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Review JoPC

Various Methods For Plastic Waste Pyrolysis To Fuels: A Review

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Abstract

The world's decreasing oil reserves and increasing energy demands are pushing experts to explore alternative ways of producing premium oils that can replace fossil fuels. Waste-to-energy recovery, which involves converting waste materials into energy, shows great potential for managing waste. Waste plastics, abundant and with a high combustion heat, are attractive for energy conversion. However, the vast use of plastic products, both industrially and domestically, leads to a surge in plastic production and disposal issues, posing environmental threats. Pyrolysis is a highly recommended method to convert plastic into high-quality liquid oil. This thermochemical process decomposes plastic at elevated temperatures in an oxygen-free environment, yielding products such as oil, gas, and char. The resulting oil has a higher energy value than conventional fuels and can be refined for transportation and power generation. This article reviews common plastics, such as polystyrene (PS), polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), high-density polyethylene (HDPE), and low-density polyethylene (LDPE) and how pyrolysis can be used to transform them into oil and electricity. The process not only reduces plastic waste but also provides a sustainable solution for global energy demands. Recent developments in pyrolysis technology, such as thermal and catalytic processes, have shown increased fuel production efficiency and environmental sustainability. The study also highlights how important it is to optimize pyrolysis parameters, including temperature, catalyst type, and reaction duration, in order to improve process efficiency. By combining energy recovery and waste management, pyrolysis offers a scalable, environmentally responsible way to deal with the expanding problem of plastic waste, helping to establish a circular economy. In addition to cutting down on plastic waste, this method generates useful energy resources like gas, oil, and char. It lessens dependency on fossil fuels, promotes sustainable energy sources, and is essential for building a sustainable economy.

Keywords: Plastic waste, Pyrolysis, fuel production, polystyrene (PS), Polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), high density polyethylene (HDPE), low density polyethylene (LDPE).

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INTRODUCTION

Every year, a lot of plastic waste is created worldwide. Most plastics don't break down naturally in landfills and can release harmful gases when burned [1]. Plastic waste continues to pose a significant threat to surface and surface water bodies such as streams, seas, and oceans, compromising the safety of both animals and humans [2]. Plastic garbage has become a large component of waste streams, containing a variety of plastic products. These products primarily comprise low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) plastics [3]. In the wake of the escalating global plastic pollution crisis, pyrolysis emerges as a promising solution, offering a pathway towards the sustainable disposal and utilization of plastic waste. Pyrolysis is the heat decomposition of organic compounds in the absence of oxygen, which produces useful products like as liquid fuels, gasses, and char [4]. Pyrolysis breaks down materials using heat in a controlled environment, typically between 400 and 500 degrees Celsius. Plastic pyrolysis mainly produces oil and steam, which can be used for energy and making certain chemicals. This process, known as "pyro cycling," is done under vacuum conditions [5].

The conversion of waste plastics into gasoline has various advantages. First, it initiates a fresh cycle of consumption from non-renewable energy sources [6]. Second, it supplies a significant source of petrochemicals, reducing the use of non-renewable energy resources [6]. Third, it provides a practical, novel, and alternative approach for reducing waste plastics, so keeping them from damaging the environment [6]. Plastics in various forms are among the most extensively used materials due to their numerous benefits and applications in everyday life [7]. In 2010, plastic output in the United States totalled about 14 million tons as containers and packaging, 11 million tons as durable products such as household appliances, and 7 million tonnes as insubstantial items such as plates and cups [6]. However, in 2010, only 8% of total waste plastics were recycled [6, 7]. High-density polyethylene (HDPE) bags are used in pipe, drums, gas tanks, furniture, toys and low-density polyethylene (LDPE) bags are commonly used for packaging [8]. Polyethylene is made from petroleum, a non-renewable resource that takes years to degrade in a landfill [9]. However, the efficiency of pyrolysis can vary depending on the type of plastic feedstock utilized. Different types of plastics exhibit distinct thermal degradation behaviours and yield varying proportions of pyrolysis products [10]. This research paper reviews into the pyrolysis process across a range of plastic such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) plastics.

ENVIRONMENTAL AND ECONOMIC DRIVERS FOR USING PYROLYSIS IN PLASTIC WASTE MANAGEMENT

There is increasing demand for innovative technology solutions to handle the worsening plastic waste problem. Pyrolysis is recognized as both an environmentally friendly and cost-effective technology for turning plastic waste into useful fuels and commodities. This section discusses why pyrolysis has become a critical approach for managing plastic waste [11].

Environmental Drivers

Landfill diversion and space optimization

The growing rate at which plastic waste accumulates has meant that landfill spaces in cities are being quickly filled up. The long-lasting plastic materials take up landfills for years without undergoing break down. It significantly cuts down the overall amount of plastic that ends up in landfills, conserving valuable land space for other uses. As a result, this solution is vital in places where space is scarce or waste management systems are still developing.

