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ECO-FRIENDLY CONVERSION OF POLYETHYLENE WASTE INTO FUELS USING PYROLYSIS TECHNOLOGY

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ABSTRACT

Context: Non-biodegradable polyethylene trash has become an important environmental issue since it stays in ecosystems and landfills for a long time. We urgently need sustainable waste management solutions to address the rising worldwide usage of plastic.

The purpose of this research is to examine pyrolysis as a green technique for recovering energy and reducing pollution from waste polyethylene byproducts by transforming them into useful fuel products.

The methodology included gathering and cleaning samples of waste polyethylene before putting them through thermal degradation in a laboratory-scale pyrolysis reactor. A regulated temperature range of 400–500°C was used to carry out the procedure in an oxygen-free atmosphere. Gathered and examined for composition and yield using conventional characterisation methods including GC-MS and FTIR were the liquid fuel, gaseous by-products, and solid char that emerged from the pyrolysis process.

The results showed that a lot of the polyethylene waste was transformed into liquid hydrocarbons that looked like regular fuel and kerosene during the pyrolysis process. The operating temperature, residence duration, and feedstock quality all had an impact on the production of liquid fuel. The overall efficiency of the process was enhanced by the little production of solid residue and non-condensable gases.

In conclusion, pyrolysis presents an exciting new direction for the environmentally friendly recovery of valuable fuels from polyethylene trash, which will help mitigate plastic pollution and our dependency on fossil fuels. If this technology is fine-tuned and scaled up, it might be a viable option for converting garbage into electricity in urban and industrial areas.

I. INTRODUCTION

Polyethylene (PE), especially high-density (HDPE) and low-density (LDPE) varieties, is one of the most frequently used and discarded materials, contributing significantly to the tremendous rise in plastic waste caused by the worldwide spike in plastic consumption. Polyethylene is highly regarded for its long-lasting nature and adaptability; it is often used in packaging, containers, and consumer products. The production of dangerous microplastics, overflowing landfills, and contamination of land and sea are only a few of the major environmental problems caused by its indegradability.

There are significant drawbacks to the conventional methods of managing plastic trash, such as burning, mechanical recycling, and landfilling. While cremation produces harmful gases, mechanical recycling often results in materials with diminished quality, and landfilling adds to the environmental load over the long run. These problems show how critical it is to find new ways to handle plastic trash that are both

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environmentally friendly and easy to implement on a large scale.

One potential alternative to traditional methods of plastic waste valorisation is pyrolysis, which involves thermochemical degradation without oxygen. The process of pyrolysis, in contrast to more conventional forms of recycling, reduces lengthy polymer chains to smaller hydrocarbons, which may then be transformed into liquid fuel, petrol and char. With this technology, you may clean up the environment and recover energy at the same time by reducing the amount of plastic trash and producing energy-rich outputs.

The pyrolytic processing of waste polyethylene into useful byproducts is the subject of this research. This research seeks to evaluate the viability and efficiency of pyrolysis as a sustainable method for waste-to-energy conversion by optimising reaction parameters including temperature, duration, and feedstock characteristics.

II. METHODS

2.1: Gathering and Preparing Feedstock

We gathered HDPE and LDPE, two types of waste polyethylene, from things like plastic bags and abandoned packaging throughout town. Before being chopped into tiny, uniform pieces (1-2 cm^2) to guarantee consistent thermal breakdown, the materials were sifted and rinsed with water to eliminate impurities.

2.2 Experimental Configuration

For the thermal conversion procedure, a laboratory-scale batch pyrolysis reactor was used. Constructed from stainless steel, the reactor had:

- A mantle that heats
- Instrument for controlling temperature
- Recovering liquid fuels using a condenser
- Discharge of gas and char stack

The device was engineered to function in an inert (absence of oxygen) setting, where controlled pyrolytic breakdown may take place without combustion.

2.3 The Pyrolysis Process

The reactor chamber was filled with 200-500 g of polyethylene feedstock.

Nitrogen gas was used to purge the reactor of oxygen for ten to fifteen minutes, creating an inert atmosphere.

The temperature was raised from room temperature to 400–500°C in a controlled manner.

Reaction Time: In order to achieve complete thermal disintegration, the plastic was heated to its peak for around 60 to 90 minutes.

Using a water-cooled condenser, the process's vapours were transformed into liquid fuel.

The liquid fuel was collected in an additional container after the reaction, and the gaseous by-products were released via a gas outlet. After the reactor chamber cooled, the remaining solid char was removed by hand.

