Available online at https://asric.africa/engineering-sciences
ASRIC Journal on Engineering Sciences Vol.6(1)(2025) 206-227

Investigating the Technical Feasibility of Plastic Waste Conversion to Fuel Using Pyrolysis

Tukahiirwa Isabel, Ssemaziga Trevor Benon, Bwambale Roice Kalengyo

Ndejje University, Kampala, Uganda;
1006762415@stud.ndejjeuniversity.ac.ug, 1006763051@stud.ndejjeuniversity.ac.ug;
rbwambale@ndejjeuniversity.ac.ug

Corresponding Author: 1006762415@stud.ndejjeuniversity.ac.ug

Received 10 July 2025; revised 20 August 2025; accepted 23 October 2025

Abstract

With the increasing plastic pollution worsening Africa's environmental and climate crises (NEMA, 2024), existing pyrolysis research overlooking scalable, low-cost solutions for mixed plastics (Al-Salem et al., 2017), this research addresses this gap by developing a simple modular pyrolysis system and using locally sourced catalysts to convert plastic waste into fuel. Plastic waste was sorted using recycling codes (HDPE, LDPE, PP and PS), cleaned and shredded. A cylindrical metallic reactor with a rocket stove improved heating efficiency and plastic breakdown into liquid fuel, usable byproducts like combustible gas (syngas), and char residue. Heating was done in anoxic conditions to yield 70 – 96% liquid oil, with PP achieving the highest yield (96%). Locally sourced sugarcane bagasse ash was tested as a cheaper catalyst vs. activated carbon to boost fuel quality and cut energy use. (Hassan et al., 2019) Emissions tests showed safe levels of CO and NOx that fell within acceptable limits. This work highlights a promising way to reduce plastic pollution and create useful energy in Africa (NEMA, 2024), but requires better tools and support to scale up.

Keywords: Plastic waste, Pyrolysis, Bagasse-ash, Activated-carbon, sustainable

1. Introduction

"Over the past 150 years, plastic materials have played a significant role in fostering innovation and advancing societal advancement", quoted from PLASTIC EUROPE. Plastic known for its unique properties that have led to its un-arguably important role in society, calls for further attention as its production, consumption and disposal result in significant negative impacts on the public, the environment, and the economy. (Wijnand et al., 2021)

Due to plastics' seemingly cheap price and flexibility, plastic has been increasingly used across millions of applications. This has caused plastic production to double over the past twenty years. (Geyer, 2020) Its production releases chemical pollutants and greenhouse gases (GHG) that lead to adverse health complications in humans and contribute to climate change. (Azoulay, 2019)

As of research published in 2021 by WWF – World Wide Fund for Nature, it found that in a year, over 11 million tonnes of plastic intrude into the ocean which results in pollution that threatens marine life, distorting the eco-system and thus damaging key economic industries such as fisheries and tourism. This quantity of waste is equivalent to dumping the contents of one garbage truck into the ocean each minute. If there is no immediate intervention to these poor waste handling practices, the leakage is expected to increase to two trucks per minute by 2030 and even four per minute by 2050. The research further said that, these impacts create significant costs for society that the market price of plastic doesn't try to account for because of its detrimental effects that can be said to be inversely proportional to the plastic market price. The lifetime cost of the plastic produced in 2019 was estimated to be US$3.7 trillion and more which is a worrying cost to pay as it can be said to even be higher than the GDP of India. (Wijnand et al., 2021)

With the current production of single use plastics, any increase in the manufacture inevitably results in increase in plastic waste. The challenge with the waste is that it is either disposed of via processes that can also release chemical pollutants contributing to climate change, or leaks into the waterbodies and soil. (Wong et al., 2015)

It is impossible to overestimate the negative effects of pollution, especially during these current times where research is highly prioritized and funded by major donors like Bill & Melinda Gates Foundation. For instance, it has been noted that even a small decline in air quality due to pollution greatly affects bee behavior in the wild, disrupting their vital roles in the ecosystem and endangering the availability of food. (Thimmegowda et al., 2020)

In addition to that, it has been discovered that there is a strong link between community exposure to toxic emissions linked to environmental pollutants and congenital abnormalities. According to a recent study, environmental pollution is a probable cause for the decline in the quality of breast milk among nursing mothers exposed to open burning of plastics as it gives off pollutants like polychlorinated biphenyls (PCBs) that have the potential to disrupt the natural balance of a mother's milk as well as change in its composition which can have negative health effects on nursing children, including allergies, endocrine abnormalities, and impaired neurodevelopment. (Pajewska-Szmyt et al., 2019)

Plastic waste is converted to fuel via thermal and catalytic processes with the aims of reducing refuse that is harmful to the environment and also to reduce on the level of dependency on the conventional fuels say fossils. (Kunwar et al., 2016)

Consumer plastics are largely made from six different polymer resins, which are indicated by a number, or resin code, from 1 to 7 molded or embossed onto the surface of the plastic product i.e. PET, HDPE, PVC, LDPE, PP, PS and all other resins. (Rudolph, 2017)

Plastic waste is anything in the form of plastic that is rendered useless by the consumer. Plastics characterized by their inherent non-biodegradable nature have posed a catastrophic threat to the environment due to their abundance in the waste stream. The continued littering of the environment with plastic wastes and has led to critical challenges such as clogging of drains and has escalated health-related issues. Therefore, their abundant presence in the waste stream poses critical challenges especially without effective waste management. (Idumah & Nwuzor, 2019)

The proposed solution to the plastic waste pollution is plastic waste conversion to fuel by pyrolysis.

Plastic waste conversion to fuel can be done using methods like pyrolysis, gasification and hydrocracking but this study will be limited to pyrolysis as the conversion process.

Pyrolysis process is carried out in a controlled environment which is cut off from oxygen supply, and thus it does not give off dioxins like gasification does because of products reacting with oxygen. Pyrolysis' main product is oil that can be used for heating purposes and other by-products, such as char, and gas. It comprises of a series of thermochemical reactions that break down long chain plastic molecules in the absence of oxygen. The yield and composition of products depends on the type of plastic waste feedstock, residence time, temperature, pressure, reactor system, and catalysts. (Salaudeen et al., 2018)

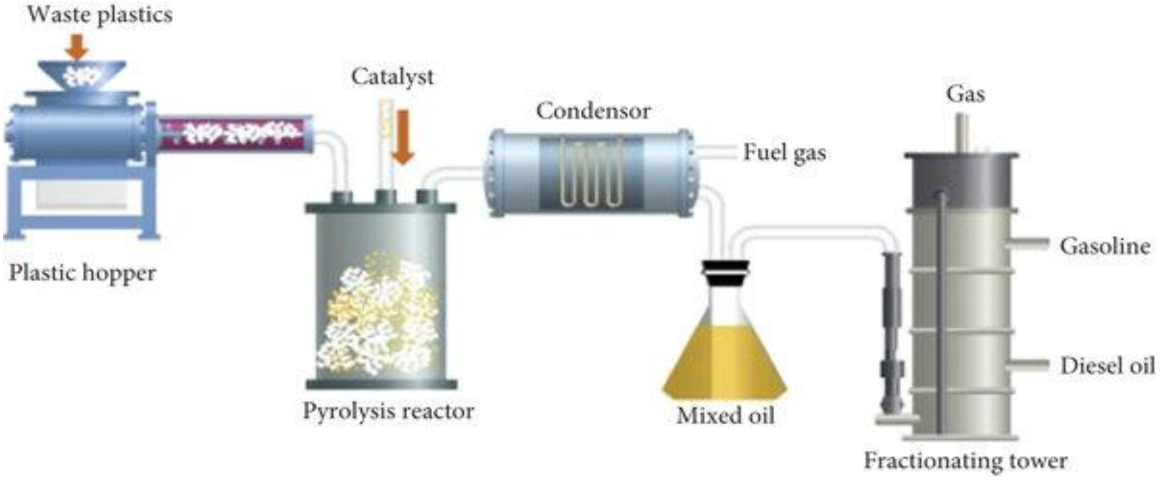


Fig. *1* shows plastic pyrolysis process (Kabeyi & Olanrewaju, 2023)

The conversion rate of plastic waste into liquid oil was found to be up to 80wt%, says (Kumar et al., 2023) and whatever is obtained from it can be affected by the parameters of pyrolysis. These include, plastic waste feedstock composition, temperatures used, presence or absence of a catalyst and the type of reactors.

A) Temperatures

The effect of temperature on the pyrolysis process is very crucial in the breakdown of the plastic bonds into smaller molecules. At an increase in temperature, the conversion process yields more of a gaseous product. At a decrease in temperature, more of a liquid product is yielded. (Umunakwe et al., 2021) Different types of plastics require specific temperatures to be broken down into specific proportions of liquid, gas, and residue. For example, according to (Murthy et al., 2023), PS heated at a temperature of 450ºC, yielded 80.8% liquid, 13.1% gas, and a residue(char) 6.1%. HDPE heated at 400ºC, yielded 81.5% liquid, 17.8% gas, and residue(char) 0.7%. PS+PP+PE heated at 450ºC, yielded 38% liquid, 40.6% gas, and residue(char) 21.4%.

B) Catalysts

In the pyrolysis process, catalysts not only speed up the reaction, but also improve the reaction rate to obtain the maximum pyrolysis oil with diesel or petrol like properties. (Murthy et al., 2023) FCC (Fluid Catalytic Cracking), zeolites and silica-alumina catalysts are commonly used. FCC catalysts can produce liquid oil of around 90wt% for HDPE and PP pyrolysis while the maximum oil yield via silica-alumina for HDPE and PP was in the range of 85-87wt%.(Banu et al., 2020) Silica-alumina catalysts are amorphous and come in different types like; SA-1, SA-2, and ZSM-5. SA-2 catalyst with lower acidity produced a maximum quantity of liquid oil (74.3wt%), while ZSM-5 catalyst with lower acidity produced lower quantity of liquid oil (49.8wt%). (Miandad et al., 2016)

C) Plastic waste feedstock

The various categories of plastics have different compositions that influence the pyrolysis process and the product contents. The compositions are the approximate moisture, volatility, fixed carbon, and ash contents or available elements. The ash content and volatile matter significantly influence the pyrolysis and thus more oil is produced when plastic gives off high volatiles, while there is a less oil yield with increase in ash content. (Abnisa & Wan Daud, 2014).