Lower Carbon Footprint in Relation to Waste Incineration

Emissions from incinerating plastics include carbon dioxide along with nitrogen oxides and hazardous substances like dioxins and furans which are most prevalent when burning chlorinated plastics like PVC. When conducted in a low-oxygen environment, pyrolysis reduces the levels of complete combustion and hence limits CO_2 emissions. Advanced pyrolysis setups combined with gas cleaning technology help maintain emissions within legal boundaries set by the EU Industrial Emissions Directive (IED).

Circular Resource Utilization

Pyrolysis transforms discarded plastics into useful new materials such as pyrolysis oil and gas which can be reused in a circular economic system. They are suitable for use as fuels or as precursors in industrial manufacturing. It minimizes reliance on new oil and supports initiatives promoted by SDG 12 related to sustainable use of resources.

Dangerous Substances Elimination and Resource Restoration

Disposal methods such as landfilling or incineration of plastics that contain additives, flame retardants or POPs is hazardous. Thermochemical decomposition performed at precise temperatures in pyrolysis prevents these substances' release into the environment or exposure to humans. Laboratory tests show that plastic e-waste can be decontaminated by 99% or more when treated by pyrolysis [12].

ECONOMIC DRIVERS

Monetization of Pyrolysis Products

Purified oil obtained from pyrolysis can serve as both a combustible fuel and a feedstock for the production of alternative diesel, naphtha and aviation fuel. Prices for pyrolytic oil tend to be $300–600 per ton, based on its heating content and the makeup of the hydrocarbon mixture. Direct use of combustible byproducts from pyrolysis as pyrolysis reactor fuel results in energy self-sufficiency and pyrolysis char can effectively replace coal and oil products.

Processing Low-Cost or Negative-Cost Feedstocks

Local governments end up spending greatly on landfilling when getting rid of their plastic refuse. Pyrolysis units are often able to procure these plastics at no extra expense which may be an inexpensive or free source of raw materials. This makes the economic viability of the process easier to achieve and expands the range of applications for older or more challenging plastic types.

Employment and Localized Economic Development

Pyrolysis facilities can be established on a local scale in urban and semi-urban areas with smaller installations. The decentralization of pyrolysis plants helps generate opportunities for local residents in sorting, operating and maintaining the facilities.

Government Incentives and Carbon Credits

Countries in many regions offer incentives such as subsidies, fiscal benefits or renewable energy credits to advance waste-based power generation. Many incentive programs recognize pyrolysis as a viable option since it commonly replaces diesel or LPG utilization. Participation in voluntary carbon markets or CDM projects enables the generation of carbon credits when pyrolysis lessens greenhouse gas emissions compared to the most common means of waste disposal [13].

TYPES OF PLASTIC MATERIALS

Plastic is widely used globally for many purposes but is often discarded and does not break down naturally [14]. This discarded plastic ends up in landfills, on garbage trucks, and in litter, causing problems like clogging storm drains, flooding streams, and harming the environment. It's crucial to protect our ecosystems from this plastic waste [15].

Polyethylene Terephthalate (PET)

PET plastics are commonly used for food and beverage packaging like soft drink and water bottles, as well as in other applications such as magnetic tapes, printing sheets, and electrical insulation [16]. However, the widespread use of PET results in a lot of plastic waste that harms the environment [17]. To reduce PET waste, recycling is a common strategy. Due to the large amount of PET containers used, collecting and transporting them for recycling can be expensive [18].

Researchers have experimented with pyrolysis to break down PET plastic. Cepeliogullar and Putun have conducted a study where PET was heated to 500°C in a fixed-bed reactor with nitrogen gas [19]. This process yielded 23.1% liquid oil and 76.9% gaseous products [19]. However, the resulting oil was acidic, which can damage engines and fuel quality [19]. Another study found by Fakhrhoseini and Dastanian [19], the liquid yield was found to be 39.89 wt%, gaseous was 52.13 wt% while solid residue was 8.98 wt%. The breakdown of PET during pyrolysis can be visualized by understanding its molecular structure and the likely ways it breaks down under heat [19].

