyrolysis



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DFD 029/2025
07th February 2025

MR. TOGOOLA PRINCE AND MS. KOBUZAARE DESIRE
REG NO. S21B32/099 AND S21B32/017
UGANDA CHRISTIAN UNIVERSITY
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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,

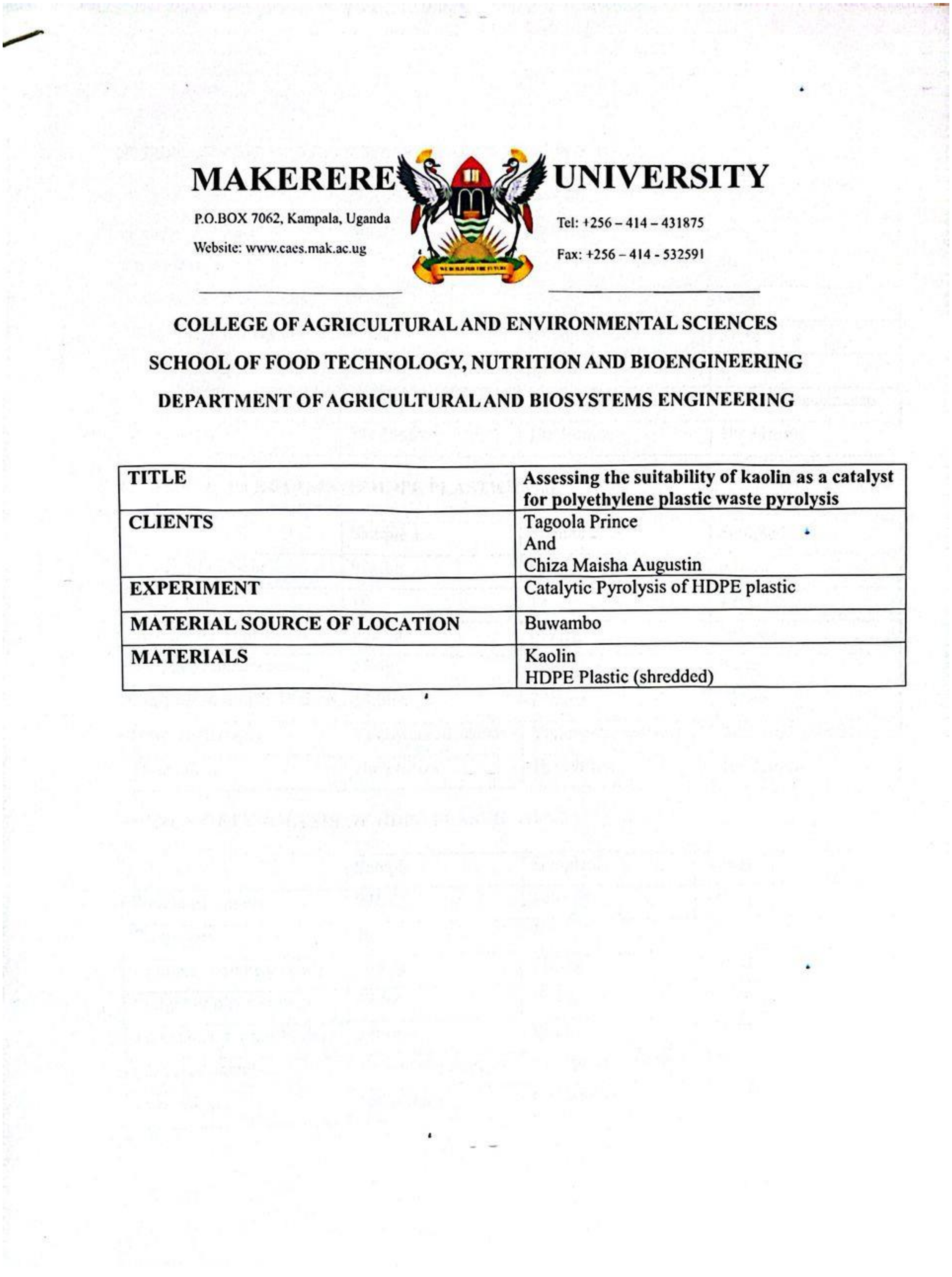
Parameter	Units	Results for DFD 029/2025 Kaolinite clay powder sample
Silicon dioxide	% m/m	53.67
Aluminium Oxide	% m/m	24.47
Potassium Oxide	% m/m	12.63
Calcium Oxide	% m/m	8.16
Manganese (II)Oxide	% m/m	0.19
Titanium di oxide	% m/m	0.17
Iron (III) Oxide	% m/m	0.05
Phosphorous pentaoxide	% m/m	0.03

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

- 07/02/25
Semalago Fredrick
Government Analyst

"Go Scientific for a Safe and Just Society"

Page 1 of 1



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SCHOOL OF FOOD TECHNOLOGY, NUTRITION AND BIOENGINEERING

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 PTROLYSIS 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 1st 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 1st 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 1st 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 1st 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 1st 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 1st 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 1st 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 1st drop	36mins	30mins	28mins
Observed sample	Yellowish substance	Yellowish substance	Yellowish substance
Time taken	1hr 30mins	1hr 26mins	1hr 25mins

Analyst:……………………………

Otim Andrew

Workshop Technician

AGRICULTURAL AND BIOSYSTEMS ENGINEERING DEPARTMENT
26 MAR 2025
MAKERERE UNIVERSITY
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