According to (Murthy et al., 2023), the various plastics exposed to different temperatures yielded the following percentages of liquid, gas and residue/char.

Table 1 below shows various plastics reacting to different pyrolysis temperatures. (Murthy et al., 2023)

Material	Operating temperature	Yield		
		Liquid	Gas	Char/Residue
PS	450	80.8	13.1	6.1
HDPE	400	81.5	17.8	0.7
LDPE	400	81.4	16.6	2
PP	375	82	17.3	0.7
PS+PP	450	50	39.8	10.2
PS+PP+PE	450	38	40.6	21.4
PE+PP	500	34.2	8.1	57.7
LDPE + Sugarcane bagasse	500	52.75	12	35.25

D) Reactor type

The choice of reactor also has a significant impact mainly when mixing plastics with catalysts, as it affects heat and mass transfer as well as residence time that further influences the product yield. The batch and semi-batch reactors have a relatively easy operation, simple design and makes it easier to control process parameters. Therefore, they are suitable as a prototype. (Yang et al., 2022) Horizontally placed reactors provide a high surface area to volume ratio which enables uniform transfer of heat with in the reactor thus suitable for the pyrolysis process. (Wong et al., 2015)

Pyrolysis is of three types namely;

i) Thermal pyrolysis

The break-down of long chain polymeric materials into smaller molecules in the absence of oxygen at a temperature range of 350◦C to 900◦C is known as thermal pyrolysis or thermal cracking. The by products are a carbonized char and a volatile fraction that may be separated into condensable liquid hydrocarbons, such as paraffins, isoparaffins, olefins, naphthenes, aromatics and a non-condensable gas. (Phanisankar et al., 2020) Thermal pyrolysis occurs in the absence of a catalyst and requires high temperatures in order to break the polymer compared to catalytic pyrolysis. (Moorthy et al., 2020)

ii) Catalytic pyrolysis

As the name suggests, a catalyst is used to speed up the process. This type of cracking is the break-down of long chain polymeric materials into smaller molecules in the absence of oxygen and presence of a catalyst. Catalytic pyrolysis can produce the same energy compositions as that of thermal pyrolysis but at low temperatures. This type of cracking also provides better selectivity of product yields by just modifying the catalysts. (Moorthy et al., 2020)

Fig. 2 shows the difference between oil formed in the absence and presence of a catalyst

iii) Hydro pyrolysis

This type of cracking chemical process is used in petroleum refineries for converting the high boiling constituent hydrocarbons in petroleum crude oils to more valuable lower boiling fractions such as petrol, diesel, kerosene and temperatures range 260–425ºC, pressures 35–200 kg/cm^2. Several catalysts used in hydrocracking reaction in refinery include transition metals such as Platinum, Nickel, Molybdenum, iron. These catalysts incorporate both cracking and hydrogenation activities to obtain gasoline and diesel. (Phanisankar et al., 2020).

Step-by-step pyrolysis process explained as follows;

The active pyrolysis activity kicks off when the heating system is initiated and as soon as the temperatures are high enough and the carbon atoms attain the respective required bond dissociation enthalpies then the atoms become unsteady and the bonds break thus changing from solid phase to molten phase and then to vapor state. With the polymers in vapor state, the vapor rises over the molten polymers as its less dense. The increased pressure in the reactor forces the vapour out of the reactor tank and into the connecting steel pipe that moves towards the condensation chamber. In the condensation chamber, the vapor rapidly loses its heat to the cold water and thus part of the vapour changes to liquid state via the condensation process giving us crude liquid fuel and the uncondensed vapor moves through the other transfer pipe into the next condensation chamber and if it stays in its vapour state, it will permanently stay in the gaseous state. However, both the liquid and gas are flammable.

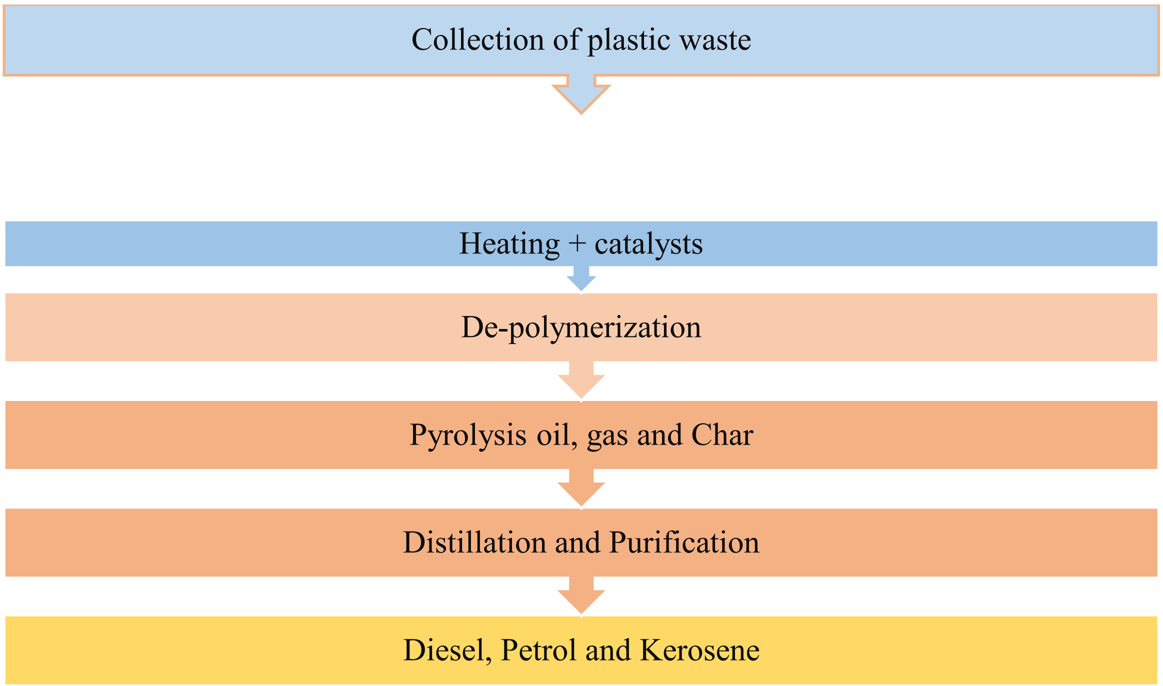


Fig. 3 shows a flow chart of Plastic Pyrolysis process (Vijayakumar & Sebastian, 2018)

This research was carried out to investigate the feasibility of plastic waste conversion to fuel by pyrolysis by characterizing the plastic wastes, developing a working prototype, and investigating the effect of pyrolysis conditions on the fuel quantity and quality.

2. Methods, Techniques, Studied Material and Area Descriptions

2.1. Material Preparation

Plastic wastes were selectively picked by resin identification codes (RIC) that are an ISO 11469 technical standard used by manufacturers to identify the plastic type resin of their products. RIC is a recycle symbol with numbers inside it ranging from 1 to 7. Jerrycans and bottle tops contributed most to the HDPE feedstock, Polyethene bags used for packaging contributed to LDPE, Disposable cups contributed to the PP, and Disposable spoons and Styrofoam packaging contributed to PS.

The feedstock was pre-treated by washing with warm water and a little detergent and rising in clean water, next the plastics were then dried under direct sunshine for 6-hours, and then the dry plastics were manually shredded to small pieces of 5mm to 20mm wide.

The catalysts we selected Activated-carbon charcoal that we obtained from Elvias Laboratory Supplies LTD and it was manufactured by GriffChem. We selected this catalyst for its physical and chemical properties that improved its efficacy in the pyrolysis process as well its thermal stability.

The sugarcane bagasse that is a fibrous residue from sugarcane after juice extraction was obtained from the Sugar Corporation of Uganda Limited (SCOUL) sugar production plant in Lugazi with bagasse in the range of 50-140mm in lengths. The obtained fibers were then cleaned thoroughly to remove any unwanted impurities and placed for sun drying for 24 hours. After drying, the husk sections of the bagasse were removed carefully and chopped to lengths of approximately 5mm. The thickness of the fibers was estimated to be in the range of 1-3mm.

The dried bagasse fibers were then incinerated at approximately 500ºC - 550°C in a kiln for 4 hours in limited oxygen condition so that to prevent complete oxidation and produce the bagasse ash. This temperature ensures the conversion of organic components into reactive silica and alumina as well as it avoids sintering of silica-rich ash. The ash was allowed to cool at room temperature. The ash was grinded and sieved to a fine particle size of 75 microns or less to increase its surface area and reactivity. The ash was then heat treated at 500ºC for 2 hours to stabilize active sites.

2.2. Experimental set-up

Given that we are students experiencing financial restraints we utilized materials and components readily available to us within our community so as to achieve approximately standard conditions as those in a laboratory.

We acquired the following;

i) A 24litre cylindrical steel container with 10-inch diameter and 18.5inch depth to act as the reactor. It had a 2-inch grooved opening for feedstock entry, and a ¾ inch hole for gas exit.
ii) 3 stainless steel pipes of ¾ inch diameter and 20-inch length with 2 corner joints to transfer the vapor from the reactor to the collecting tin.
iii) 4 litre metallic container to receive the vapor and condense the vapour to liquid.
iv) ¼ inch PVC pipe of 2 metre length to transfer the non-condensable gas to the collecting gas tube.
v) 6 small bicycle-tyre tubes for collecting the gas.
vi) 8 tubes of Silicon sealant to seal the joints and connections in an attempt to stop leakages.
vii) 1mm thick steel plate piece of dimensions 1.5m by 1.5m and used it to make a rocket-stove. We also acquired firewood and matchboxes.
viii) A K-Type thermocouple thermometer, 50kg capacity weighing scale, 500ml beaker and 250ml sample bottle from Elvias Laboratory Supplies limited in Kampala.
ix) A basin that when filled with water it shall be a condenser system.