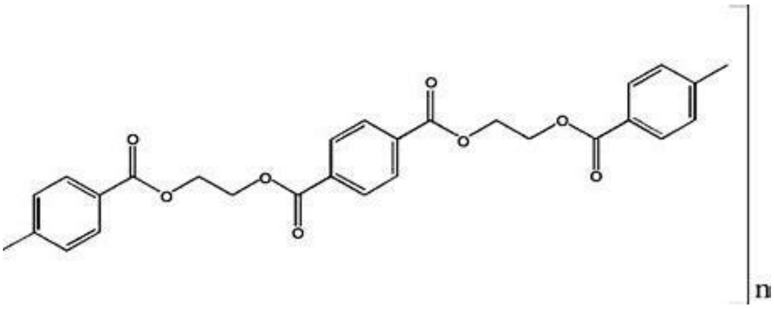

Figure 1. Structure of polyethylene terephthalate (PET)

From above (Figure 1) PET has a triclinic crystal structure and molecules in nearly flat planes bind together through Van der Waals forces, so its crystalline density is 1.455 g/cm³. X-ray study of drawn fibers found that many crystals are tilted and some molecular chains are no longer lined up with the fiber's main direction. Aromatic rings give benzene a rigid structure which is what causes its high melting point rather than the strong forces holding the molecules together. The degree of crystallinity in fibers rises to 64.5% depending on how densely packed the fibers [69].

High- Density Polyethylene (HDPE)

High-density polyethylene (HDPE) is a strong plastic made of long, linear chains of polymer. It's used in various products like toys, oil and milk bottles, and detergent containers, and is one of the most common plastics found in municipal solid waste [20]. Researchers have studied how to break down HDPE through pyrolysis [20].

In one study which was conducted by Ahmad et al, HDPE was heated to temperatures between 300°C and 400°C in a steel reactor with nitrogen gas [19]. This process resulted in 80.88% of the plastic turning into liquid at 350°C, with some solid residue left at lower temperatures [19]. Other study which was conducted by Kumar and Singh heated HDPE to higher temperatures, such as 550°C, which produced more liquid oil but also more gaseous products [19]. However, heating above certain temperatures, like 550°C, can cause the HDPE to break down further, producing more gas and less liquid oil [19].

For instance, at 650°C, a study conducted by Mastral et al found that 68.5% of the HDPE turned into liquid oil and 31.5% into gas [19]. This shows that heating HDPE too much can turn the liquid oil into gas, reducing the amount of useful oil produced [19].

HDPE changes its structure so that it becomes more crystalline when it is affected by the environment, because the polymer chains separate and can move more freely. The loss of material quality, ductility and increased brittleness happens when polymer is exposed to sunlight or weathering. Using infrared, it can be confirmed that carbonyl and vinyl groups were created. Radicals in combinations with carbon monoxide copolymers allow them to degrade more rapidly while still undergoing the same changes based on (Figure.2) [70].

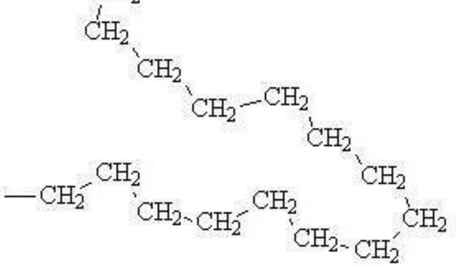

Figure 2. Structure of high- density polyethylene(HDPE).

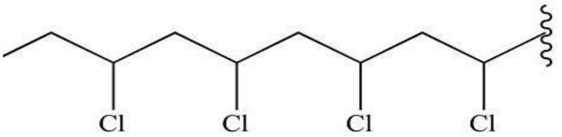

Figure 3. Structure of polyvinyl chloride(PVC).

Polyvinyl Chloride(PVC)

Polyvinyl chloride (PVC) is different from other plastics like polyethylene or polypropylene because it's made from a combination of carbon (42%) and chlorine (58%)[21]. PVC is known for being resistant to fire and is often used for electrical insulation due to its high chlorine content[22]. However, PVC is not commonly pyrolyzed (broken down by heat) because it releases hydrogen chloride (HCl) fumes at high temperatures[23].

In a study found by Jin et al[19] when he heated PVC in a batch reactor at temperatures ranging from 220°C to 520°C, increasing at a rate of 10°C per minute[19]. This process produced a liquid oil with a weight percentage ranging from 0.45% to 12.79%. Additionally, about 58.2% of the trial's output was hydrogen chloride (HCl), a byproduct extracted during the experiment[19].

The changes in PVC's structure are responsible for hydrogen chloride release, discoloration, joining of molecules and a decrease in solubility. Through free radicals, heat or light are some of the main causes that start this process. Stabilizers interrupt these extreme phases and making sure there is oxygen plays a role in directing the ways the substances break down according to (Figure.3) [71].

