

INVESTIGATING THE POTENTIAL OF FUEL PRODUCTION FROM PLASTICS IN MALAWI

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ABSTRACT

Malawi faces dual challenges of energy shortages and plastic waste pollution. This study investigated the feasibility of converting plastic waste into usable fuel via pyrolysis to simultaneously address both issues. A small-scale pyrolysis experiment was conducted using 2kg of locally collected plastic waste as feedstock. The plastic sample contained High-Density Polyethylene (HDPE), polyethylene terephthalate (PET), Polystyrene (PS) and a mixture of all of them. A simple steel reactor heated to 300°C thermally decomposed the plastic into crude pyrolysis oil which was condensed and collected for analysis. Fuel properties like calorific value, viscosity, density and water content were tested for pyrolysis oils derived from HDPE, PET, PS and mixed plastics. HDPE oil had the most suitable characteristics including 43.67 MJ/kg calorific value and 1.75 cSt viscosity at 50°C. However, additional treatment is required to refine the oils to fuel grade quality. Though current limitations exist, results verify the fundamental technical viability of extracting usable oils from plastic waste using pyrolysis. With optimized systems tailored to prevalent local waste types, pyrolysis could sustainably convert Malawi's plastic waste into a domestic energy source. This would boost energy affordability and access for citizens while alleviating pollution. Realizing the potential requires supportive policies, infrastructure development, technical capacity building and research to scale up pyrolysis fuel production in Malawi. Overall, plastic-to-fuel conversion warrants serious exploration as an innovative solution offering substantial socioeconomic and environmental benefits for the country.

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ACRONYMS/ABBREVIATIONS

IEA	International Energy Agency
HDPE	High-Density Polyethylene
LDPE	Low-Density Polyethylene
PP	Polypropylene
PS	Polystyrene
PET	Polyethylene terephthalate
PVC	Polyvinyl chloride
MJ/kg	Megajoules per kilogram

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CHAPTER ONE: GENERAL INTRODUCTION

1.0. Chapter Introduction

The escalating global demand for energy has stimulated the quest for alternative fuel sources, partly driven by the environmental and public health concerns related to petroleum usage. The utilization of petroleum as an energy source releases large amounts of greenhouse gases, particularly carbon dioxide, which contribute to climate change and global warming (IEA, International Energy Agency, 2019). In this context, the production of fuels from plastic waste presents a promising solution that not only mitigates plastic waste pollution but also offers an alternative fuel source. And since the energy deficit in Malawi necessitates innovative solutions to meet the country's energy requirements, fuel-from-plastics seems a good potential resolution to that.

1.1. Background

Plastic waste pollution and petroleum energy dependence are two critical challenges facing Malawi today. At present, around 280,000 tons of solid waste is not collected each year in urban areas of Malawi (Turpie et al. 2019). most of which ends up discarded in landfills and the environment, there is an urgent need to find ways to productively repurpose this waste. At the same time, Malawi continues to rely heavily on imported petroleum to meet its energy needs, with petroleum being one of the primary energy sources (Chima, 1998).

This dependence not only creates economic vulnerabilities but also has negative environmental impacts in terms of greenhouse gas emissions from petroleum consumption (Achuo, Miamo, & Nchofoung, 2022). Converting plastic waste into usable fuel could provide a promising solution that simultaneously addresses both plastic pollution and energy deficiency in Malawi. Plastic-to-fuel conversion offers a means to create a local, renewable energy source while also mitigating plastic waste.

However, this phenomenon may seem to entail that petroleum geoscientists in Malawi would face the dilemma of choosing between abandoning their primary field of study to endorse synthetic oil usage or persisting with petroleum exploration, yet risk adverse environmental consequences. As such, this research approaches the solution to this in the form of a middle ground, wherein the body of knowledge from petroleum geoscience can be used to study these synthetic fuels, thereby improving their quality, and diversifying their use.

This can also be seen to reasonably follow from the fact that one of the most of the plastics, are compounds derived from petroleum (Khairy, et al., 2022). Therefore, petroleum is a crucial raw material for the production of plastics, and hence, analytical skills in petroleum fuels can be useful in the production and utility of the fuel from plastics, as it involves reversing the materials.

1.2. Problem Statement

Malawi is burdened by two interconnected challenges: a chronic energy crisis that leaves much of its population without reliable access to affordable energy, and a mounting plastic waste problem that stresses waste management systems and pollutes the environment. Converting plastic waste into fuel represents a promising opportunity to simultaneously address both issues. However, research is lacking on the feasibility and sustainability of plastic-to-fuel in the Malawian context. Without sufficient investigation into the technical viability, economic rationale, and environmental impacts of generating energy from post-consumer plastics, policymakers lack the knowledge needed to develop effective solutions that harness this potential.

This dissertation aims to fill this research gap by thoroughly assessing the potential of plastic-to-fuel to mitigate Malawi's energy crisis and plastic pollution challenges in a clean, cost-effective, and socially responsible manner.

The core problem is the current shortage of research informing policy decisions on alternatives for sustainable energy generation and plastic waste management. By

conducting an in-depth examination of the opportunities and limitations of plastic-to-fuel in Malawi, this study will provide policymakers, industry leaders, and civil society the knowledge base needed to make informed choices regarding sustainable energy and waste management strategies.

1.3. Main and Specific Objectives

1.3.1. Main Objective

The main objective of this research project is to conduct a comprehensive investigation of the potential and feasibility of fuel production from plastic waste in Malawi. This will determine factors that can enhance the sustainability, efficiency, and utility of plastic-to-fuel systems to help address Malawi's dual challenges of energy deficiency and plastic pollution.