Fig. 4 shows a working Prototype during an experimental run.

2.3. Experimental Procedure

A. Arrangement of set-up.

We cut the 1mm steel plate into four pieces via plasma cutting. We then welded the four pieces using a Miller Multimatic 220 welding machine and ER70S-6 filler wire to create a rocket stove frame.

We vertically set-up the reactor, with a ¾ inch steel pipe system joined at its top to receive the vapor. The pipe delivered the condensed vapor and non-condensable gas into the collecting metallic tin. The hot vapor was cooled and condensed by a metallic to wet-cloth system and metallic-water system. The metallic tin was placed in a partially full basin of water to condense the vapor. A gas tube to collect the non-condensable gas was connected by the help of silicon sealant. The gas was collected in a bicycle tire. We firmly placed the reactor onto the heating platform.

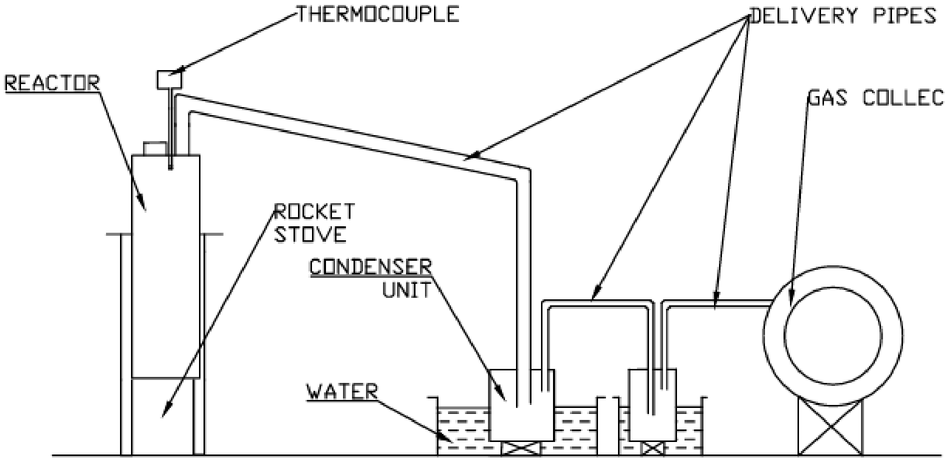


Fig. 5 shows the pyrolysis Set-up.

B. Loading reactor

We placed the plastic waste in a standard container of known weight, say, a plastic bucket of 0.145kg and a sack of 0.07kg which we then hang on a weighing scale hook and recorded the weight and poured it into the reactor. We loaded the reactor with plastics of 1kg or 2kg.

For the experimental runs requiring catalyst, we placed catalyst into the reactor in the given ratio of catalyst: plastic say 1:10 and 1:20.

Regions around the cover that were prone to gas leak, we sealed off with silicon sealant so as to ensure that pyrolysis occurred in an air-tight environment.

The set-up was then checked again to ensure that all components were properly connected to avoid vapor leakage.

C. Active operation

The heat source was then ignited, and here the plastic waste polymer carbon-carbon bonds broke down creating shorter polymers and monomers which transformed into vapor state and on condensation via the metal to air interface as well as metal to water interface, the fuel was collected in the metallic.

We then had a K-Type thermocouple and contact system that displayed a variation of temperature readings.

With temperatures between 250°C to 450°C, we had crude liquid fuel and syngas produced.

We then varied the residence times 30, 60, 120, 180 and 240 minutes on the fuel quantity produced. We also assessed the effect of the activated carbon catalyst, bagasse ash or no catalyst on the fuel quantity produced and quality mainly colour at this stage.

For the metallic to wet-cloth system, we socked the towel in water and then slightly wringed it and then rolled it around the slightly inclined pipe. We placed the wet cloth around the pipe in 5minute intervals as every after 5 minutes, we unrolled it, resoaked it again and re-rolled it again. This procedure was repeated till the active operation came to a stop.

D. Collection and labelling of containers

We collected the produced oil or fuel from the various plastic types tests and poured it into bottles and labelled them in preparation for the fuel characterization tests. The produced syngas was collected into a bicycle tube and sealed it off to ensure no leakage.

We calculated the respective yields of the liquid, solid and gas fractions using Equation 1 to 4.

Percentage of conversion = $((M - M_2)/M) * 100$ -------------------------(1)----

Yield of liquid fraction (Y_L) = $(M_1/M) * 100$ ----------------------------(2)----

Yield of solid fraction (Y_S) = $(M_2/M) * 100$ -----------------------------(3)----

Yield of gaseous fraction (Y_G) = $100 - (Y_L + Y_S)$ -----------------------(4)----

Where;

M is the mass of plastic feed (g)

M_1 is the mass of liquid yield (g)

M_2 is the mass of solid residue (g)

2.4. Analysis of plastic derived fuel

In addition, we conducted fuel properties tests such as the flash point, calorific value and viscosity at the laboratory of the department of Geology and Petroleum Studies Makerere. In addition, we carried out the gravimetric density test for the fuel samples.

We conducted emission-oriented tests at Uganda Petroleum Institute Kigumba (UPIK) using the Voice type Multifunctional Gas Detector and Nova-plus emission monitoring system so that to determine whether the trace gases known to be toxic or pollutants are present and if present to determine whether they are in the tolerable limits. These tests determine whether the fuel production should proceed or not.

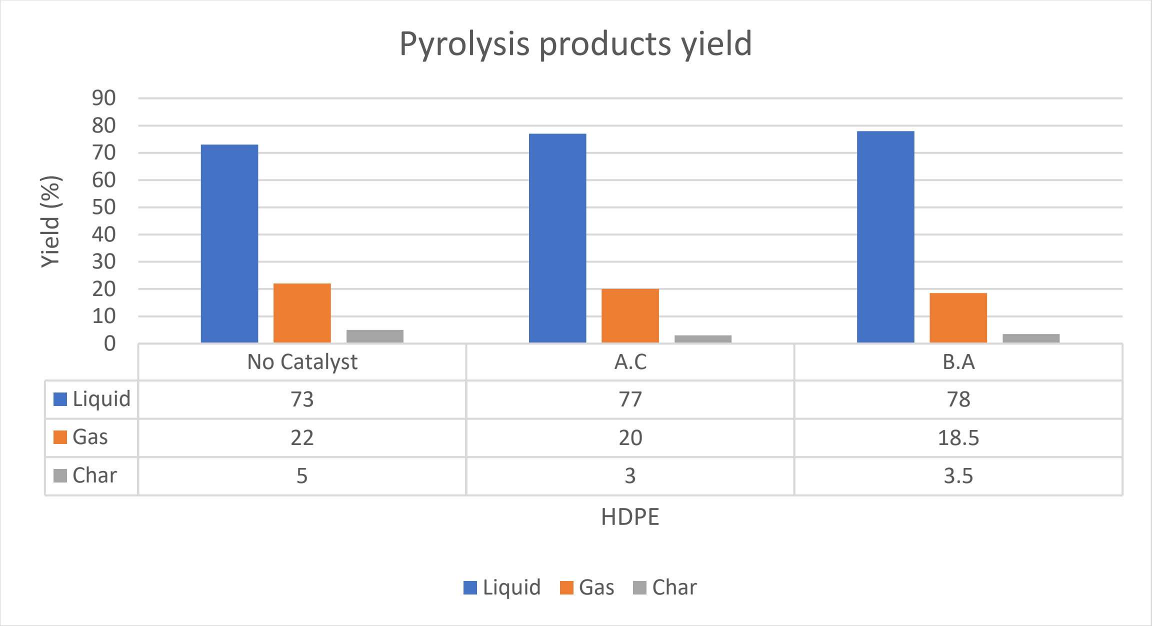
The Nova-plus system monitored the following parameters like Air temperature, Gas temperature, Carbon-dioxide percentage, Draft and Carbon monoxide Content. The gas detector measured CO, O_2, and H_2S.

We placed the analyzer probe into the sample container, the analyzer then drew a sample of the flue gases from the duct using a built-in gas pump through the probe, the probe is automatically cleaned and dried using condensate separator with built-in filter and the base then analyzes the extracted gas with electrochemical sensors, and displays the results on a screen.