Low-Density Polyethylene (LDPE)

Low-density polyethylene (LDPE) is a type of plastic that is not very strong and is not very hard because its molecules are not strongly attracted to each other. LDPE has more branches compared to another type of plastic called high-density polyethylene (HDPE) [24]. LDPE waste is one of the most common types of plastic waste found in regular trash. Researchers have studied what happens when LDPE is heated up in a controlled environment. For example, Bagri and Williams heated LDPE in a special container at a high temperature of 500°C using nitrogen gas to help the process [19]. They found that most of the LDPE turned into liquid oil with a little bit of gas and solid material left over. Other studies have also looked at heating LDPE to different temperatures to see what kinds of substances are produced. A study which was conducted by Marcilla et al, when he heated LDPE to 550°C, it mostly turned into liquid oil [19]. From the research conducted by Koizumi et al. [19], 75.6 wt% of liquid oil was obtained in a batch reactor at 400°C. These experiments help us understand how LDPE breaks down when heated and what kinds of products can be made from it [19].

Polypropylene (PP)

Polypropylene (PP) is a type of plastic known for its ability to withstand high temperatures and chemicals [25]. It has a straight chain of carbon atoms bonded together and is very stable below 160°C, meaning it doesn't melt easily at low temperatures [26]. PP is favoured in the plastics industry because it is strong and rigid but not very dense compared to other plastics. PP is used in making a wide range of products like flowerpots, folders, car bumpers, carpets, furniture, and storage containers [27,28].

Researchers have studied how PP breaks down when heated in a controlled environment to maximize the production of liquid oil. One experiment which was conducted by Ahmad et al heated PP between 250°C and 400°C and found that at 300°C, nearly 70% of the PP turned into liquid oil [19]. Another study by Sakata et al at 380°C resulted in 80.1% liquid oil, 6.6% gas, and 13.3% solid residue [19]. When PP was heated to 500°C, Fakhrhoseini and Dastanian obtained 82.12% liquid oil, but higher temperatures above 500°C led to less liquid oil [19]. Demirbas conducted an experiment at a very high temperature of 740°C, which produced 48.8% liquid, 49.6% gas, and 1.6% solid residue. This study showed that as the temperature increases, the amount of liquid oil produced decreases [19]. These experiments help us understand how PP behaves under different conditions and what products can be obtained from it through heating [19].

Polystyrene (PS)
Polystyrene (PS) is a type of plastic made from styrene molecules derived from petroleum. It consists of long chains of carbon and hydrogen atoms, with each carbon atom attached to a phenyl group. PS is clear but can be coloured easily with dyes [29,30,32]. It's used in various industries like food packaging, electronics, construction, medicine, toys, and appliances because it's strong, durable, and lightweight [31]. However, as its use grows, there's a lot of PS waste accumulating since it's often not accepted in regular recycling programs.

The only effective way to deal with PS waste currently is through pyrolysis, a process that turns it into high-quality liquid oil and gasoline [32]. Researchers have studied PS pyrolysis extensively. For instance, Onwudili et al used a special pressurized reactor and heated PS waste between 300°C and 500°C for an hour [19]. At 425°C, they obtained 97.0% liquid oil and 2.5% gas. Similarly, Liu et al used a fluidized bed reactor at temperatures ranging from 450°C to 700°C and achieved 98.7% liquid oil at 600°C [19]. Even at lower temperatures like 450°C, they still obtained a good amount of liquid oil. However, Demirbas found lower liquid oil yields in his experiments with PS, reaching 89.5% at 581°C in a batch reactor. These studies help us understand how to efficiently convert PS waste into valuable liquid oil through controlled heating processes [19].

Different kinds of plastic such as PS, PE, PP and PET, were evaluated in their ability to undergo pyrolysis is reported in Table 1. Most liquid oil was produced by PS and it had favorable fuel properties and was high in styrene. All the pyrolysis oils were similar to diesel and could be used for energy purposes. On the other hand, post-treatment plays a key role in cutting aromatics for transport fuel [68].

Method of Pyrolysis of Plastic
Pyrolysis represents one of the practical methods for turning plastic waste into fuel. In the absence of oxygen, pyrolysis is a complex sequence of chemical and heat events that depolymerize an organic molecule [33].

Table 1. Types of plastics and their applications

S no.	Plastic types	Characteristics	Applications	As Pyrolysis feedstock
1)	Polystyrene (PS)	* Heat resilience * Lightness * High strength * Reasonable durability	* Toys * Medical stuff * Electronics * Food packaging * Construction stuff	*Requires low temperature in comparison to PP and PE plastic types
2)	Polyethylene (PE)	HDPE * It is a long polymer chain * Highly crystalline * High strength properties polymer LDPE *Less tensile strength * Less hardness *Excellent water resistant *Desirable polymer for various applications	* Toys * Oil containers * Detergents bottles * Milk bottles *Trash bags *Wrapping foil for packaging *Plastic bags	*Requires high temperature greater than 500 °C due to its long chain structure * It converts into wax instead of liquid fuel in thermal pyrolysis
3)	Polypropylene (PP)	* Good heat and chemical resistance * Low density * High rigidity * High hardness	*Carpets *Furniture *Storage box *Office folder *Flower pot *Car bumpers	*Requires high temperature * Produces liquid yield with high aromatic compounds under catalytic pyrolysis
4)	Polyvinyl chloride (PVC)	*Resistant to fire *Versatile plastic	* Credit cards * Medical devices * Packaging * Food foil * Boots * Window frames	*Produce hazardous chlorine gas *Dichlorination via low temperature (250 – 320 °C) or physical or chemical adsorption