1.3.2. Specific objectives

- Characterize the plastic waste in Malawi and investigate the feasible processes for converting it into fuels.
- Analyze the physical and chemical properties of the plastic feedstock to understand its composition and potential for pyrolysis conversion
- Compare the energy output from plastic pyrolysis with the conventional fuels in Malawi to assess its viability as an alternative energy source.

1.4. Research question

The study will answer the following question:

- What is the feasibility and potential of using pyrolysis as a method for fuel production from plastic waste in Malawi, to address the energy crisis and mitigate plastic waste challenges?

1.5. Significance of Study

This study holds substantial importance for the country's energy sector, economy, and environment.

On the energy front, successfully scaling plastic-to-fuel conversion would allow Malawi to tap into a domestically available energy source in the form of its mounting plastic waste. This could significantly diversify Malawi's heavily import-dependent energy mix and enhance energy security in the face of frequent fuel shortages. If proven viable, fuels derived from plastics using pyrolysis and other conversion methods can provide a clean, renewable energy source to help bridge the acute energy access gaps that leave many Malawians without enough fuel. In particular, the transport sector which accounts for most petroleum fuel consumption could benefit immensely from locally produced plastic-based fuels. The study aims to thoroughly assess the technical and economic feasibility of scaling up plastic-to-fuel to determine its potential as a sustainable indigenous energy source for Malawi.

Additionally, given projections that plastic waste generation in Malawi could triple within the next few decades (Turpie, et al, 2019, Griffin & Karasik, 2022), scaling plastic-to-fuel conversion also presents a practical solution to the country's mounting plastic pollution predicament. Currently poorly managed plastic waste clogs waterways, pollutes public spaces, and poses hazards for communities and wildlife in Malawi. Harnessing this waste stream for productive fuel production would simultaneously alleviate plastic pollution across cities and countryside while meeting energy needs. However, significant technical and economic barriers including costs, lack of infrastructure, lack of expertise and unsuitable fuel qualities need to be addressed. This underscores the importance of this study's comprehensive techno-economic of plastic-to-fuel pathways to determine the combinations of conversion technologies, infrastructure, expertise, and waste stream management needed for sustainable and optimally performing plastic-to-fuel systems in Malawi.

The environmental significance is also substantial considering plastic waste mismanagement is a major contributor to environmental degradation across Malawi (Turpie, et al, 2019). The toxins, greenhouse gases and particulates emitted when plastics are openly burned or buried in landfills could be avoided by converting the waste into usable fuels. However, a full life cycle assessment examining environmental tradeoffs is essential, as plastic-to-fuel systems have their own emissions and impacts. This study will provide a rigorous evaluation of the net environmental costs and benefits to guide decisions on plastic-to-fuel implementation.

Economically, this research could catalyze growth in Malawi's waste management and renewable energy technology sectors, while creating business opportunities and jobs spanning waste collection to distribution of domestically produced plastic-based fuels. The market feasibility analysis and industry stakeholder perspectives gathered will be invaluable in determining techno-economic potential and crafting policies to enable private and public sector participation.

Overall, this study assessing the promise of plastic-to-fuel to sustainably enhance both energy access and plastic waste management in Malawi will generate actionable, empirical insights to inform policy and investment decisions. The knowledge produced could be pivotal in unleashing innovative solutions to two of Malawi's most pressing and interconnected development challenges.

CHAPTER 2: LITERATURE REVIEW

2.0. Chapter introduction

Pyrolysis of plastic waste into usable fuels has emerged as a sustainable solution to address the mounting plastic waste crisis (Rashid et al., 2019). This literature review examines current research on converting plastics like polyethylene and polypropylene into liquid pyrolysis oil that can be further refined into fuels like gasoline and diesel.

The chapter overviews suitable plastic types, typical pyrolysis product yields, key processing parameters like temperature and catalysts, and fuel properties of the resulting oil.

2.1. Plastic Pollution and Energy Deficit in Malawi

Malawi faces the dual challenges of managing plastic waste pollution while simultaneously confronting a severe energy deficit. As in many other developing countries, plastics have become ever-present in product packaging, containers and single-use items (Thompson et al, 2009). However, as Turpie (2019) noted, insufficient waste collection infrastructure and limited recycling facilities mean that a significant proportion of post-consumer plastic waste is disposed of through uncontrolled dumping or burning. The four principal urban centers of Malawi - Lilongwe, Blantyre, Zomba, and Mzuzu - collectively generate over 1,000 tons per day of municipal solid waste between their aggregated populations of approximately 1.5 million residents (Griffin et al., 2022)

Malawi's waste management infrastructure has failed to keep pace with the rising tide of plastic waste being generated by growing household consumption. Studies indicate that only around 42% of total plastic waste is properly collected through municipal systems, likely an overestimate (Turpie et al., 2019). This haphazard disposal enables large volumes of plastic waste to readily enter and accumulate in the natural environment.

On the other hand, Malawi has no operational oil refineries and instead relies almost entirely on imported refined petroleum products. Approximately 97% of refined fuels utilized in Malawi are brought in from abroad, with the remaining 3% consisting of locally-produced ethanol blended with gasoline at a 20:80 ethanol to petrol ratio (Gamula et al., 2013). The lack of domestic refining capacity coupled with complete import dependency for meeting fuel demands makes Malawi highly vulnerable to global oil price shocks and supply disruptions.

Malawi's heavy dependence on imported petroleum products combined with its landlocked location and inadequate transportation infrastructure leaves the country susceptible to fuel shortages. With minimal storage capacity and costly fuel imports that burden foreign exchange reserves, disruptions in the fuel supply chain readily produce long queues at filling stations and hamper economic productivity as occurred in 2011 (Johnson & Jumbe, 2013).

Developing localized plastic-to-fuel conversion systems could bolster Malawi's energy security while simultaneously addressing plastic pollution, reducing reliance on uncertain foreign petroleum imports transported over long distances.

