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THE INVESTIGATION, CONVERSION OF WASTE PLASTICS INTO FUELS

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Abstract

This study examines three methods for converting plastic waste into fuel: pyrolysis, catalytic degradation, and gasification, each offering unique advantages and challenges [1]. Pyrolysis, conducted at temperatures between 370°C and 420°C, effectively reduces plastic waste volume by 50-90%, producing liquid, gaseous, and solid fuels. Fast pyrolysis, in particular, proves to be the most efficient method due to its high temperatures and short residence times, allowing energy recovery from renewable sources such as municipal solid waste. Catalytic degradation, using solid acid catalysts like zeolites and silica-alumina, lowers the activation energy required for cracking plastics, enabling fuel production at lower temperatures and enhancing the yield of lighter hydrocarbons. This process shows promise for commercial polymer recycling, though optimization of catalyst performance is needed for cost-efficiency. Gasification, which involves partial combustion of plastic waste, generates syngas and other hydrocarbons, offering an alternative to traditional waste incineration with higher energy recovery and a smaller environmental footprint. By varying parameters such as temperature, catalyst type, and particle size, all three methods were optimized to maximize fuel production and minimize environmental impact [2]. The study demonstrates the feasibility of these technologies for sustainable plastic waste management, with opportunities for further refinement to improve efficiency and reduce costs.

Keywords: *Plastic waste, fuel conversion, pyrolysis, catalytic degradation, gasification.*

1. Introduction

Plastic waste management is a growing concern due to its environmental impact and increasing volumes generated globally. One promising solution to this issue is the conversion of plastic waste into valuable fuels through various thermochemical processes. This study investigates three such methods: pyrolysis, catalytic degradation, and gasification. Each method presents distinct advantages in terms of waste reduction and fuel production. Pyrolysis operates at temperatures between 370°C and 420°C and significantly reduces waste volume by 50-90%, producing liquid, gaseous, and solid fuels [3]. Fast pyrolysis, known for its high temperatures and short residence times, is particularly efficient in converting municipal solid waste into usable energy. Catalytic degradation, utilizing solid acid catalysts like zeolites and silica-alumina, lowers the energy required for cracking plastics, enabling fuel production at lower temperatures and enhancing the yield of lighter hydrocarbons. This process holds potential for commercial polymer recycling, although further optimization is necessary for cost-effectiveness [4]. Gasification, which involves partial combustion of plastic waste, generates syngas and other hydrocarbons, providing an alternative to incineration with higher energy recovery and reduced environmental impact. The study explores how these methods can be optimized through variations in parameters such as temperature, catalyst type, and particle size to maximize fuel output and minimize environmental harm, offering sustainable solutions for plastic waste management.

1). Current Scenario of Plastics: The plastic industry has experienced significant growth over the years, particularly in the production of synthetic polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyvinyl alcohol (PVA), and polyvinyl chloride (PVC). It is estimated that nearly 60% of plastic solid waste (PSW) is either discarded in open spaces or sent to landfills worldwide. A survey revealed that India generates over 10,000 metric tons of plastic waste daily, of which only 40% is recycled, leaving the remaining 60% to be disposed of improperly [5].

2). Present Scenario in India: Both the formal and informal sectors have struggled to manage plastic waste, with industries like packaging and the production of polyvinyl chloride (PVC) pipes growing at rates of 16–18% annually. The demand for plastic products, ranging from household goods to industrial applications, is increasing at an annual rate of 22%. By 2007, polymer production in India had reached 8.5 million tons. Over a quarter of India’s plastic consumption is PVC, which is being phased out in many regions. Poly bags and other plastic items, excluding PET, have become a major focus due to their significant contribution to environmental issues in India, such as clogged sewers, animal deaths, and soil degradation.

Table 1 Plastics consumption in India.

S. No.	Year	Consumption (Tons)
1	1996	61,000
2	2000	3,00,000
3	2001	4,00,000
4	2007	8,500,000

3). Different Recycling Categories

Primary Recycling: Also known as mechanical reprocessing, primary recycling involves feeding plastic waste into the original production process of basic materials. This method allows for the production of a product with the same specifications as the original. However, it is only feasible with semi-clean scrap and is thus not commonly used by recyclers. Degraded plastic waste partially substitutes virgin material, and as the recycled plastic fraction increases in the feed mixture, the quality of the product decreases. Primary recycling requires clean waste that is not contaminated and is of the same type as virgin resin. The steps involved in the primary recycling process are:

- Separation of waste by resin type and color, followed by washing [6].
- Re-extrusion of the waste into pellets with better melting properties, which can then be added to the original resin

Table 2 Polymers demands in India (million tons).

S. no	Type of polymer	1995-96	2001-02	2006-07
1	Polyethylene	0.83	1.83	3.27
2	Polypropylene	0.34	0.88	1.79
3	Polyvinyl	0.49	0.87	1.29
4	Polyethylene	0.03	0.14	0.29

Source: National Plastic Waste Management Task Force Projection (1997).