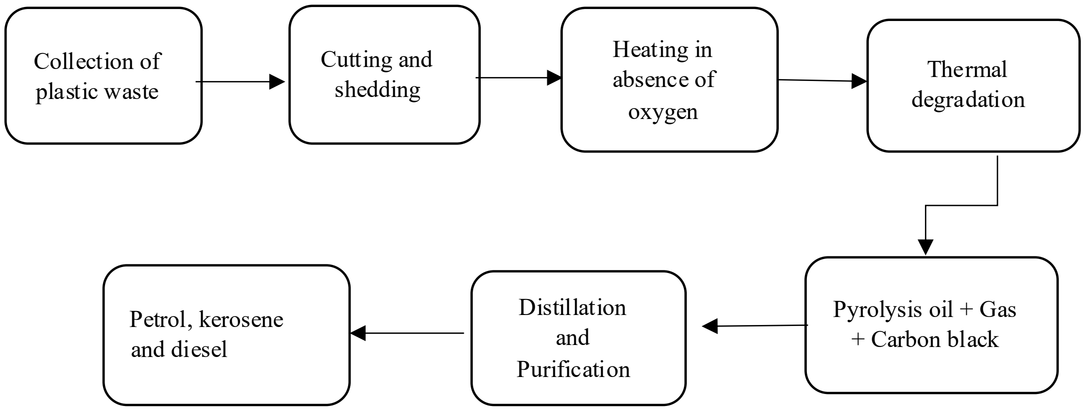

Figure 4. Schematic diagram of plastic pyrolysis

Plastics must first be heated to a high temperature to extract or distil the volatile substance, which can then be used again as an energy source [34]. During waste plastic pyrolysis, the plastic waste is heated to high temperatures without oxygen and with a catalyst present to aid in the slow breaking down of lengthy chains. Low-sulfur waste plastic oil is made by condensing the generated gases in a condenser [35,36]. Furans, or benzene rings, and dioxins cannot develop during the procedure if catalysts are used [35]. Plastics' three primary constituent gas, crude oil, and solid residue are broken down by heat. The hydrocarbons with higher boiling points that result from non-catalytic pyrolysis process make up crude oil. Plastics can be converted into fuels using pyrolysis, incineration, gasification, and the plasma process. Through the process of pyrolysis, plastic wastes are broken down into simpler, shorter molecules without the presence of oxygen, resulting in the production of solid, liquid, or gaseous fuels. Combustible gas with a high calorific value, combustible oils, and carbonized char are the principal byproducts of pyrolysis [36].

This waste-to-energy procedure uses plastic to create high-calorific liquid oil and it serves as a way to move away from using fossil fuels. With growing waste from plastic being used at home and work, pyrolysis is a good answer for generating energy and helping protect the environment. The method uses the heat of plastics to turn them into high quality fuel which makes it a safe way to get rid of plastic waste [63]. Figure 4 illustrates various steps involved in converting plastics to fuels.

Pyrolysis is the process of thermally breaking down long-chain polymers into less complicated molecules in the absence of oxygen to transform plastics into solid, liquid, or gaseous fuels. Carbonized char, premium oils, and high calorific gas are the by-products of pyrolysis. At moderate conditions, pyrolysis can yield up to 80 weight percent and needs temperatures between 300 and 900 degrees Celsius [50,37,38]. The four primary processes are flash, catalytic plastic pyrolysis, slow, rapid, and fast [39]. Among the different forms of pyrolysis is conventional pyrolysis, also known as slow pyrolysis, which produces a substantial amount of solid, liquid, and gaseous products while heating at a low rate. It's an old method mostly applied to the making of charcoal [50,40]. Tar-related fast pyrolysis can occur at lower temperatures (850– 1250 K) or at higher temperatures (1050–1300 K) with a gas. Catalytic pyrolysis and thermal pyrolysis are two more [50,41]. The most popular method, known as fast or flash pyrolysis, occurs at high temperatures and brief residence times. Fast thermolysis, also known as fast pyrolysis, is the process of quickly heating a carbonaceous substance to a high temperature without the presence of oxygen [42].