2.2. Pyrolysis as a Viable Plastic-to-Fuel Conversion Technique

Of the various plastic-to-fuel conversion techniques, pyrolysis has emerged as the most viable option (Lubongo et al., 2022).

Other techniques involved in obtaining usable fuel from plastics include; gasification, depolymerization, hydrogenation, thermal degradation under microwave, thermal cracking/cohydrogenation hydrothermal liquefaction, and aqueous phase hydrodeoxygenation (Al-Fatesh, et al., 2023; Miao, von Jouanne, & Yokochi, 2021; Ali, et al., 2022).

Many researchers (Radhakrishnan, et al., 2023; Shahnawaz, Sangale, Daochen, & Ade, 2022) have discovered that among these, pyrolysis is the most effective and commonly

used technique for converting plastic waste into fuel, because, it is a simple, clean and cost-effective process that can handle a wide range of plastic waste types.

By definition, **Pyrolysis** is the thermochemical decomposition of plastics at elevated temperatures, in absence or little supply of oxygen, into a range of useful products: gas, liquid, and solid residue (Kafle, Gaire, & Tuladhar, 2023), with the fuel's energy content depending on the plastic material's calorific value (Schwarz, et al., 2021).

Plastic waste is collected as the raw material and then pretreated to remove any impurities before conversion into fuel. The pretreated plastic is ground into small pieces of the desired size to enable smooth and efficient reactions later in the process.

The pyrolysis chamber or reactor is loaded with the ground plastic and an appropriate catalyst to promote specific chemical reactions. The absence of oxygen is important to prevent combustion and to ensure that the plastic waste is broken down into smaller molecules.

Fahim, Mohsen and ElKayaly (2021) pointed out that the temperature in the chamber ranges from 200-900°C depending on the desired quality of the liquid oil product, but usually about 500°C (900°F). The plastic first melts and then vaporizes in the chamber.

The vapors are condensed into a liquid oil through a series of condensers. This oil undergoes further refining to produce the final multipurpose fuel product that can be categorized as a biofuel depending on the initial plastic waste source.

The pyrolysis oil produced can be purified using methods such as vacuum distillation, fractional distillation, decontamination technology, and adsorption. The purified pyrolysis oil can be used as an industrial fuel, for combustion in boilers and furnaces, for electricity generation, for refining into diesel fuel, and for the production of chemicals.

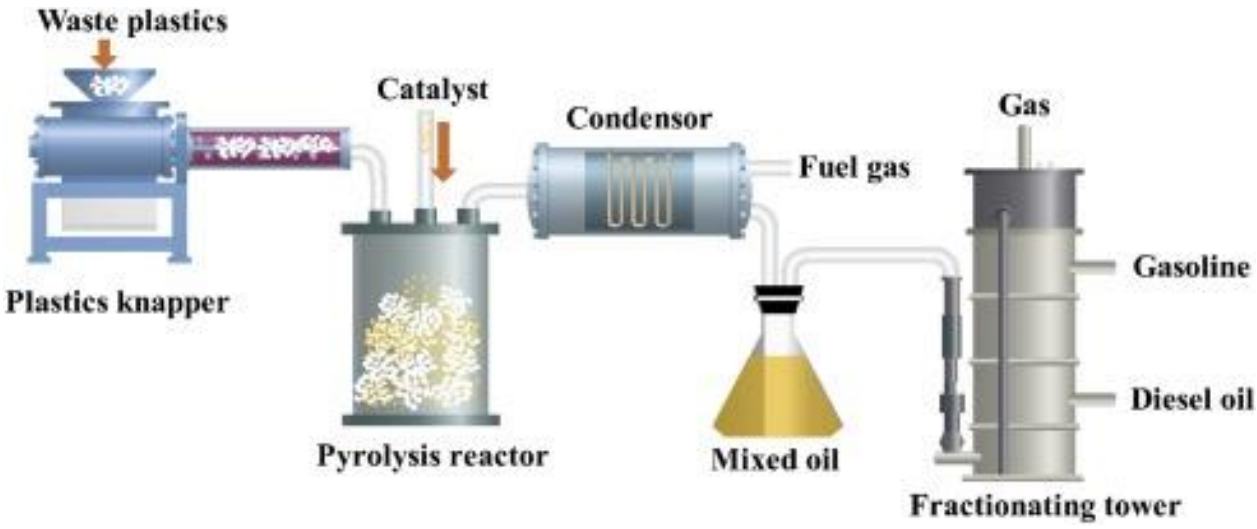


Fig 2.1. Flowchart of plastic waste pyrolysis process. (Maqsood, Dai, Zhang, Guang, & Li, 2021)

The primary focus in pyrolysis is on the liquid product, and its characteristics are influenced by various factors, including the temperature of pyrolysis and the rate at which heating occurs (Basu, 2018).

2.2.1. Products of Pyrolysis

Dai et al (2022) indicate that the pyrolytic conversion of plastics to fuel results into three main categories of products;

1. **Liquid products**, which encompass tars, heavier hydrocarbons (which can be further refined into gasoline, diesel, and other fuels), and water.
2. **Solid products**, predominantly composed of char or carbon and wax.
3. **Gaseous products**, which consist of substances like CO_2 and CO

The proportions of these product types are determined by various factors, including the rate at which heating occurs and the final temperature reached by the plastic feedstock.

2.2.2. Types of Pyrolysis

It has been established that there are three broad categories of pyrolytic reactions distinguished by the duration and temperature at which plastics are processed: slow pyrolysis, fast pyrolysis, and flash pyrolysis (Patni et al., 2013; Papari & Hawboldt, 2015):

Slow pyrolysis occurs at 350-550°C with slow heating rates of 1-10°C per minute and longer vapor residence times. It primarily produces char. The slower heating favors solid char formation over other reactions.