3. Results

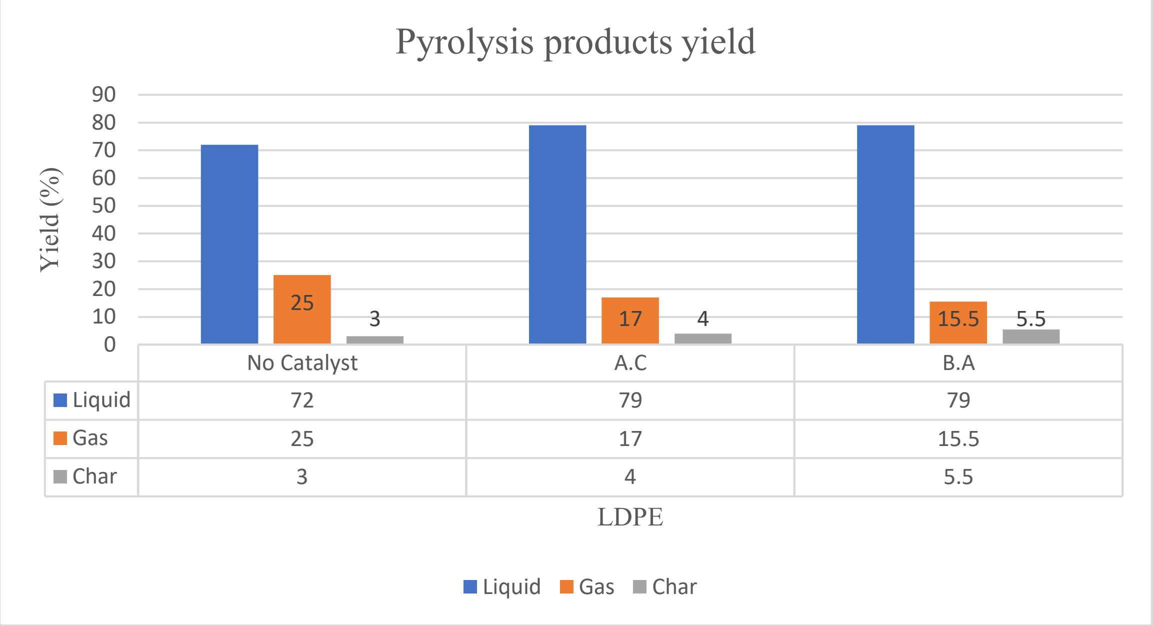
3.1. Experimentation Results

The results shown in Figure 6 - 11 are for experiments carried out on the different plastic feedstocks at varying catalyst ratios (1:30, 1:20, 1:10 & 1:5). In our experiments, the independent variables were the feedstock type and temperature range as for the dependent variables were the residence times, fuel quantity, and fuel quality.



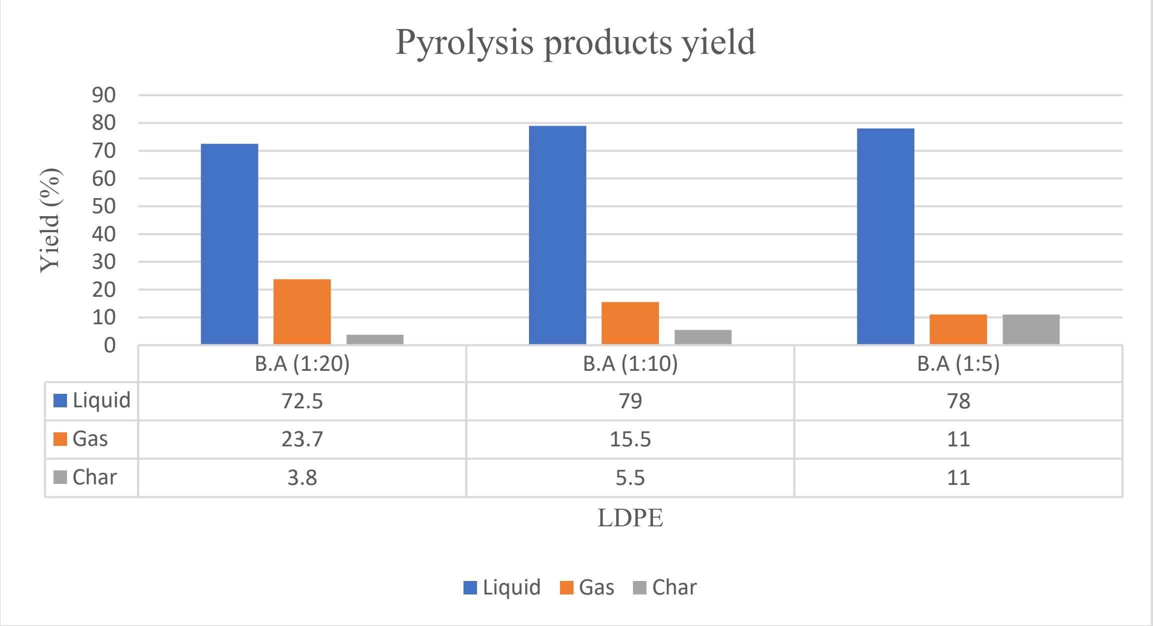
	No Catalyst	A.C	B.A
Liquid	73	77	78
Gas	22	20	18.5
Char	5	3	3.5

Fig. 6 shows a chart of the product yields for HDPE



	No Catalyst	A.C	B.A
Liquid	72	79	79
Gas	25	17	15.5
Char	3	4	5.5

Fig. 7 shows a chart of the products yield for LDPE



	B.A (1:20)	B.A (1:10)	B.A (1:5)
Liquid	72.5	79	78
Gas	23.7	15.5	11
Char	3.8	5.5	11