2.4 Defining the Product

Fuel in a liquid state: GC-MS for hydrocarbon identification and FTIR for functional group identification are used in the analysis.

Gas and Char: In order to assess their possible future applications, qualitative observation and basic analysis were carried out on materials such as syngas and activated carbon.

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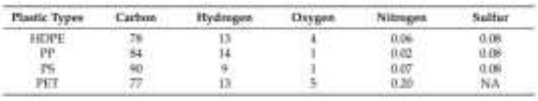
III. PLASTIC WASTE PROPERTIES

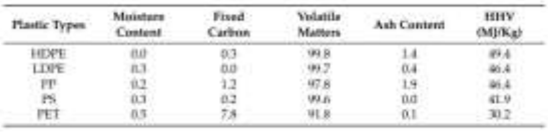
It is common practice to crush, shred and filter plastic trash into fine flakes (less than 2 mm) in order to get an excellent heat/mass transmission during pyrolysis. Here are the results of the proximate and final analyses of various plastic wastes: Tables 1 and 2. Plastic trash is well-suited for pyrolysis because of its high carbon and hydrogen concentration, high volatile matter content (more than 90 wt.%), and high conversion to the gas and liquid byproducts.

Table 1. Ultimate analysis of different plastic wastes [23].



Plastic Types	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur
HDPE	78	13	4	0.06	0.08
PP	84	14	1	0.02	0.08
PS	90	9	1	0.07	0.08
PET	77	13	5	0.20	NA

Table 2. Proximate analysis of various plastic types [2].



Plastic Types	Moisture Content	Fixed Carbon	Volatile Matters	Ash Content	HHV (MJ/Kg)
HDPE	0.0	0.3	99.8	1.4	49.4
LDPE	0.3	0.0	99.7	0.4	46.4
PP	0.2	1.2	97.8	1.9	46.4
PS	0.3	0.2	99.6	0.0	41.9
PET	0.5	7.8	91.8	0.1	30.2

IV. PYROLYSIS PROCESS

At temperatures greater than 400 ◦C, pyrolysis takes place, a multipurpose thermal cracking process that doesn't need oxygen. The three main categories of pyrolysis procedures are slow, rapid, and flash [24,25]. In this thermochemical process, heat and chemical processes are used to break down the long chain polymer molecules into smaller, less complicated ones. The usual conditions for slow pyrolysis include a lengthy vapour residence time, heating rates ranging from 1 to 10 ◦C/min, and temperatures between 350 and 550 ◦C. The main byproduct of slow pyrolysis is char, a solid residue that forms as a result of the several parallel-competitive processes that benefit from a low heating rate [25]. Typical temperatures for rapid pyrolysis are 500 to 700 ◦C. Vapour residence periods are typically a few seconds, and the feedstock experiences heating rates over 1000 ◦C/min [26]. The pyrolysis of polyolefin materials may produce a surprising amount of liquid, up to 90 weight percent, depending on the kind of feedstock [27]. This is because fast pyrolysis is favourable to liquid generation. The feed goes through a very rapid heating rate and vapour residence periods are measured in milliseconds during flash pyrolysis, which typically occurs at temperatures exceeding 700 ◦C [25]. On the one hand, flash pyrolysis may generate more oil from biomass feedstocks than fast pyrolysis [28]. On the other hand, when it comes to plastic waste, rapid pyrolysis creates more gas than any other product. There are three distinct kinds of byproducts that may be generated from the pyrolysis of plastic waste: gas, solid residues, and liquid/wax [29].

Plastic oil, once manufactured, can take the form of a liquid or a wax. At ambient temperature, the wax is quite viscous and has a yellowish hue. Its main constituents are hydrocarbons with a high boiling point (C20+)—alkanes and alkenes [34]. To transform wax into liquid fuels, an additional procedure is usually necessary, such as fluid catalytic cracking (FCC). The majority of the chemicals in liquid plastic oil are aliphatic, with some mono- and polyaromatic components as well [29]. Further cracking at higher temperatures and very short contact durations may convert the plastic oil into ethylene and propylene, making it an intermediate that has potential fuel uses as well. Methane, propylene, ethylene, butadiene, and butane are the main gaseous species that make up the "gas product" [35]. The process may be made self-sustaining and independent of external energy sources by using the gas product as an energy source to deliver the needed pyrolysis energy. Furthermore, the gas stream contains important olefin components that may be collected and used for chemical recycling by separation. The leftover byproduct of pyrolysis, known as the solid residue, is mostly composed of ash and coke [36].