Fast pyrolysis uses very high temperatures of 500-700°C with ultra-fast heating exceeding 1000°C per minute. Vapors only remain for seconds. It yields very high quantities of liquid oil, up to 90% for plastics.

Flash pyrolysis operates at very high temperatures above 700°C with extremely fast heating. Vapor residence times are just milliseconds. For biomass, it can produce more oil than fast pyrolysis. For plastics, it generates more gas than other products.

2.3. Plastics as Feedstock for Fuel Production

Typically, plastic materials are non-biodegradable and are primarily produced for single-use purposes, using petrochemical sources like naphtha, ethylene glycol, styrene, ethylene, and propylene, all of which are derived from crude oil (Al-Salem, Lettieri, & Baeyens, 2009). Plastic waste contains various hydrocarbons with a substantial amount of chemical energy that can be harnessed to meet energy demands. It is estimated that recycling all plastic waste worldwide could yield an energy equivalent to 3.5 billion barrels of oil each year (Singh, Ruj, Sadhukhan, & Gupta, 2019a).

Generally, there are six major types of plastics, each with unique properties and characteristic (Worrell & Vesilind, 2002), and all these can be found in Malawi;

1. **Polyethylene terephthalate (PET)**: PET is a common plastic used in beverage bottles and food packaging.
2. **High-density polyethylene (HDPE)**: A very resistant resin used for grocery bags, milk jugs, recycling bins, agricultural pipe, toys, lids, and shampoo bottles among others.

3. **Polyvinyl chloride (PVC)**: It comes in two basic forms: rigid and flexible. In its rigid form, PVC is largely used in the building and construction industry to produce door and window profiles and pipes (drinking and wastewater).
4. **Low-density polyethylene (LDPE)**: Used for manufacturing grocery bags, bread bags, shrink wrap, coatings for paper cups and cartons, etc.
5. **Polypropylene (PP)**: Used for manufacturing reusable containers such as Tupperware, medicine bottles, yogurt containers, etc.
6. **Polystyrene (PS)**: Used for manufacturing disposable cups, plates, cutlery, CD cases, etc.
7. **Other plastics**: This category includes all other types of plastics that do not fall under the above six categories such as polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS), etc.



Fig 2.2. Different types of plastics (http://www.bestpyrolysisplant.com/uploads/191219/1-1912191134aD.jpg)

The type of plastics that are most suitable for conversion to fuel depend on the specific method used for the conversion process.

2.3.1. Most Suitable Plastics for Pyrolysis

Ghodke, et al (2023) noted that Pyrolysis can convert a wide range of plastics, including **high-density polyethylene** (HDPE), **low-density polyethylene** (LDPE), **polypropylene** (PP), and **polystyrene** (PS), into fuel products. The mentioned plastics have a high carbon and hydrogen content and are commonly used in consumer products such as packaging, containers, and disposable utensils. The fact that they have a high carbon and hydrogen content is important for their potential conversion to fuel, as these elements are the primary components of many types of fuel such as diesel, gasoline, and kerosene.

Many studies have pointed out that polyethylene(PE) has the highest oil yield; that includes high-density polyethylene (HDPE) and low-density polyethylene (LDPE). The oil yield for PE can reach about 94% (Fahim, Mohsen, & ElKayaly, 2021)

Now, the **calorific value** of fuels is a measure of amount of energy that can be obtained from the fuel when it is burned completely. The calorific value is an important factor in determining the usefulness of a fuel for energy production. Fuels with a high calorific value are more energy-dense and can produce more heat per unit of fuel than fuels with a lower calorific value (Jahirul, et al., 2022).

2.4. Factors affecting Fuel production from Plastics

Various factors, such as temperature, retention time, feedstock composition, moisture content, catalyst choice, reactor type, pressure, and carrier gases, among others, play a significant role in the quality, quantity, reaction time, and distribution of the products in the pyrolysis of waste polymers (Gao et al., 2012; Aguado et al., 2007; Karthikeyan et al., 2016). These factors also have an important impact on the proportion of by-products,

including gas and char, in the pyrolysis process during plastic waste conversions (Radhakrishnan et al., 2023).

2.4.1. Temperature and Heating Rate

Temperature is the most critical factor in plastic pyrolysis to fuel (Gebre et al., 2021). Typical temperature range is 300-900°C based on plastic type and desired product (Kiang et al., 1980). With optimized heating rate, temperature, and product evacuation, oil yield can reach 80% (Basu, 2018). Slower heating and lower temperatures increase char. Faster heating and higher temperatures boost gas yields. For maximum liquid oil, higher heating rates, moderate temperatures, and brief residence times are ideal.

2.4.2. Catalysts

As already explained, the use of catalysts can improve the pyrolysis process of plastic waste overall and enhance process efficiency. They have a pivotal role in optimizing process efficiency, directing specific reactions, and reducing both process temperature and duration (Serrano, Aguado, & Escola, 2012).

The most extensively used catalysts are ZSM-5, zeolite, Y-zeolite, FCC, and MCM-41. The use of low-cost catalysts like zeolite, clay, and bimetallic material has also been highlighted in recent research (Fadillah et al., 2021), and this would be a good consideration in Malawi, for economic purposes.

Hafeez and colleagues (2019) have highlighted the significant interest in catalytic conversion of plastic solid waste as a process that avoids generating harmful gases and produces lower carbon monoxide and carbon dioxide emissions compared to other plastic waste treatment methods.

2.4.3. Type of Plastics

The composition of plastic waste feedstock influences pyrolysis outcomes. Different plastics have distinct structures, impacting quantity and properties of products. PP is a preferred feedstock, giving superior oils for engines versus other plastics. However, plastics like PVC and polyethylene yield low quality oils. Some plastics like PVC form harmful HCl and can

damage the reactor in the process (Kabeyi & Olanrewaju, 2023). Feedstock choice is key for optimizing oil yield and quality while minimizing hazardous emissions.