Fig. 8 shows a chart of the products yield for LDPE at different catalyst ratios

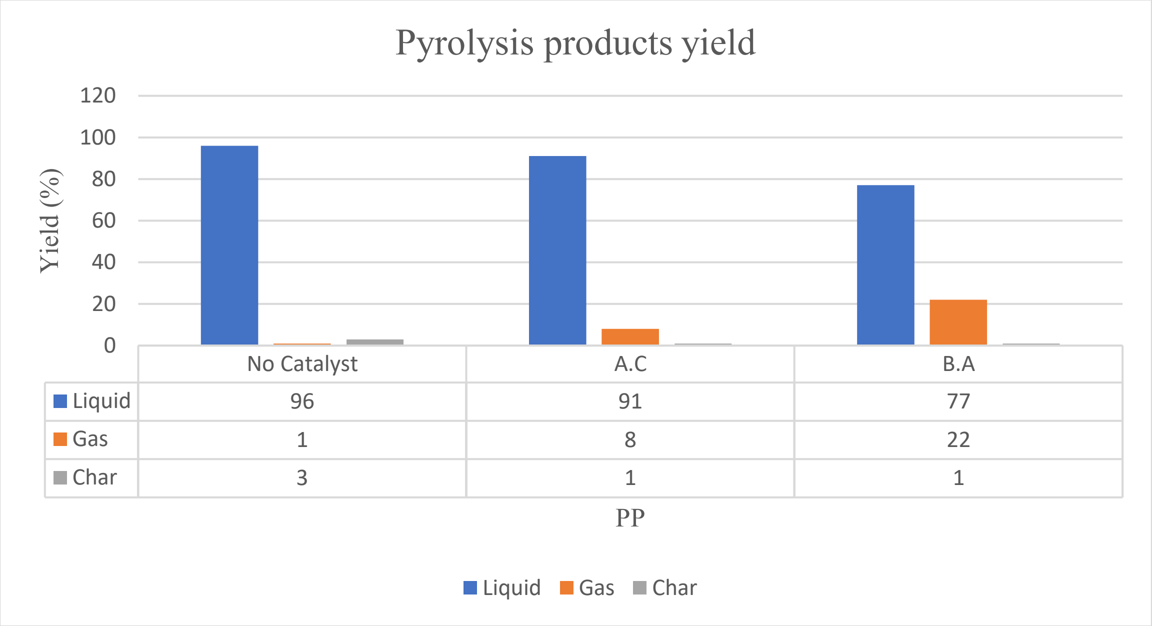


Fig. 9 shows a chart of the products yield for PP

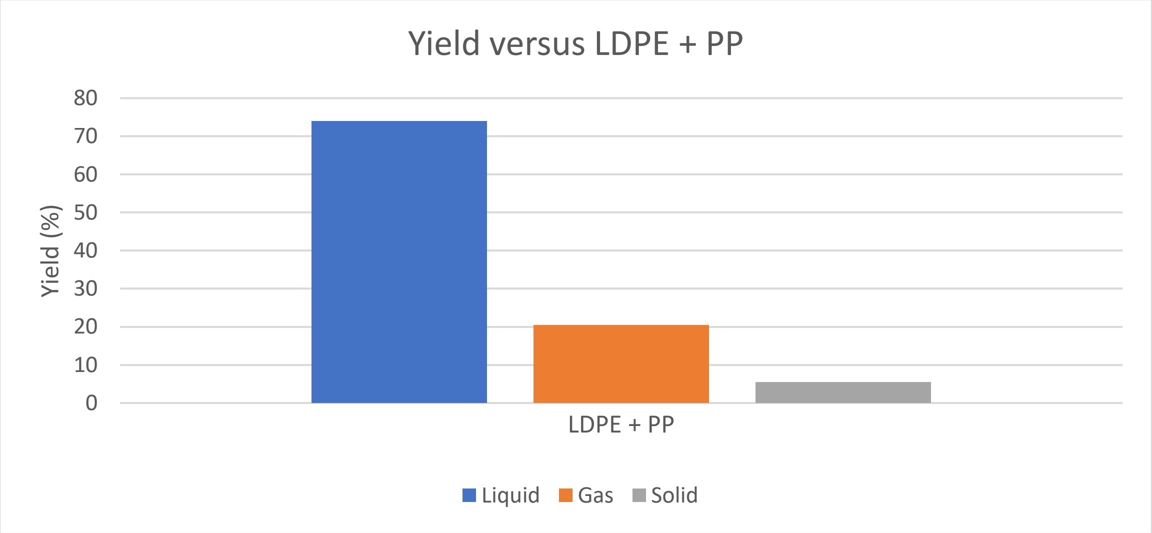


Fig. 10 shows a chart of the products yield for mixed LDPE + PP

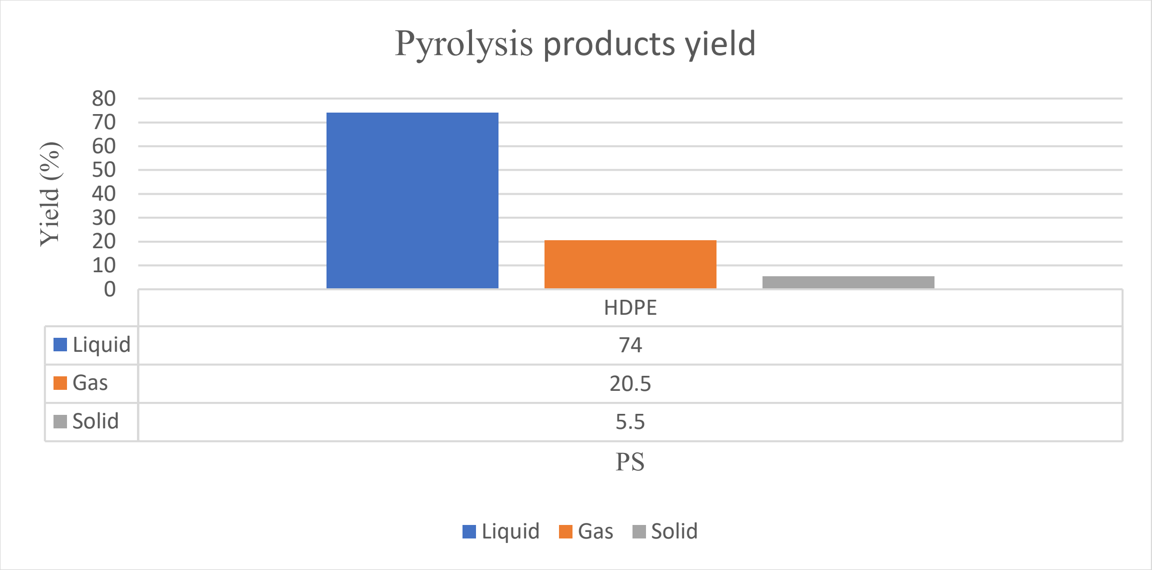


Fig. 11 shows a chart of the products yield for PS

From the trials of 1kg of HDPE in figure 6, the highest fuel yield of 78% was obtained from the trial of bagasse ash catalyst (1:10), followed by Activated Carbon (1:10) and eventually for no catalyst we obtained the lowest fuel yield of 73%.

For the trial of 3kgs of white coloured HDPE, we obtained a 73.2% of fuel yield and at room temperature it retained its liquid state however for the trials of 1kg of mixed coloured HDPE we obtained liquid fuel but on cooling to room temperature the samples of no catalyst and activated carbon turned to a viscous-waxy mixture while the sample from the bagasse ash turned from liquid to wax.

Loading the reactor with HDPE feedstock and catalyst reduced the residence time from 90minutes to 75minutes.

From the trials of 1kg of LDPE in figures 7 and 8, the highest fuel yield of 79% was obtained from both the trials of bagasse ash catalyst (1:10) and Activated Carbon (1:10) and eventually for no catalyst we obtained the lowest fuel yield of 72%.

For the trial of 2kgs of LDPE, we obtained a 72.5% of fuel yield but at room temperature it turned to wax and the same applies to the other trials.

Loading the reactor with LDPE feedstock and catalyst reduced the residence time from 75minutes to 60minutes.

Bagasse ash catalyst effect was studied at different catalyst ratios (1:20, 1:10 & 1:5). At No catalyst and Bagasse ash (1:20), the fuel yield was approximately the same as the effect was minimal and the same applied for bagasse ash (1:10 & 1: 5).

Other researchers like (Wong et al., 2015) found out that pyrolysis of PE produced mainly n-paraffins and 1 olefins in liquid products, however the presence of olefins is generally undesirable, as they easily recombine with each other to form larger molecules thus wax formation. They also suggested running the pyrolysis in hydrogen atmosphere to convert olefins to n paraffins.

However, for Bagasse Ash (1:5) reaction, the wax quantity reduced to allow more liquid fuel to be collected in the secondary collecting container say 0.12 litres of liquid fuel.

Bagasse ash catalyst ratio of 1:5 reduced the residence times from 75minutes to 45 minutes.

From the experiment of LDPE + PP, we yielded 0.75litres of wax and 0.145litres of liquid fuel.

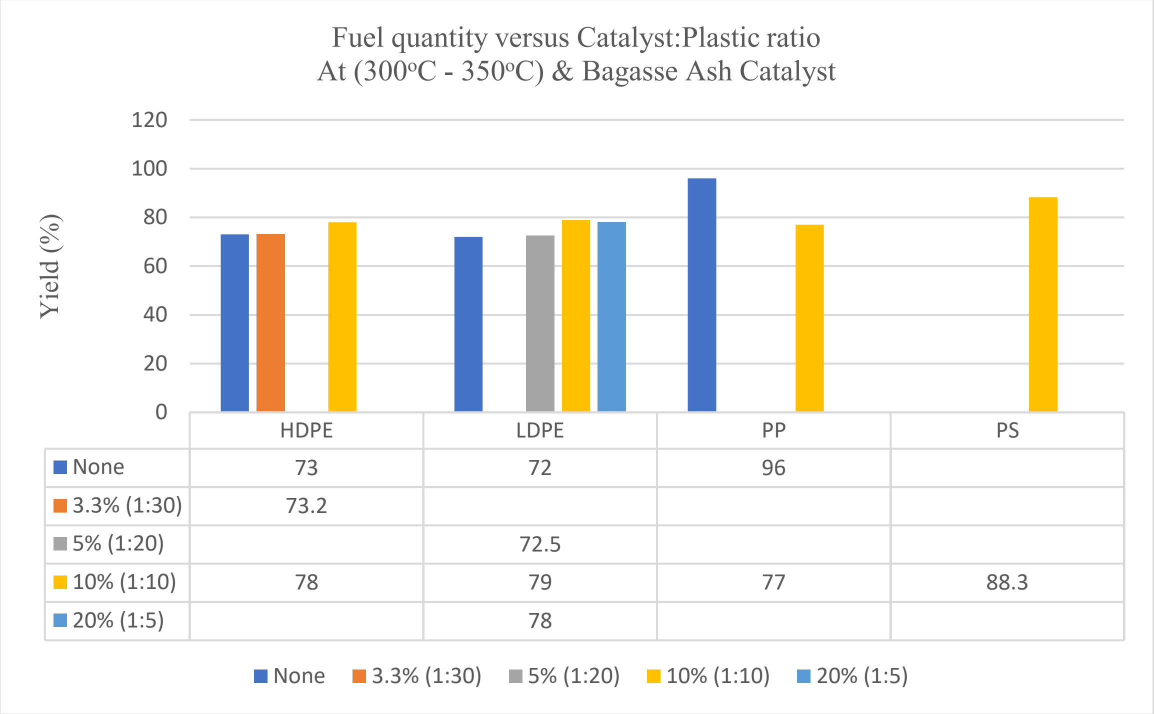
From the PP trials, we achieved the highest fuel yield of 96% from the No-catalyst experiment. The catalytic pyrolysis using Activated Carbon yielded 91% and for Bagasse Ash yielded 77%.

Loading the reactor with catalyst reduced the residence time from 75minutes to 60minutes.

The PS trial had a fuel yield of 88.3%.

- Comparison of quantity of fuel produced by the different plastic types at different Bagasse Ash catalyst ratios

Plastics of 1 kg were pyrolyzed at catalyst ratios of 1:30, 1:20, 1:10 and 1:5.



	HDPE	LDPE	PP	PS
None	73	72	96	
3.3% (1:30)	73.2			
5% (1:20)		72.5		
10% (1:10)	78	79	77	88.3
20% (1:5)		78		

Fig. 12 shows a Chart of the Fuel Quantity verse Catalyst: Plastic ratio

From Figure 12, HDPE produced the highest fuel yield (78%) at catalyst ratio of 1:10, followed by 73.2% at 1:30 and 73% at no-catalyst. LDPE produced the highest fuel yield (79%) at catalyst ratio of 1:10, followed by 78% at 1:5, followed by 72.5% at 1:20 and 72% at no-catalyst. PP produced the highest fuel yield (96%) at catalyst ratio of 1:10 and 77% at 1:10. PS produced a fuel yield of 88.3% at catalyst ratio of 1:10.

In addition, the fuel yields were maximum at catalyst ratio of 1:10 for HDPE, LDPE and PS, however for PP, the highest fuel yield was at no-catalyst ratio which implies that PP didn't require catalytic action as this action produced more non-condensable gas.

- Chart of fuel yields from experiments conducted

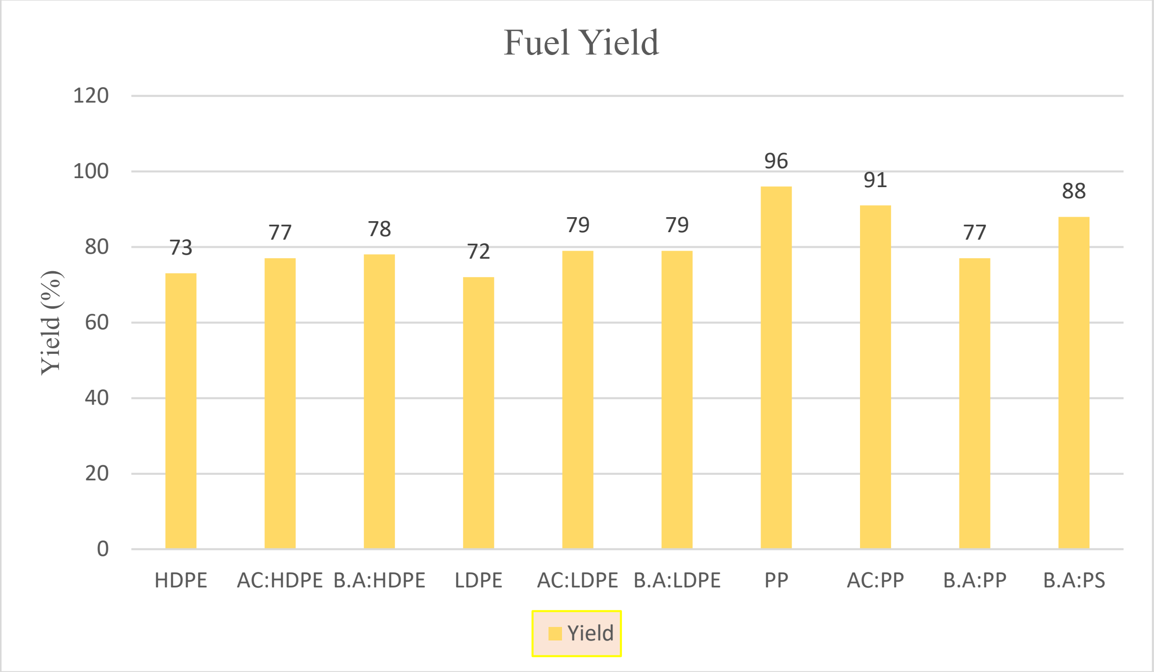


Fig. 13 shows a chart for the comparison of the obtained Fuel Yields

PP produced the highest fuel yield potential, folowed by PS, LDPE and HDPE.