4.1. Slow Pyrolysis

In Table 3, we can see the results of the slow pyrolysis experiments that were run on different reactors with different operating parameters to convert plastic waste with or without the use of a catalyst. The findings show that delayed pyrolysis usually results in an oily liquid instead of a waxy one. When LDPE is pyrolysed at 550 ◦C, the oil production may approach 93 wt.%, which is an impressive yield with several potential uses [21]. In addition to its direct usage in steam boilers to generate power, plastic oil has many additional potential uses as a platform chemical in fields as diverse as transportation fuels, monomer recovery, and the manufacture of carbon nanotubes (CNTS). Because plastic trash has more volatile materials and lower fixed carbon than biomass, the solid residue output is much lower than bio-based char (Table 1). Since the C6–C12 petrol fraction may make up as much as 90% by weight of the liquid product, it is very desirable for use as a substitute for regular petrol.

4.1.1. Influence of Plastic Types

Table 3 shows that, in the absence of a catalyst, the liquid oil obtained from the pyrolysis of polyolefins (such as LDPE, HDPE, and PP) usually contains a high percentage of aliphatic (alkanes and alkenes). Later, in Section 3.1.2, we'll talk about how the catalyst affects the plastic oil composition. In order to get a high conversion rate of polyolefins during pyrolysis, the ideal temperature is more than 450 ◦C. This is because, below this temperature, the solid residue grows significantly. An impressive number of aromatic chemicals, including benzene, toluene, and ethyl benzene, may be produced by a liquid containing polystyrene (PS) [2]. When polyolefins and polystyrene are pyrolysed, a liquid oil is produced. This oil has many potential uses as a fuel or chemical precursor. On the other hand, when PET and PVC are pyrolysed, large quantities of benzoic acid and hydrochloric acid are produced. These acids are harmful to the reactors and can cause corrosion [2,37]. That is why pyrolysis is usually not used for these two polymers.

Table 3. Slow pyrolysis of different plastic wastes

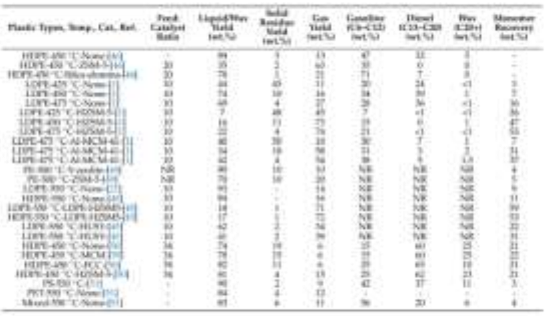
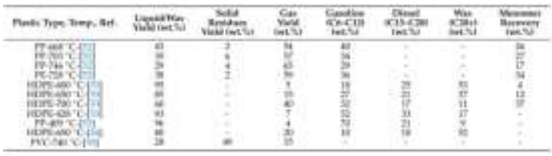


Table 4. Fast pyrolysis of different plastic wastes



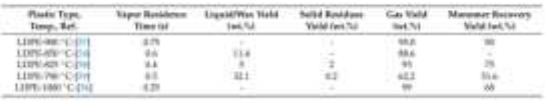
Influence of Temperature

Regardless of the feedstock source, temperature is a critical factor in all pyrolysis processes. As with any pyrolysis process, the gas yields from the improved cracking processes grow rapidly as the temperature rises in the case of plastic waste pyrolysis, whereas the oil/wax yield falls (Table 4). As one would anticipate from a variable that influences the pyrolysis kinetic processes, temperature not only changes yields but also effects product quality. The conversion of long-chain paraffins and olefins to shorter molecules is the primary mechanism by which high temperatures promote the synthesis of oily compounds rather than waxy ones. On the other side, higher temperatures result in a lower solid residue yield. An evaluation of plastic oil's quality reveals that heating it to high temperatures promotes a rise in petrol production, which is proportional to an increase in aromatic content [52]. Increasing the temperature results in a higher production of ethylene and propylene.

4.3. Flash Pyrolysis

A viable alternative is flash pyrolysis, which occurs within milliseconds, to prevent over-cracking reactions during pyrolysis, particularly at high temperatures (over 700 ◦C), which transform a substantial quantity of liquid into gaseous products. Table 5 shows that flash pyrolysis of plastic waste creates more gas than liquids, in contrast to rapid pyrolysis of biomass, which produces the most bio-oil. Flash pyrolysis may recover up to 75 weight percent of monomers, namely ethylene and propylene, as shown in Table 5. The oil that is produced as a byproduct may be used to provide the energy needed for the operation. Kannan et al. [56] examined the impact of temperature on monomer recovery (olefin yield) by conducting a flash pyrolysis of LDPE in a microreactor with negligible heat/mass transfer resistance at temperatures ranging from 600 to 1000 ◦C and a vapour residence time of 250 ms. Up to 68% of the monomers may be recovered within the temperature range of 950 to 1000 ◦C.