2.4.4. Residence Time

Mastral et al (2002) in their study, pointed out that high moisture content in plastic waste feedstock can hinder pyrolysis. The heat first evaporates water before plastics decompose at higher temperatures. This leads to incomplete pyrolysis and lower yields. Moist feedstock also takes longer to heat up, delaying the pyrolysis reaction. Moreover, generated water vapor alters reactions, producing more oxygenated oil compounds instead of pure hydrocarbons. Pre-drying or blending moist plastic waste improves pyrolysis efficiency.

This is why pre-drying moist plastic waste or blending it with drier materials is needed, as it adds up to the effectiveness of the process.

2.4.5. Pressure

The pressure within the pyrolysis reactor can influence both the quantity and characteristics of the pyrolysis products. Elevated pressure conditions tend to result in increased liquid oil production, whereas lower pressure conditions are more likely to yield higher quantities of gas (K. Radhakrishnan, et al., 2023).

The effect of pressure on pyrolysis of plastics to fuel is rarely explored in the literature and needs to be addressed in detail (Pal et al., 2022)

2.5. Characterizing and Improving the Final Products

In the “Recent Trends in the Pyrolysis of Non-Degradable Waste”, Gabre and colleagues (2021), noted that the oil resulting from the condensation of pyrolytic gases exhibits properties that closely resemble those obtained from solid feedstock. Both can provide usable energy through their calorific value alone, making them candidates for applications like electricity generation without additional processing.

Gebre further noted that the pyrolysis oil is less stable for long-term storage due to the fact that it is mixed with oxygenated compounds. The pyrolysis oil produced can be further refined through additional processing, similar to how crude oil is processed in petroleum refineries to produce fuels like gasoline and diesel.

To maximize the yield of liquid hydrocarbon products from pyrolyzing polymer feedstocks, the process should utilize lower temperatures, faster heating rates, and brief gas residence times (Gebre et al., 2021).

2.5.1 Blending Pyrolysis Oil with the Conventional Fuels

Currently, in Malawi, it is not feasible to refine pyrolysis oil into finished fuels, given the lack of existing refining infrastructure and economic constraints. However, blending the crude pyrolysis oil with conventional fuels could offer a more viable alternative for utilizing the pyrolysis products as transportation fuels in Malawi's context.

Fuel blending involves mixing alternative fuels with conventional petroleum-based fuels in specific proportions to reduce overall petroleum content. According to three studies (Krutof & Hawboldt, 2016; Pozarlik, Pander, & Brem, 2011; Szwaja, et al., 2021), Pyrolysis oil can also be blended with diesel oils to enhance its fuel properties, it can be blended with alcohols and diesel to improve its properties for combustion in gas turbines and it can also be blended with ethanol to be used as a fuel for spark-ignition engines.

This method could potentially be applied in Malawi using the crude pyrolysis oil and locally available conventional fuels. With basic blending infrastructure, the pyrolysis liquid could be utilized without the need for full-scale refining capabilities. Blending pyrolysis oil with other fuels can help overcome some of the challenges associated with using pyrolysis oil as a fuel, such as high viscosity, delayed ignition time, low heating value, corrosion effect, and solid content, just as the aforementioned studies show.

CHAPTER 3: METHODOLOGY

3.1. Research design

The research employed a quantitative approach to address the objectives of the study. This involved analyzing the characteristics of plastic waste samples, categorizing them and conducting experiments on plastic pyrolysis. Finally, the properties of the resulting products were examined, and an evaluation was made to compare the energy output from plastic pyrolysis with that of conventional fuels in Malawi.

Since the main objective was to conduct a comprehensive investigation of the potential and feasibility of fuel production from plastic waste in Malawi, locally available materials were used wherever possible and necessary, in place of expensive equipment, while also making sure they don't compromise the process.

3.2. A Small Scale Pyrolysis Experiment

The feasibility study involved setting up a small-scale pyrolysis experiment to convert plastic waste samples collected into pyrolysis oil.

2 kg of plastic waste was obtained through stratified random sampling from a municipal dumpsite. The sample contained a mix of High-Density Polyethylene (HDPE), polypropylene (PP) and polyethylene terephthalate (PET) plastics as determined by visual inspection and water floatation. The waste was shredded, cleaned, dried for 24 hours, and manually cut into small pellets using scissors and knives, in preparation for pyrolysis.

What was utilized as a pyrolysis reactor was a cube-shaped chamber made of welded steel sheet metal. Originally constructed to serve as part of an industrial machine, the steel cube was repurposed for this project to act as the reactor. One side of the box was fitted with a removable, tightly bolted lid to allow the plastic waste sample to be loaded inside. One pipe was attached to the top of the reactor box to serve as the outlet line. An electric

furnace heated the steel reactor box to conduct the pyrolysis reaction on the plastic waste sample contained within.

The temperature was set to 300 °C , as Fahim, Mohsen and ElKayaly (2021) pointed out that the temperature in reactor should range from 200-900°C.

The pyrolysis vapors were condensed using a water-cooled condenser attached to the reactor outlet pipe. The condensed liquid oil was collected for analysis. The experiment yielded approximately 700 ml of pyrolysis oil along with some char residue.

The collected samples of pyrolysis oil from different plastic types were analyzed in the lab.

The byproducts like char, gas, and syngas also have useful applications. The char can be blended into asphalt, used to manufacture bricks or as a solid fuel.

Figures 3.1, 3.2, 3.3, and 3.4, show the experimental set up of the pyrolytic conversion of plastics to liquid oil, which followed the schematic diagram in figure 1 in the literature review.