- Chart of Average temperature during a sample experimental run.

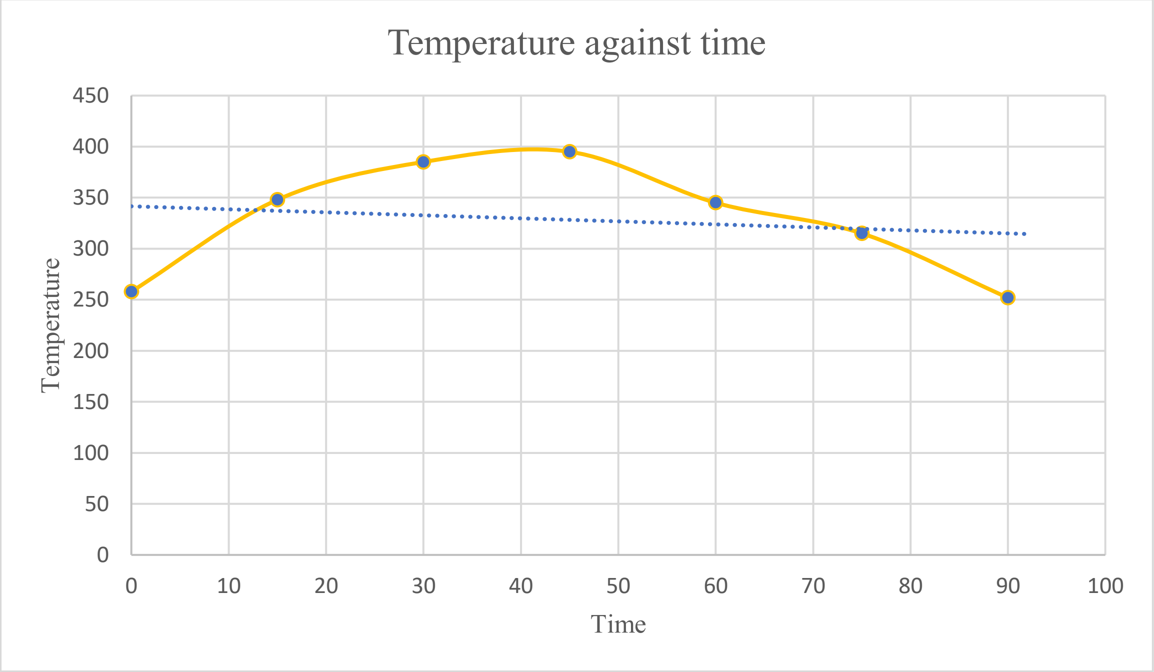


Fig. 14 shows a graph of Temperature against time for a sample run.

The thermocouple and contact system displayed the highest temperature range of 350 – 400ºC. However, during the experimentations we manually regulated the heat source to have an average temperature range between 300 – 350ºC.

Table 2 shows Oil, Gas and Residue Yields for Each Plastic-Catalyst combination

Fixed conditions: Feedstock and 300-350°C

Plastic Type	Catalyst	Oil Yield (%)	Gas Yield (%)	Residue (%)
HDPE	-	73.0	22.0	5.0
HDPE	A.C	77.0	20.0	3.0
HDPE	B.A	78.0	18.5	3.5
LDPE	-	72.0	25.0	3.0
LDPE	A.C	79.0	17.0	4.0
LDPE	B.A	79.0	15.5	5.5
PP	-	96.0	1.0	3.0
PP	A.C	91.0	8.0	1.0
PP	B.A	77.0	22.0	1.0
PS	-	n.a	n.a	n.a
PS	A.C	n.a	n.a	n.a
PS	B.A	88.3	10.0	1.7

HDPE and LDPE were observed to give off higher gas yield when no-catalyst was used, for PP was observed to give off higher gas yield with catalysts used say 8.0% for Activated carbon and 22.0% for Bagasse Ash.

3.2. Laboratory results

The laboratory tests were carried out to determine the suitability of the plastic derived fuel as a replacement for conventional diesel in some of its applications. The tests were further carried out to determine whether the associated emissions are toxic or not.

1) **Emissions properties tests**

Table 3 below shows the Emissions indicators results displayed by the Nova-plus emission monitoring system and Voice Type Multifunctional Gas Detector system

Plastic Type	Catalyst	T-gas (°C)	T-air (°C)	CO_2 (%)	Draft (hPa)	CO (ppm)	NO (ppm)	H2S (ppm)	O2 (%)
HDPE	-	26.9	25.7	13.0	0.00	95	0	2.0	20.2
HDPE	A.C	27.6	25.7	13.2	-0.00	100	0	5.0	22.1
HDPE	B.A	26.3	25.6	13.8	-0.00	93	0	7.0	20.4
LDPE	-	26.5	25.6	11.8	0.00	90	0	5.0	20.8
LDPE	A.C	26.3	25.6	12.0	0.00	88	0	2.0	21.2
LDPE	B.A	27.0	25.6	11.2	-0.00	95	0	3.0	21.8
PP	-	26.3	25.6	13.1	0.00	95	0	3.0	21.7
PP	A.C	26.1	25.9	13.0	0.02	94	0	4.0	20.8
PP	B.A	25.5	25.9	12.3	-0.00	95	0	3.0	20.7
PS	-	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
PS	A.C	n.a	n.a	n.a	n.a	n.a	n.a	n.a	n.a
PS	B.A	27.6	25.6	13.5	-0.00	95	0	2.0	20.4

n.a – not assessed

The Nova-plus system and gas detector system collectively gave off readings of Temperature of gas (T-gas), room temperature of air (T-air) and Draft at near-neutral that the machines were making measurements of other parameters. Near-neutral draft suggests proper airflow balance, minimizing backdraft or pressure issues.

Combustion efficiency indicators such as CO_2 values that were below the upper limit of 30% and CO values peaked at 100ppm. The value of 100ppm (CO) is at the upper EPA limit for stationary sources (50 – 100ppm), this suggests low combustion temperatures during pyrolysis. O_2 values were within the range of 19.5% to 23.5% favourable for thermal efficiency during combustion of fuel in its applications.

Hazardous Emissions indicators such as H_2S values peaked at 7.0ppm that was below the industrial exposure limits for OSHA's 10ppm ceiling, however H_2S presence suggests sulphur-containing additives or contaminants in our plastic feedstock. NO values at 0ppm were observed, this greatly reduces the risk of NOx emissions.

With the low values of CO_2, CO, H_2S and NO, the fuel can be said to pose a low contribution to the quantity of greenhouse gases produced annually.

The Voice type multifunctional gas detector also detected 0% lower explosive gas; thus, the fuel is relatively safe for handling at normal temperatures.

Table 4 below shows the Tolerable limits (Gmbh, 2020)

	Alarm point	
Gas to be measured	Low	High
CO_2	0%	30%
CO	50ppm	150ppm
NO	50ppm	150ppm
O_2	19.5%	23.5%
H2S	10ppm	35ppm

Table 5 below shows the Emissions composition for plastic derived fuels.

Plastic Type	Catalyst	Diesel	Propane	Butane	Pellets	Holz trocken
HDPE	-	15.4	13.7	14.1	20.3	20.3
HDPE	A.C	15.4	13.7	14.1	20.3	20.3
HDPE	B.A	15.4	13.7	14.1	20.3	20.3
LDPE	-	15.4	13.7	14.1	20.3	20.3
LDPE	A.C	15.4	13.7	14.1	20.3	20.3
LDPE	B.A	15.4	13.7	14.1	20.3	20.3
PP	-	15.4	13.7	14.1	20.3	20.3
PP	A.C	15.4	13.7	14.1	20.3	20.3
PP	B.A	15.4	13.7	14.1	20.3	20.3
PS	-	n.a	n.a	n.a	n.a	n.a
PS	A.C	n.a	n.a	n.a	n.a	n.a
PS	B.A	15.41	13.7	14.1	20.3	20.3

The Nova-plus system produced identical values for Diesel (15.4%), Propane (13.7%), Butane (14.1%), Pellets (20.3%), and Holztrocken (20.3%) across HDPE, LDPE, PP and PS because HDPE, LDPE and PP are all polyolefins with similar hydrocarbon structures and pyrolysis breaks these into shorter alkanes/alkenes that are diesel-like hydrocarbons. PS contains aromatic rings, but under pyrolysis, it breaks into styrene monomers and lighter hydrocarbons. With identical values, it is said that the emissions detector categorizes hydrocarbons into the predefined groups on detection.

2) Fuel properties tests

During analysis, Calorific value was determined using a bomb calorimeter, Flash point was determined using Open cup method and hydrocarbon components by using FTIR 8400S Shimadzu.

Table 6 below shows Polypropylene-derived fuel properties that were obtained.