Through the years, advances in pyrolysis technology have allowed for the profitable extraction of liquid oils from organic sources. The various feedstock types that are used in the process continue to present difficulties [43]. The development of novel reactor designs that maximize product yields while lowering energy consumption and process expenses is essential to the success of pyrolysis. Many industrial facilities are currently using the well-established technology of pyrolysis to process plastic and biomass feedstock [44].

Pyrolysis oil, a hydrocarbon-rich gas with a heating value of 25–45 MJ/kg that is perfect for process energy recovery and char, is one of the byproducts of plastic pyrolysis. As a result, the pyrolysis gas can be recycled back into the process to recover energy for process heating, significantly lowering the need for outside heating sources [45,50].

In a process known as cracking, waste plastics are combined and heated in an oxygen-free environment to produce a gas. Products ranging from light oils and gas to heavy wax and oils are made by distilling the gas or vapor. The majority of these goods could serve as fuel or serve as additional sources of polymer building blocks [46,50]. The reactor, condenser, fractionating tower, and condenser are the primary components of a plastic pyrolysis process plant [47].

Even difficult-to-recycle plastics, such as polystyrene and flexible packaging, may be converted into 75% liquid oil by a pyrolysis plant, which can then be utilized as a feedstock for plastic production and as a sustainable fuel. The remaining 25% can be utilized as a wax substitute to make paint and candles, and the plant can employ the gas and char that are created as energy sources [50,48]. The most popular method for getting rid of plastic trash is thermal treatment, which produces heat for steam production, electricity generation, or process heating [49,50]. Feeding a cylindrical chamber with heat is the first step in the process. Thermal pyrolysis is a process that breaks down organic materials in plastics into liquid and gaseous fuels by heating them under inert circumstances. But because the products of thermal pyrolysis have a reduced molecular weight, the high temperatures cause lower-quality fuels to be produced [50]. In a condenser system, the produced pyrolytic gases are condensed to yield a hydrocarbon distillate. Aromatic, cyclic, and straight- and branched-chain aliphatic hydrocarbons make up the distillate. Fractional distillation is used to separate these components and create liquid fuel. Pyrolysis of plastic occurs between 300°C to 9000°C. First, the plastic is heated uniformly over a small range of temperatures without experiencing significant temperature fluctuations [50,51]. Next, the oxygen in the plastic pyrolysis chamber is removed. Managing the carbonaceous char leftover in the third step prevents it from acting as a thermal insulator and reducing the amount of heat transfer to the plastic. Condensation and fractionation vapours are used in the last step to create a consistent, high-quality distillate [50,52].

Main Products Obtained from Plastic Pyrolysis

The products of plastic pyrolysis vary depending on the feedstock type, temperature, residence time, and reactor configuration. However, the three principal outputs—pyrolytic oil, non-condensable gases, and char—each hold distinct physicochemical properties and potential industrial applications [53].

Pyrolytic Oil (Liquid Fraction)

Pyrolytic oil is the major product, especially when operating under medium to high-temperature ranges (400–600°C). The oil typically comprises a complex mixture of hydrocarbons, including alkanes, alkenes, cycloalkanes, and aromatic compounds. Its calorific value generally ranges from 40 to 45 MJ/kg, comparable to commercial diesel.

- *PE and PP*: Yield light fractions with high paraffin and olefin content, suitable for fuel blending or chemical recovery.
- *PS*: Yields a high proportion of styrene monomers, making it attractive for monomer recovery and re-polymerization.
- *PET and PVC*: Not ideal due to oxygen and chlorine content respectively, which can reduce oil quality and increase corrosion risk.

The oil can be directly used in boilers and furnaces, or upgraded via hydro-treatment or distillation for transportation-grade fuels [54].

Non-Condensable Gases (NCGs)

Non-condensable gases are primarily composed of light hydrocarbons such as methane, ethane, propane, hydrogen, and small amounts of CO and CO_2. These gases are often recycled within the system to maintain the process temperature, which significantly improves the energy balance and lowers operational costs.

- *Composition depends on feedstock and temperature*: Higher temperatures tend to favor gas production.
- *Energy content*: Can reach up to 25–30 MJ/Nm^3.

In larger setups, excess gas may be collected and used for combined heat and power (CHP) generation or gas turbine applications [55].

Solid Residue (Char)

Char is a carbon-rich solid residue, usually constituting 10–20% of the total product mass. It includes:

- Unconverted carbonaceous material.
- Fillers and additives from the plastic (e.g., calcium carbonate, talc).
- Ash content depending on contamination.

Char can be utilized as a solid fuel, a precursor for activated carbon, or as an additive in construction materials and asphalt. In certain contexts, char from electronics waste pyrolysis may also contain recoverable metals such as copper and gold, warranting further valorization [56].