Fig 3.1. A steel cube repurposed as a reactor



Fig 3.2. Condensation chamber



Fig 3.3. Sample collection point

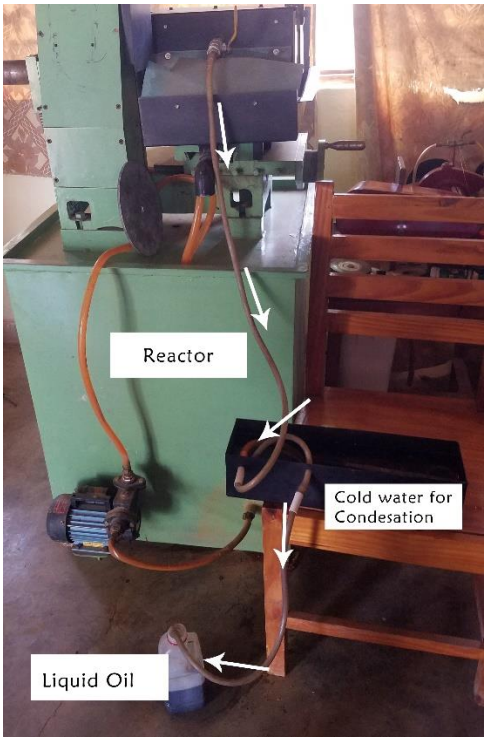


Fig 3.4. Full experimental setup

3.2. Plastic Characterization Methods

A Fourier Transform Infrared Spectroscopy (FTIR) Analysis was supposed to be used to determine the polymer composition of the plastic waste sample (Leri & Pavia, 2022), but it requires expensive and specialized equipment, as such, a low-cost alternative method for determining plastic types was visual inspection and water floatation, as mentioned.

Visual inspection involved examination of properties like opacity, rigidity, and texture. Generally, PET bottles are clear and rigid. Shopping bags are often transparent LDPE with high flexibility. Marks and labels are also indicators. Recycling codes (numbers in the triangular arrow) identify plastic types. Some items have plastic polymer abbreviations molded into the product.

Whereas. water Floatation is a simple separation technique which takes advantage of the different densities of plastic polymers, where plastics are shredded into small flakes. The flakes are placed in water and agitated. Less dense PE and PP float while PET and PVC sink.

Though not as definitive as FTIR, these basic hands-on methods could allow Malawian small-scale waste processors to roughly characterize and separate their plastic feedstocks into broad polymer categories like PE, PP, PET and PVC for pyrolysis applications. The use of these alternatives add up to the feasibility of fuel production from waste plastics in a developing country.

3.5. Apparatus for Sample Analysis

The parameters of interest when testing the liquid product of each plastic type were as follows: Density, viscosity, water content, elemental composition, and calorific value.

The testing of these parameters helped to evaluate the quality and viability of the pyrolysis oil as a fuel product. They also help to identify contaminants and properties that need to be addressed through further processing and upgrading to meet fuel standards. And the resultant data can help to optimize the pyrolysis process for maximum oil yields and quality.

Below are the apparatus/methods for each of the parameters:

Density (g/ml): A hydrometer was used.

Water content (wt%): Moisture content loss was measured upon heating the samples

Viscosity (cSt): A glass capillary viscometers was used.

Calorific value (MJ/KG): The heat released from the known mass of oil burning was measured

CHAPTER 4: RESULTS AND DISCUSSION

This chapter presents the test results of key physicochemical properties measured for different pyrolysis oil samples produced from HDPE, PET, PS and Mixed plastics under the reactor temperature of 300°C. The specific parameters analyzed include density, viscosity, water content, and calorific value.

The properties and quality of the oil depend heavily on the pyrolysis conditions and the feedstock plastic types. Thorough characterization and analysis are crucial to determine the viability of pyrolysis oils for engine and fuel applications.