Plastic Type	Catalyst	Flash point (°C)	Calorific Value (MJ/kg)	Density (kg/m3)	Viscosity cSt	Alkanes (%)	Alkenes (%)		Aromatics (%)
PP	-	28.9	48.9	750	2.2	53	nd		18
PP	B.A	34.4	47.4	790	2.7	66	nd		21

Table 7 below shows the fuel properties for Gasoline and Diesel (Anuar Sharuddin et al., 2016)

Property	Standard value	
	Gasoline	Diesel
Flashpoint (°C)	42	52
Calorific value (MJ/kg)	42.5	43.0
Density (kg/m^3) @ 15°C	780	807
Viscosity (cSt), kinematic	1.17	1.9 – 4.1
Dynamic (cP)		1.52 – 3.44

Both samples' flashpoints 28.9°C and 34.4°C are below gasoline (42°C) and diesel (52°C) standards, indicating higher flammability risks. The bagasse ash catalyst increased flashpoint by 19%, likely due to stabilization of heavier fractions.

Both samples viscosity values 2.2cSt and 2.7cSt align with diesel's viscosity range (1.9cSt – 4.1cSt) but exceed gasoline (1.17cSt). The catalyst slightly increased viscosity, suggesting formation of longer-chain hydrocarbons.

Both samples calorific values of 48.9MJ/kg and 47.4MJ/kg surpass gasoline (42.5MJ/kg) and diesel (43.0MJ/kg), indicating better energy potential. However, the bagasse ash catalyst reduced the calorific value by 3%, possibly due to incomplete cracking.

Sample 1 is observed to have a density of 750kg/m^3 and Sample 2 has a density of 790kg/m^3 that lies in between the gasoline (780kg/m^3) and diesel (807kg/m^3). Increased density with catalytic action, implies more heavier hydrocarbons (alkanes).

Alkanes increased from 53% to 66% due to catalytic action, higher alkanes improve fuel stability and combustion efficiency. Aromatics increased from 18% to 21% due to catalytic action, however increased aromatic content results in higher particulate emissions. Absence of alkenes is advantageous, as unsaturated compounds reduce oxidation stability.

4. Discussion

4.1. Suitability of materials

Polyolefins (HDPE, LDPE & PP) were found most suitable for pyrolysis as they had favorable fuel yields in the range of (70 – 97%). PVC and PET were found not suitable for use as feedstock in our pyrolysis experiments as other researchers like (Miandad et al., 2016) have found them to contain heteroatoms like chlorine and oxygen that complicate pyrolysis and produce harmful by-products like hydrogen chloride gas and dioxins that cause equipment corrosion and environmental toxicity. PET's ester linkages (-COO-) lead to production of carboxylic acids and carbon dioxide during pyrolysis which lower oil stability and calorific value.

4.2. Effect of catalysts on fuel yield and quality.

For HDPE, highest fuel yield (78%) was achieved with Bagasse Ash (B.A) catalyst (1:10 ratio). The yield decreased slightly with Activated Carbon (A.C) (77%) and further without a catalyst (73%). For both A.C and B.A catalysts yielded 79% fuel, higher than the no-catalyst trial (72%). Surprisingly, for PP the highest yield (96%) was without a catalyst, suggesting PP may not require catalysts for optimal conversion. Catalytic trials yielded 91% (A.C) and 77% (B.A). For PS, only B.A catalyst was tested, yielding 88.3%, indicating high potential for PS conversion. For mixed Plastics (LDPE + PP), Yielded

74% with B.A catalyst, showing compatibility for mixed feedstock but with lower efficiency than pure PP.

PP showed the highest yield (96% without catalyst), suggesting it is the most suitable feedstock. This result is similar to that achieved by (Williams & Slaney, 2007) of 95% without catalyst. Catalysts improved yields for HDPE/LDPE but not PP, possibly due to PP's simpler polymer structure.

These results indicated that the use of catalysts, increased the fuel yield as the fuel yields were maximum at catalyst ratio of 1:10 for HDPE, LDPE, and PS, however for PP, the highest fuel yield was at no-catalyst ratio which implies that PP did not require catalytic action as this action produced more non-condensable gas. Bagasse Ash (B.A), improved yields for HDPE and LDPE but reduced PP yield. Activated Carbon (A.C), improved yields for HDPE and LDPE but was less effective for PP.

It was noted that higher catalyst ratios (e.g., 1:5 for LDPE) did not significantly improve yields but reduced gas and residue, suggesting over-cracking.

The results indicated an increase in aromatic hydrocarbons from 18% to 66% when Bagasse ash was used, this is supported by (Anuar Sharuddin et al., 2016) as percentage of aromatics increased with increase in SiO_2/Al_2O_3 ratio in his research.

Bagasse Ash's silica-alumina content likely promoted cracking, while A. C's porosity aided vaporization. However, overuse (e.g., 1:5 ratio) may have led to excessive gas production.

It was observed that the liquid fuel from PP with no-catalyst was golden-brown while for PP with bagasse ash or activated carbon, the liquid fuel was pale green in color.

The results from researchers show that the chemical composition of bagasse ash is mainly SiO_2 with the highest percentage, followed by Al_2O_3, K_2O, Fe_2O_3, and CaO (minor amounts Ti, Mn, Zn, Zr, V, Sr, Pd oxides). (Monzo et al., 2002) The high ratio of silica to aluminate that act as active sites that favor cracking of plastic bonds.

Bagasse Ash is a low-cost, effective catalyst for HDPE/LDPE, while PP performs best without catalysts. Bagasse ash may introduce residues in the fuel, reducing calorific value and increasing viscosity.

4.3. Effect of catalysts on residence time.

Bagasse Ash (B.A) catalyst and Activated Carbon reduced residence times for all experimental runs as follows for example it reduced for HDPE from 90minutes to 75minutes, for LDPE from 75minutes to 60minutes, for PP from 75 to 60 minutes for PP.) For the LDPE + PP, residence time was shortest at 45minutes. It was noted that catalysts improved efficiency of the experiments thus reducing on the energy consumed by each experiment. The reduction in residence times with respect to catalytic activity is consistent with findings by (Kassargy et al., 2017) where they used USY Zeolite for degradation of PP and it reduced the residence time from 80 to 45minutes and 120 to 50minutes of PE.

4.4. Combined Effect of Temperature and Catalyst

With the fuel yield ranging between (74% to 96%) for our experiments, we note that the optimal temperature range was 300 – 350°C as higher temperatures may favor gas production over liquid fuel. Also, the recommended temperature range for thermal cracking of plastics as mentioned by other studies is 350 – 650°C, however with firewood as the heat source it was complicated to maintain the temperatures within the desired range but fortunately the Bagasse Ash catalyst and Activated Carbon allowed efficient cracking of the plastic bonds within the immediate lower range of 300°C to 350°C.

4.5. Effect of color pigment

On pyrolysis of HDPE of the same color pigments we did obtain liquid fuel but on pyrolysis of HDPE of mixed color pigments we obtained wax. This observation aligns with the discussions of (Ragaert et al., 2017) as they found out that pigments are sources of heteroatoms and impurities which end up in the pyrolysis products leading to wax formation. Studies such as http://hdl.handle.net/11462/2359 also investigated into this issue and the presence of color pigments led to more wax formation.

4.6. Fuel Properties

Density ranged from 0.75kg/L (PP) to 0.88kg/L (PS), comparable to conventional diesel (0.807kg/L). Density: PS-derived fuel had the highest density (0.88kg/L), potentially requiring blending with lighter fuels for engine use.

Emissions associated to the Greenhouse effects and pollution such as CO_2, H_2S, NO and CO were within safe limits, indicating a relatively clean combustion thus aligning with environmental goals and thus comparable to conventional diesel.

Both samples have low flashpoints below gasoline/diesel standards (42 – 52°C), posing safety risks during transport. An aromatic content (21%) exceeds typical diesel standards e.g., EN590 limits aromatics to < 35% but recommends <20% for cleaner combustion thus an emissions concern. In addition, have a superior calorific value and viscosity within diesel range.

5. Conclusion

The experimental study was carried out to investigate the technical feasibility of plastic waste conversion to fuel by pyrolysis, evaluating plastic derived fuel properties against gasoline/diesel standards and optimizing catalytic efficiency using bagasse ash. The results from this study show the effect of pyrolysis conditions on the fuel quality and yield for example the addition of bagasse ash as a catalyst and use of the rocket stove principle generally improves the efficiency of the process. Specifically, the following conclusions were drawn from the study.

1. Mixed color pigments in plastic feedstock affects the liquid fuel product distribution resulting in wax formation, therefore pre-treatment of feedstock by sorting, increase in pyrolysis temperature to greater than 500°C and use of zeolite catalysts are required to eliminate the wax formation. In addition, (Wong et al., 2015) suggested introducing hydrogen conditions such that the olefins hydrocarbons that combine with each other are converted to n-paraffin molecules thus wax elimination.
2. The performance of the rocket stove principle was significant as it improved the system efficiency for example reducing the residence times from 120 to 60 minutes and increasing of the temperature from (150°C – 200°C) to (300°C to 400°C).
3. Bagasse Ash catalyst performance was equally satisfactory as that of Activated Carbon as they both did improve system efficiency. Derived from agricultural waste, use of bagasse ash aligns with circular economy principles reducing environmental burdens associated with waste incineration or landfill disposal. Its inherent composition that is rich in silica and alumina enhances hydrocarbon selectivity and stabilizes pyrolysis reactions, as evidenced by increased alkane yields in pyrolysis of PP from 53% to 66%. In addition, the material used for catalysts should be sustainable and environmentally friendly.
4. The laboratory testing was based on PP derived fuel samples, thus the results from the pyrolysis of PP in absence and in the presence of Bagasse ash catalyst were compared. From the FTIR analysis it is confirmed that use of catalyst increases the stabilization of heavier hydrocarbons thus the pyrolysis fuel becomes more diesel like. The use of higher catalyst percentages produces more gas phase products for all plastics whereas absence of catalyst caused increased oil product during pyrolysis for PP. The impact of catalyst on the char was insignificant. The physical analysis of oil shows that catalytic oil is superior in quality with a higher flashpoint and heavier hydrocarbon content as well as high enough calorific value. The fuel quantity was significantly affected by catalyst as higher yields were obtained for HDPE, LDPE, and PS, however for PP the yields lowered due to its simple structure leading to higher gas production.
5. Catalytic pyrolysis using Bagasse Ash has proved to have several advantages over the thermal process, as it improves efficiency by decreasing the process's residence time and affects the product selectivity, also it is way less costly and more accessible than standard catalysts such as zeolites and silica-alumina. This is in line with other studies that suggested finding of alternative catalyst sources from waste material such as agricultural waste would be helpful as

most catalysts in pyrolysis use today are made of noble, rare-earth, or transition metals that face a critical need to make them reusable. (Yang et al., 2022).