Byproducts and Contaminants

When pyrolyzing halogenated plastics like PVC, hydrogen chloride (HCl) is released, posing corrosion and health risks. This is managed through:

- Pre-treatment steps like dehalogenation or separation.
- Gas scrubbing systems using alkaline solutions to neutralize acid gases.
- Use of catalysts (e.g., $CaCO_3$) to trap halogens in the char.

Additives in consumer plastics (e.g., flame retardants, pigments) may also yield complex organics or toxins, highlighting the need for downstream gas treatment and proper residue disposal [57].

Characterization of Pyrolysis Product

Gas analysis

Methane, ethane, propane, propene, butane, butene, and hydrogen gases were among the hydrocarbons up to C4 that were generated during the pyrolysis of plastics. Methane and hydrogen were deemed essential in determining the heat-kill values (HHVs) of various gases [58,62]. Methane was the principal gas produced during the pyrolysis, and with a value of about 55.38 MJ/kg. Williams investigated the pyrolysis of HDPE, LDPE, PP, PS, PET, and PVC separately and discovered that the principal gas components formed during pyrolysis of each plastic were hydrogen, methane, ethane, ethene, propane, propene, butane, and butene [62]. However, PET created additional gas components such as carbon dioxide and carbon monoxide, whilst PVC additionally produced hydrogen chloride. The gas produced during the pyrolysis process has a substantial calorific value. Jung et al. found that the gas produced by the pyrolysis of PE and PP alone had a high calorific value of 42 to 50 MJ/kg. Thus, pyrolysis gas showed a significant potential for utilization as a heating source in pyrolysis industrial plants [62]. Furthermore, ethene and propene, when separated from other gas components, can be used as chemical feedstock for polyolefin production [59]. Pyrolysis gas can also be used in gas turbines to generate power and in direct firing boilers, eliminating the need for flue gas treatment [59,60].

Pyrolysis Oil

Pyrolysis oil, resulting from the pyrolysis of plastic, is a complex mixture of hydrocarbons and other organic compounds. Pyrolysis oil from plastic waste primarily comprises hydrocarbons, oxygenates, water, and light gases [61]. The composition may vary based on the types of plastics being processed and the conditions of the pyrolysis, but it generally includes a mix of organic compounds formed during the thermal decomposition of plastic polymers. The calorific value of PS was low due to the presence of an aromatic ring in the chemical structure, which had less burning energy than an aliphatic hydrocarbon [59]. Overall, PET and PVC had the lowest calorific value of less than 30 MJ/kg due to the presence of benzoic acid in PET and a chlorine component in PVC, which reduced fuel quality [59]. The low calorific value of PET was due to the presence of an aromatic ring in benzoic acid [59]. Overall, it was showed that the physical parameters of plastic pyrolysis oil were extremely similar to those of commercial gasoline and diesel [59]. Therefore, plastic pyrolysis oil has very high potential to be used as new energy resources.

Tar Analysis

The tar's physical state was liquid at high temperatures. But when the tar was exposed to room temperature, it solidified and eventually became a solid state[62].Because carbon-to-carbon double bonds have a high dissociation energy (146 kcal/mol) and are hence the most difficult to break, carbon was the most common element found in the tar [62]. The breakdown of carbon and hydrogen in the tar product accounts for the drop in Higher heating value(HHV)[62]. The tar's HHV decreased after pyrolysis, but it remained greater than the HHV of conventional coal, which is normally between 36 and 41 MJ/kg [62]. The tar that was so formed has a great deal of promise for use as a substitute solid fuel[62]. Tar from plastic pyrolysis can be used as a fuel for heat and power generation, a chemical feedstock for producing valuable compounds, and as a binder in road construction, offering versatile applications in energy, industry, and infrastructure [53].

Environmental Trade-Offs of Pyrolysis Compared to Mechanical Recycling or Landfilling

Plastic waste management presents complex environmental trade-offs. This section delves into the comparative sustainability of three major treatment methods pyrolysis, mechanical recycling, and landfilling by analyzing multiple criteria such as feedstock tolerance, environmental emissions, material circularity, and long-term ecological impact. Pyrolysis serves as a promising middle ground, especially for contaminated, mixed, or multilayer plastic waste that mechanical recycling cannot process, while landfilling remains the least sustainable option [63-64].

Pyrolysis vs. Mechanical Recycling

Mechanical recycling is the most energy-efficient and environmentally preferred method when dealing with clean and sorted plastics. However, its strict feedstock requirements limit its scalability, especially in regions lacking efficient waste segregation. Pyrolysis, on the other hand, can process a broader range of plastic waste, including multilayer films and heavily contaminated materials, converting them into fuel and energy albeit with higher energy consumption and lower material retention as mention in below in [Table.2] [65].

Table 2. Pyrolysis vs. Mechanical Recycling [65].