4.1. Results from different plastics

Fig.4.1. Samples collected from different plastic types

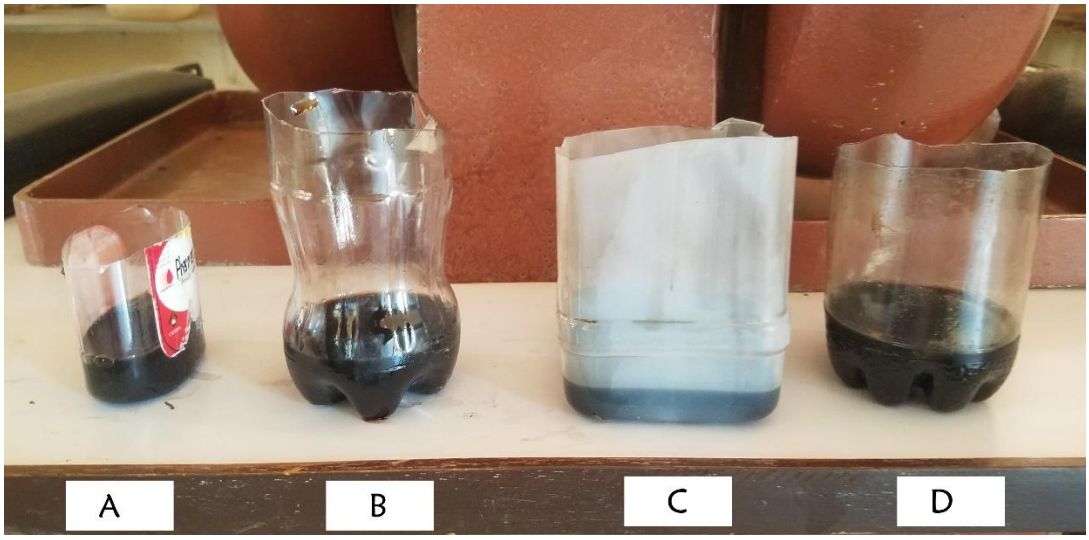
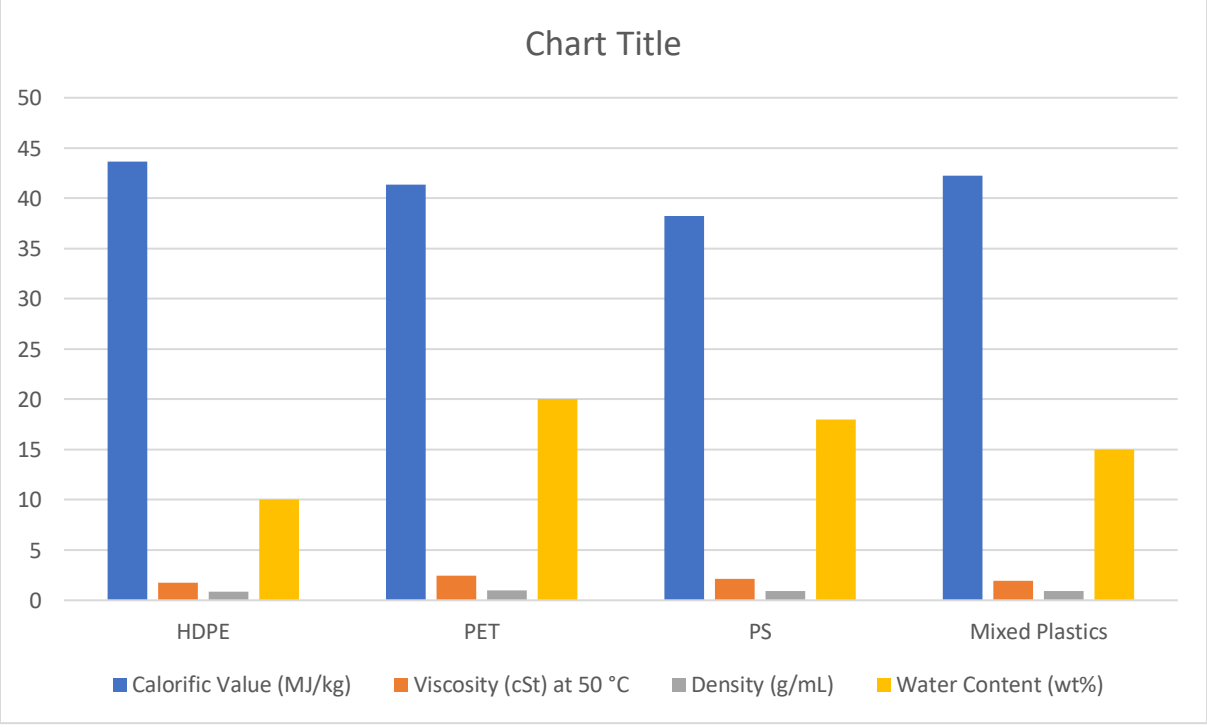


Table 4.1: Results of properties of pyrolysis oil from different plastic types

Property	HDPE	PET	PS	Mixed Plastics
Calorific Value (MJ/kg)	43.67	41.34	38.25	42.28
Viscosity (cSt) at 50 °C	1.75	2.43	2.15	1.92
Density (g/mL)	0.88	0.96	0.94	0.92
Water Content (wt%)	10	20	18	15

Figure 4.2: Bar chart showing properties of pyrolysis oil from different plastic types



The test results in Table 4.1 showcase some key fuel properties of the pyrolysis oils derived from various plastic feedstocks.

The calorific values range between 38.25-43.67 MJ/kg, which are suitable for use as fuels. However, these are lower than petroleum fuels, indicating the presence of oxygenated compounds. The PS oil has the lowest heating value of 38 MJ/kg likely due to its higher oxygen content.

The viscosity is between 1.75-2.43 cSt at 50°C, which is close to the viscosity of diesel. PET produces the most viscous oil while HDPE oil has the lowest viscosity closer to commercial fuels. The high viscosity oils would require preheating and filtration before use in engines.

The density follows a similar trend with HDPE oil having the lowest density of 0.88 g/mL and PET oil being the densest at 0.96 g/mL. The higher density is due to larger hydrocarbon compounds and the oxygenates. This could impact the oil's flow properties.

Water content is highest for PET oil at 20% and lowest for HDPE oil at 10%. This indicates PET pyrolysis requires improved condensers to capture water vapors. High water is undesirable as it leads to microbial growth and corrosion.

The mixed plastics oil has intermediate properties, with calorific value and viscosity between that of HDPE and PET/PS oils. This is likely due to the blend containing HDPE. This highlights that the composition of the plastic waste feedstock impacts the properties of the resulting pyrolysis oil.

Overall, HDPE oil shows the most promising fuel properties among the samples tested. PS and PET oils require additional treatment to reduce viscosity, oxygen content, and water before they can meet fuel specifications.

4.2. Comparison between pyrolysis and the commercial fuels

Table 4.2: A Comparison of properties of pyrolysis oil to diesel, and petrol

Property	Pyrolysis Oil	Diesel	Petrol
Calorific Value (MJ/kg)	41.34 - 43.67	35-43	44
Viscosity (cSt)	1.75 - 2.43	2.0-4.5	0.4-0.8
Density (g/mL)	0.88 - 0.96	0.79-0.87	0.72-0.78
Water Content (wt%)	10 - 20	<0.01	0

Table 2 allows for an effective comparison between pyrolysis oil and conventional diesel and petrol fuels. Several key observations were made:

The table shows that pyrolysis oil has a comparable calorific value and viscosity to diesel fuel, indicating potential as an alternative fuel. However, the density is on the higher side and water content is significant at 10-20 wt%.

In contrast, petrol has a higher heating value with lower viscosity and density than pyrolysis oil. Both diesel and petrol limit water to trace levels.