6. Pyrolysis presented itself as a sustainable and an efficient treatment method to treat plastic waste accumulation in landfills and other non-conventional areas of waste disposal. The pyrolysis process breaks the plastic bonds and thus waste converted into its raw material and high energy density products that are suitable for energy generation, hence sustainable energy recovery. This could minimize the dependency on non-renewable fossil fuels. Pyrolysis has its environmental benefits compared to other treatment methods as it takes place in absence of oxygen therefore no dioxins released to the atmosphere and has reduced carbon monoxide and dioxide emissions.
7. Furthermore, a PID Controller for temperature regulation and electric resistance furnace are recommended for pyrolysis experiments as they establish precise user defined temperature thus fuel yields can further be investigated at different temperature values to determine the optimal temperatures for the different plastics. Incentives to integrate pyrolysis into Uganda's waste management systems as well as design of larger reactors for batch consistency and economic viability should be implemented.
8. It can be concluded that plastic waste conversion to fuel is technically feasible given that the pyrolysis derived fuel had better energy potential with viscosity and density lying within the expected ranges. The scope of this research project was limited to Polyolefins and Polystyrene as well as the fuel properties testing was limited to only Polypropene samples due to the high costs involved.

Acknowledgement(S)

We convey our sincere appreciation to Mr. Bwambale Roice, our supervisor for the unending supportive response and advice rendered to us throughout the project formation. In addition, we convey our sincere appreciation to our colleagues Mutumba Ivan, Deborah, Phillip and Winnie for the support and team work during the various pyrolysis trial runs. We are truly grateful to Mr. Kasule the technician of the department of Geology and Petroleum Studies Makerere and Mr. Ronald the technician of the Instrumentation workshop UPIK for the assistance offered with the fuel tests.

References Cited

Al-Salem, S. M., Antelava, A., Constantinou, A., Manos, G., & Dutta, A. (2017). A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). *Journal of Environmental Management*, *197*(1408), 177–198. https://doi.org/10.1016/j.jenvman.2017.03.084

Anuar Sharuddin, S. D., Abnisa, F., Wan Daud, W. M. A., & Aroua, M. K. (2016). A review on pyrolysis of plastic wastes. *Energy Conversion and Management*, *115*, 308–326. https://doi.org/10.1016/j.enconman.2016.02.037

Azoulay, D. (2019). Plastic & Health: THE HIDDEN COSTS OF A PLASTIC PLANET. *Science News*, *152*(25/26), 84. https://doi.org/10.2307/3980907

Banu, J. R., Sharmila, V. G., Ushani, U., Amudha, V., & Kumar, G. (2020). Science of the Total Environment Impervious and in fl uence in the liquid fuel production from municipal plastic waste through thermo-chemical biomass conversion technologies - A review. *Science of the Total Environment*, *718*, 137287. https://doi.org/10.1016/j.scitotenv.2020.137287

Geyer, R. (2020). Production, use, and fate of synthetic polymers. In *Plastic Waste and Recycling*. Elsevier Inc. https://doi.org/10.1016/b978-0-12-817880-5.00002-5

Gmbh, M. R. U. (2020). *USER MANUAL NOVAplus*. 1–95.

Hassan, H., Lim, J. K., & Hameed, B. H. (2019). Bioresource Technology Catalytic co-pyrolysis of sugarcane bagasse and waste high-density polyethylene over faujasite-type zeolite. *Bioresource Technology*, *284*(March), 406–414. https://doi.org/10.1016/j.biortech.2019.03.137

Idumah, C. I., & Nwuzor, I. C. (2019). Novel trends in plastic waste management. *SN Applied Sciences*, *1*(11), 1402. https://doi.org/10.1007/s42452-019-1468-2

Kabeyi, D., & Olanrewaju, O. (2023). Review and Design Overview of Plastic Waste-to-Pyrolysis Oil Conversion with Implications on the Energy Transition. *Journal of Energy*, *2023*, 1–25. https://doi.org/10.1155/2023/1821129

Kassargy, C., Awad, S., Burnens, G., Kahine, K., & Tazerout, M. (2017). Experimental study of catalytic pyrolysis of polyethylene and polypropylene over USY zeolite and separation to gasoline and diesel-like fuels. *Journal of Analytical and Applied Pyrolysis*, *127*(September), 31–37. https://doi.org/10.1016/j.jaap.2017.09.005

Kumar, M., Bolan, S., Padhye, L. P., Konarova, M., Ying, S., Lam, S., Wagland, S., Cao, R., Li, Y., Batalha, N., Ahmed, M., & Bolan, N. (2023). *Retrieving back plastic wastes for conversion to value added petrochemicals : opportunities , challenges and outlooks*. *345*(June). https://doi.org/10.1016/j.apenergy.2023.121307

Kunwar, B., Cheng, H. N., Chandrashekaran, S. R., & Sharma, B. K. (2016). Plastics to fuel: a review. *Renewable and Sustainable Energy Reviews*, *54*(February), 421–428. https://doi.org/10.1016/j.rser.2015.10.015

Miandad, R., Barakat, M. A., Aburiazaiza, A. S., Rehan, M., & Nizami, A. S. (2016). Ac ce pt us cr t. *Process Safety and Environmental Protection*. https://doi.org/10.1016/j.psep.2016.06.022

Monzo, J., Borrachero, M. V, & Dı, L. (2002). *Sugar-cane bagasse ash (SCBA): studies on its properties for reusing in concrete production †*. *325*(September 2001), 321–325. https://doi.org/10.1002/jctb.549

Moorthy, K., Chintala, V., Sharma, A., Pal, S., Pandey, J. K., & Ghodke, P. (2020). Review of catalyst materials in achieving the liquid hydrocarbon fuels from municipal mixed plastic waste (MMPW). *Materials Today Communications*, *24*(January), 100982. https://doi.org/10.1016/j.mtcomm.2020.100982

Murthy, K., Shetty, R. J., & Shiva, K. (2023). Environmental Effects Plastic waste conversion to fuel : a review on pyrolysis process and influence of operating parameters. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *45*(4), 11904–11924. https://doi.org/10.1080/15567036.2020.1818892

NEMA. (2024). *NATIONAL STATE OF THE ENVIRONMENT REPORT 2024*.

Pajewska-Szmyt, M., Sinkiewicz-Darol, E., & Gadzała-Kopciuch, R. (2019). The Impact of Environmental Pollution on the Quality of Mother's Milk. *Environ. Sci. Pollut. Res.*, *26*, 7405.

Phanisankar, B. S. S., Rao, N. V., & Manikanta, J. E. (2020). Materials Today : Proceedings Conversion of waste plastic to fuel products. *Materials Today: Proceedings*, *xxxx*. https://doi.org/10.1016/j.matpr.2020.02.880

Ragaert, K., Delva, L., & Van Geem, K. (2017). Mechanical and Chemical Recycling of Solid Plastic Waste. *Waste Manage.*, *69*, 24.

Rudolph, N. (2017). *Understanding Plastics Recycling* (M. Smith (ed.)). https://doi.org/10.3139/9781569906774

Salaudeen, S. A., Arku, P., & Dutta, A. (2018). Gasification of plastic solid waste and competitive technologies. In *Plastics to Energy: Fuel, Chemicals, and Sustainability Implications*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-813140-4.00010-8

Thimmegowda, G. G., Mullen, S., Sottilare, K., Sharma, A., Mohanta, S. S., Brockmann, A., Dhandapany, P. S., & Olsson, S. B. (2020). A Field-Based Quantitative Analysis of Sublethal Effects of Air Pollution on Pollinators. *Proc. Natl. Acad. Sci. U.S.A.*, *117*, 20653.

Umunakwe, R., Ugbaja, M. I., Eze, W. U., & Madufor, I. C. (2021). *Plastics waste management : A review of pyrolysis technology Plastics waste management : A review of pyrolysis technology*. *July*. https://doi.org/10.3934/ctr.2021003

Vijayakumar, A., & Sebastian, J. (2018). Pyrolysis process to produce fuel from different types of plastic - A review. *IOP Conference Series: Materials Science and Engineering*, *396*(1). https://doi.org/10.1088/1757-899X/396/1/012062

Wijnand, D., Erin, T. B., Guinchard, J.-C., & Ahmed, N. (2021). Plastics: the cost to society, the environment and the economy. *WWF International*, 25. https://wwfint.awsassets.panda.org/downloads/wwf_pctsee_report_english.pdf

Williams, P. T., & Slaney, E. (2007). Analysis of products from the pyrolysis and liquefaction of single plastics and waste plastic mixtures. *Resources, Conservation and Recycling*, *51*(4), 754–769.

https://doi.org/10.1016/j.resconrec.2006.12.002

Wong, S. L., Ngadi, N., Abdullah, T. A. T., & Inuwa, I. M. (2015). Current state and future prospects of plastic waste as source of fuel: A review. *Renewable and Sustainable Energy Reviews*, *50*(October), 1167–1180. https://doi.org/10.1016/j.rser.2015.04.063

Yang, R., Jan, K., Chen, C., & Chen, W. (2022). *Thermochemical Conversion of Plastic Waste into Fuels , Chemicals , and Value-Added Materials : A Critical Review and Outlooks*. *202200171*. https://doi.org/10.1002/cssc.202200171