Criteria	**Pyrolysis**	**Mechanical recycling**
Input Tolerance	*High*: Accepts dirty, mixed, and multilayer plastics	*Low*: Requires clean, mono-material streams
Output	Fuel oil, syngas, char – low material circularity	Reprocessed plastic – potential for downcycling
Energy Use	High: Thermochemical process (300–700°C)	*Low*: Mechanical melting and extrusion
Environmental Emissions	*Moderate*: VOCs, CO_2 – can be managed via scrubbers	*Low*: Minimal if energy source is clean
Circularity	Limited: Breaks polymer chain (chemical change)	*High*: Retains polymer integrity (physical change)
End-of-Life Impact	Converts to energy, removes material from loop	Allows reuse, but quality degrades over cycles

Insights

- *Material retention*: Mechanical recycling retains 85–90% of the original plastic's value in a closed-loop system, while pyrolysis retains only 30–40% due to conversion into low-value fuel.
- *Emission control:* Pyrolysis requires robust emission control systems (scrubbers, condensers), especially when dealing with halogenated plastics like PVC [65].

Pyrolysis vs. Landfilling

Landfilling remains the default option in many regions, but it poses long-term environmental hazards. Pyrolysis offers a more sustainable alternative by reducing the volume of waste and recovering energy-rich products. While pyrolysis does emit CO_2 and VOCs, these emissions are short-lived and manageable, unlike methane and leachate emissions from landfills that can persist for decades [66]. Various aspects of land filling in table 3

Insights

- *Landfill methane*: Methane is ~25x more potent than CO_2 in terms of global warming potential. Even with gas capture systems, leakage is common.
- *Leachate pollution*: Landfills generate toxic leachate that can contaminate nearby water bodies, while pyrolysis produces fewer aqueous residues [66].

Key Environmental Trade-Offs and Strategic Role of Pyrolysis

This is a comparative analysis of the three major plastic waste management methods mechanical recycling, pyrolysis, and landfilling based on environmental performance, resource recovery, and system-level impacts. Pyrolysis emerges as a strategic solution for handling plastic waste streams that are unsuitable for conventional recycling, offering a balance between environmental safety and resource utilizationVarious aspects of pyrolysis and landfilling are illustrated in Table 4. While it does not fully support circularity like mechanical recycling, pyrolysis significantly reduces the burden on landfills and enables energy recovery from otherwise unrecyclable plastics [67].

Table 3. Pyrolysis vs. Landfilling [66].

Criteria	Pyrolysis	Landfilling
Space Requirement	*Very low:* Volume reduced by ~90%	*High*: Requires large land areas
Emissions	Moderate: CO_2, VOCs – manageable with technology	*High*: Methane, leachate – long-term pollution
Resource Recovery	*Yes*: Produces fuel, gas, and char	*None*: Plastic remains inert or degrades slowly
Environmental Hazard	*Moderate*: Controllable if engineered well	*High*: Soil, groundwater, and air pollution risks
Public Acceptance	*Increasing*: Especially in cities with waste crises	*Decreasing*: Due to NIMBYism and regulations

Table 4. Complete Analysis [67].

Aspect	Mechanical recycling	Pyrolysis	Landfilling
Circularity	High (closed-loop)	Medium (feedstock recovery)	None
Versatility	Low (clean plastics only)	High (all plastic types)	High (no segregation)
Environmental Emissions	Low	Moderate (manageable)	High (long-term)
Infrastructure Requirement	Moderate	High (reactors, gas treatment)	Low
Climate Impact	Lowest	Moderate	Highest

Mechanical recycling is most effective in regions with well-developed waste segregation systems and supports the goals of a circular economy by preserving material value. Pyrolysis plays a vital role in managing contaminated, composite, or non-recyclable plastics, offering a practical solution where traditional recycling fails. In contrast, landfilling though cost-effective poses severe long-term environmental risks and should be minimized to promote more sustainable waste management practices. [67]

CONCLUSION

This review provides a concise summary of the various kinds of plastics and how pyrolysis can be used. It also summarizes the results of the several categories of plastic pyrolysis. The pyrolysis process is accepted as a possible way to produce energy from plastic trash based on the investigations. Rather than causing rubbish to build up in landfills, it produced valuable liquid oil, gaseous fuel, and char, which significantly decreased environmental pollution. Liquid fuel is preferred for small-scale batch pyrolysis processes because it is easier to handle and store. On the other hand, pyrolysis offers a dependable and environmentally friendly way to address the nation's growing problem of plastic waste accumulation. Plastic wastes can be efficiently managed by the process of pyrolysis. Additionally, the procedure is in expensive and cost-effective. Furthermore, utilizing the benefits of pyrolysis properly might lessen reliance on traditional energy sources like fossil fuels. As a result, the increase in energy demand can be reduced.

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