In summary, while the calorific value and viscosity of pyrolysis oil are close to diesel, additional treatment is required to reduce density and remove water and particulates. With further refining, pyrolysis oils show good potential as alternative fuels, especially in diesel engines. This provides insights into the key differences that need to be addressed through processing optimizations to improve oil quality.

4.3. Reasons for the Poor Quality of Fuel

Several factors currently contribute to the poor quality of pyrolysis oils compared to commercial fuels:

- Impurities in plastic waste feedstocks - contaminants like paper, wood, dirt etc. lower the quality.
- Presence of plastic additives - fillers, stabilizers, pigments end up in the oil.
- Non-optimal pyrolysis conditions - insufficient temperature, residence time, rapid quenching lead to heavy tarry oils.

With proper plastic waste pre-treatment and optimized reactor design, these limitations can be addressed to significantly enhance the fuel properties of the derived pyrolysis oils.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

This research aimed to comprehensively assess the feasibility and potential of fuel production from plastic waste in Malawi using pyrolysis conversion. The study was conducted against the backdrop of Malawi's dual challenges of a severe energy deficit and a plastic pollution crisis.

The small-scale pyrolysis experiment yielded approximately 700 ml of crude pyrolysis oil from 2 kg of plastic waste. Despite the rudimentary reactor set-up and small scale experimentation, this demonstrated the fundamental viability of deriving a liquid fuel product from abundant plastic waste using pyrolysis technology.

Analysis of key fuel properties for oils derived from various plastic types revealed that HDPE pyrolysis oil exhibited the most promising characteristics including relatively low viscosity, high calorific value, low density and water content. PET and PS derived oils require further treatment to reduce viscosity, oxygenates and moisture before they can meet fuel quality standards.

While the pyrolysis oils obtained currently fall short of commercial fuel specifications, this is attributable to limitations in feedstock purity, suboptimal pyrolysis conditions, and lack of upgrading. Nonetheless, the results verify the potential to extract a usable oil from plastic waste via pyrolysis.

Blending the crude pyrolysis oil with conventional petroleum fuels could offer a pragmatic way to utilize the pyrolysis products as transportation fuels in the Malawian context, without the need for costly dedicated refining infrastructure.

The research concludes that converting the mounting plastic waste in Malawi into a domestic energy source is technically feasible. Pyrolysis can produce a usable bio-oil from

plastic waste that can potentially be blended with other fuels or further refined into finished products like gasoline and diesel.

Realizing this potential will require optimizing pyrolysis systems for the prevalent plastic types generated locally in Malawi. It will also necessitate effective plastic waste collection and separation systems to ensure consistent feedstock quantity and purity.

Scaling up pyrolysis-based plastic-to-fuel conversion in Malawi could deliver far-reaching benefits for citizens across the country. On an individual level, accessing cleaner, lower-cost, domestically produced plastic-derived fuels could greatly improve energy affordability for Malawian households and businesses. This would alleviate burdens from frequent fuel shortages and price hikes that currently disrupt transportation, agriculture, industry and everyday activities for many citizens.

Additionally, the new value chain from plastic waste collection to fuel production can create green jobs and entrepreneurship opportunities in both cities and rural areas. The environmental and public health benefits from proper plastic waste management through pyrolysis will further improve quality of life. Overall, wide-scale adoption of plastic-to-fuel systems tailored for Malawi could catalyze substantial socioeconomic development that uplifts and empowers citizens across the country. The multi-pronged benefits make a compelling case for exploring and investing in this local energy solution.

5.2. Recommendations

Based on the research findings, the following recommendations are proposed, especialily in the context for scaling up plastic-to-fuel conversion in Malawi:

5.2. 1. Policy and Regulation

Comprehensive national standards and regulations need to be developed specifically for the production, testing, and blending of pyrolysis fuels to ensure quality control as this new alternative fuel comes online. The standards should establish specifications for fuel

properties, production protocols, blending ratios, and safety procedures to guarantee high quality consistent output from pyrolysis facilities.

Providing incentives like tax rebates and subsidies will also be pivotal to enabling substantial private sector investment into commercial-scale plastic-to-fuel facilities. The incentives can help improve the financial viability and may be necessary initially before pyrolysis fuel production becomes independently cost-competitive. However, the incentives should be designed to support genuine sustainable operations rather than waste-to-energy facilities merely chasing subsidies. Well-designed regulations and incentives can mutually reinforce each other to stimulate responsible private sector participation that scales up high-quality pyrolysis fuel production using plastic waste feedstocks.

5.2. 2. Technology and Infrastructure

Several key infrastructure and technology investments and optimizations will be needed to actualize plastic-to-fuel systems tailored for Malawi. Reactor design and pyrolysis parameters including temperature, catalyst use, and gas residence time must be optimized to maximize fuel yields from the specific plastic waste types generated locally.

Sorting facilities are essential to guarantee consistent, high-quality feedstock supply to pyrolysis plants. Starting with small, decentralized pyrolysis units in urban centers can enable building technical experience and cost efficiencies before scaling up production capacity.

As a priority, infrastructure must be constructed for blending raw pyrolysis oil with conventional fuels and distributing the blended products to Malawi's transport sector. This blending and distribution infrastructure will be pivotal to channeling usable pyrolysis fuel to reach consumers. A phased approach focused on optimizing technology and engineering solutions for Malawi's context and needs will best facilitate wide-scale, sustainable adoption of plastic-to-fuel systems.

In summary, a supportive policy environment, targeted funding and incentives, infrastructure development, and capacity building are needed to actualize the potential benefits of plastic-to-fuel in helping advance Malawi's development objectives. This

emerging opportunity warrants dedicated efforts to pilot, evaluate and scale a solution tailored to local conditions.

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