Table 5. Flash pyrolysis of LDPE with different experimental parameters.



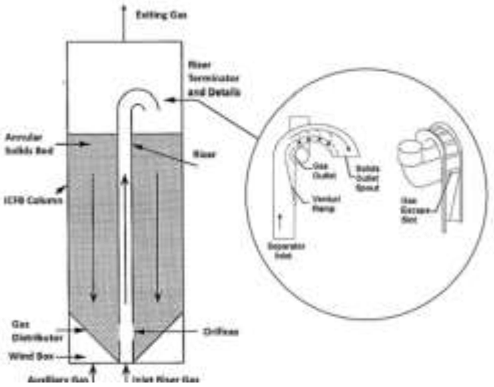


Figure 1. Internally circulating fluidized bed (ICFB) and riser terminator (adapted from [58,60])

V. PLASTIC OIL CRACKING

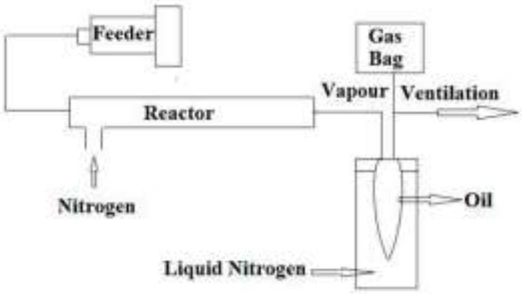
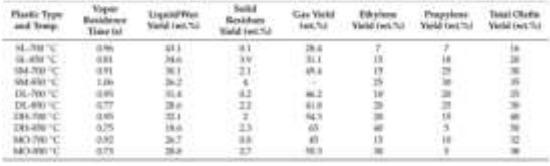


Figure 2. Schematic diagram of the experimental apparatus for cracking of raw plastic pyroland extracted oil after separation of aromatics (adapted from Reference)

Table 6.Pyrolysis of different plastic Wastes[35]



VI. UPGRADING OF PYROLYSIS PLASTIC OILS

6.1. Blending

We have already shown that raw pyrolysis plastic oil is very hot (40-55 MJ/kg), very dry (<1 wt.%), and has a pH that is almost neutral. Boilers may easily use it as-is to generate power. According to amodharan et al. [21], the current engine infrastructure does not need odification as diesel engines can run plastic oil smoothly. But there are a number of academics who think that in order to satisfy EN590 criteria, plastic oil quality has to be improved [8,62-64]. There have been reports of a significant heat release and delayed ignition as downsides of using pyrolysis plastic oil in internal combustion engines [61]. For this reason, a mixture of regular petrol and plastic oil could work. Blended fuels have shown consistent performance in conventional engine experiments, with lower NOx and SOx emissions than diesel and petrol alone [65]. There have been reports of lower specific fuel use as well [61]. According to Awasthi and Gaikwad [66], using 20 wt.% pyrolysis plastic oil improved the overall performance of the diesel-plastic oil mixture in a one-cylinder four-stroke VCR diesel engine. Regular diesel engines may readily use a plastic oil/diesel mix of up to 50%, according to experiments conducted by Singh et al. [61].

6.2. Hydrogenation

An unsaturated molecule, hydrogen, and a catalyst are the three necessary elements for the hydrogenation process to occur. A heterogeneous catalyst allows the reaction to take place at lower temperatures and pressures by facilitating the transfer of hydrogen pairs to the unsaturated molecule. As an example, plastic oil undergoes hydrogenation to change its alkenes to alkanes [67]. Some storage instability issues may arise with plastic oils over time because of the high concentration of unsaturated chemicals in them. The presence of a catalyst, such as ZSM-5, may convert unsaturated molecules into saturated ones, and the hydrogenation of pyrolysis oil, which happens at temperatures over 700 C and pressures about 70 bar, stabilises the oil. To improve the plastic oil's quality to satisfy the EN590 standard, a mix of hydrogenation and blending has been proposed [67]. Table 8 compares the fuel attributes of the EN590 standard with those of diesel, plastic oil, and hydrogenated plastic oil.

Table 8. Physicochemical properties of diesel, plastic oil and hydrogenated plastic oil [67]

Properties	Lower Limit Standards EN590	Upper Limit Standards EN590	Diesel	Plastic Pyrolysis Oil	Hydrogenated Plastic Pyrolysis Oil
Density (kg/m³)	820	845	837	771	851
Pour Point (°C)	-	-	−15	−30	−29
Flash Point (°C)	55	-	72	20	68
Fire Point (°C)	-	-	82	30	72
Calculated Cetane Index	46	-	52	60	62
Kinematic Viscosity (mm²/s)	2	4.5	2.51	1.78	3.5
Gross Calorific Value (MJ/kg)	-	-	46	45	45
Ash Content (wt.%)	-	0.1	0.01	0.01	0.01
Conradson Carbon Residue (wt.%)	-	-	0.18	0.2	0.1

VII. CARBON NANOTUBES

Anisotropy, a perfect one-dimensional (1D) structure, high thermal conductivity, stable chemical properties, and a mechanical strength 100 times that of steel are just a few of the unique features that have contributed to carbon nanotubes' (CNTs') rise to prominence as a desirable material [69–72]. The manufacture of carbon nanotubes has traditionally relied on nonrenewable resources such as benzene, acetylene, natural gas, and methane. Researchers have recently focused on the possibility of creating CNTs from plastic trash using pyrolysis, which might give these materials new life. There are two steps involved in the process of making CNTs from plastic trash (Figure 3). The first step involves heating the plastic trash to a moderate temperature (around 550 ◦C) and removing oxygen so that it may be transformed into a volatile vapour. Afterwards, the vapour that has been formed is transferred to the second

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stage, where it undergoes a chemical vapour deposition process to transform into carbon nanotubes on the catalyst surface. This conversion takes place at a high pressure of 1 MPa and a temperature of 750 ◦C, in the presence of a catalyst that is based on nickel. The CNT yields may be as high as 25 wt.% using this sophisticated method [73]. Plastic waste vapours undergo further decomposition in the second step, which occurs during pyrolysis at 750 ◦C, to mixes of their monomers, such as ethylene, propylene, and styrene. Carbon nanotubes (CNTs) are formed when these light gases donate carbon. The initial stage's vapours also include a lot of hydrogen, which is obviously important for CNT synthesis. Continuous surface cleaning of the catalyst surfaces by hydrogen minimises deactivation and poisoning and moderates the rate of carbon deposition [69-72]. See Figure 4 for a scanning electron micrograph (SEM) showing CNTs growing on a Ni-based catalyst.

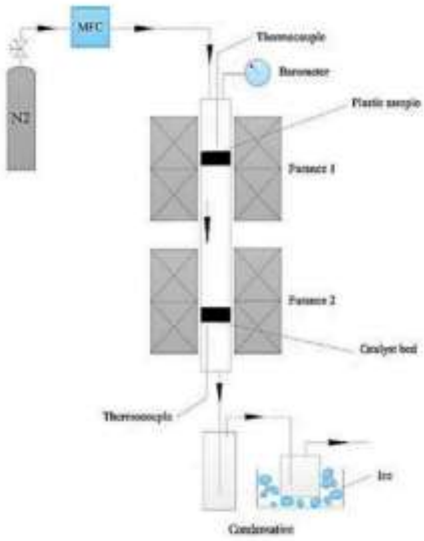

Figure 3. Schematic diagram of two-stage pyrolysis reactor system (adapted from [74]). Schematic diagram of two-stage pyrolysis reactor system (adapted from [73]).

Figure 4. CNT growth on Ni-based catalyst (adapted from [73]).

VIII. CONCLUSIONS

A sustainable and practical method for recycling waste polyethylene plastics into useful goods, mainly liquid fuels, can be shown by this study: pyrolysis. Polyethylene was successfully transformed into various byproducts, such as liquid hydrocarbons, flammable gases, and char, by means of controlled thermal breakdown in an oxygen-free atmosphere.

This technology has the potential to solve environmental and energy problems simultaneously by tackling the growing problem of plastic waste and adding to energy recovery efforts. The circumstances that produced the most liquid fuel, with physical and chemical characteristics similar to those of regular diesel and kerosene, were those with temperatures between 400 and 500 degrees Celsius.

To sum up, pyrolysis is a nice, green substitute for the old ways of getting rid of plastic trash. By lowering environmental effect and turning trash into money, this technology might become a crucial component of circular economy initiatives with more refining and scalability.

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