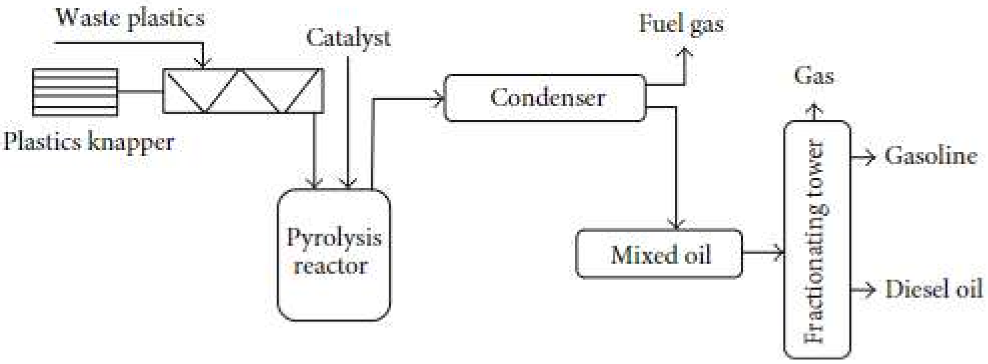

Figure 1 Pyrolysis Process of generating fuel oil from the waste plastics.

This process is expensive compared to other recycling methods due to the stringent requirements for plastic properties. If waste can be sorted by resin but cannot be pelletized due to contamination from mixed colors, the waste can be used in molding applications, where the reactant properties are less demanding.

Secondary Recycling: Secondary recycling uses plastic solid waste (PSW) in the manufacturing of plastic products through mechanical means, incorporating recyclates, fillers, and/or virgin polymers [7]. The goal is to retain some energy from the plastic production process to achieve financial benefits. Unlike primary recycling, secondary recycling can utilize contaminated or less separated waste, but this waste must still be cleaned. The recycling process results in products that differ from those produced in the original production process.

Tertiary Recycling: Also known as the cracking process, tertiary recycling involves breaking down plastics at high temperatures (thermal degradation) or at lower temperatures with the presence of a catalyst (catalytic degradation). This process breaks plastics into smaller carbon chains. The resulting feedstock can be used in chemical production, such as polymerization or fuel fabrication, although the original value of the raw material is lost. Tertiary recycling is particularly important when dealing with highly contaminated waste. The monomers of condensation polymers can be recovered using mechanisms like hydrolysis, methanolysis, or glycolysis (for example, PET, polyesters, and polyamides). However, addition polymers like polyolefins, polystyrene, and PVC require stronger thermal treatments, gasification, or catalytic degradation for cracking.

Quaternary Recycling: Quaternary recycling focuses on the recovery of energy content. Since most plastic waste has high heat content, it is incinerated to generate heat energy. The main advantage of this process is the generation of heat. However, the residual ash from incineration constitutes about 20% by weight and 10% by volume of the original waste, which is disposed of in landfills. While this process addresses energy recovery, it does not solve the solid waste problem and contributes to air pollution.

2. Methodology

The methodology of this study focuses on evaluating three primary methods for converting plastic waste into fuel: pyrolysis, catalytic degradation, and gasification. In the pyrolysis process, plastic samples were subjected to thermal degradation in an anaerobic environment, operating at temperatures between 370°C and 420°C. Oxygen was purged from the reactor, and the resulting pyrolytic gases were condensed and separated into liquid fuels using fractional distillation. The effects of different heating rates and residence times on fuel yield and composition were analyzed. For catalytic degradation, solid acid catalysts like zeolites and silica-alumina were used to facilitate the cracking reaction at lower temperatures than pyrolysis [8]. The catalysts' ability to lower activation energy and improve the cracking process was assessed, with the reaction mechanisms monitored through gas chromatography and mass spectrometry. The gasification process involved the partial combustion of plastic waste using a gasification agent, producing syngas (CO, H_2) and other gaseous hydrocarbons. The efficiency of gasification was evaluated by measuring gas yield, composition, and energy recovery, ensuring a more sustainable alternative to waste incineration. Each method was optimized by varying key operating parameters such as temperature, particle size, and catalyst types to maximize fuel production and minimize environmental impact.

3. Result & Discussion

Methods of Converting Plastic to Fuel

Pyrolysis/Thermal Degradation: Pyrolysis is a process of thermal degradation in the absence of oxygen, where plastic is subjected to high temperatures. The plastic is fed into a cylindrical chamber, and the pyrolytic gases are condensed in a specially designed condenser system. This results in a hydrocarbon distillate that includes straight and branched-chain aliphatic hydrocarbons, cyclic aliphatic hydrocarbons, and aromatic hydrocarbons [9]. The liquid is then separated using fractional distillation to produce liquid fuel products. The plastic undergoes pyrolysis at temperatures between 370°C and 420°C.

The essential steps in the pyrolysis of plastics are as follows (see Figure 1):

1. Heat the plastic evenly within a narrow temperature range to avoid excessive temperature variations.
2. Purge oxygen from the pyrolysis chamber.
3. Manage the carbonaceous char by-product to prevent it from acting as a thermal insulator, which would reduce heat transfer to the plastic.
4. Carefully condense and fractionate the pyrolysis vapors to produce high-quality, consistent distillates.

Table 3 Main operating parameters for pyrolysis process.

Parameters	Conventional	Fast	Flash
Pyrolysis temprature (K)	550–900	850–1250	1050–1300
Heating rate (K/s)	0.1–1	10–200	>1000
Particle size (mm)	5–50	<1	<0.2
Solid residence (s)	300–3600	0.5–10	<0.5

Advantages of Pyrolysis Process: The pyrolysis process offers several advantages:

- The volume of waste is significantly reduced (by 50–90%).
- Solid, liquid, and gaseous fuels can be produced from the waste.
- Storable and transportable fuel or chemical feedstocks are obtained.
- Environmental issues are alleviated.
- The process is desirable as it generates energy from renewable sources like municipal solid waste or sewage sludge.
- The capital cost is relatively low.

There are various types of pyrolysis processes. Conventional pyrolysis (slow pyrolysis) operates under low heating rates, resulting in significant portions of solid, liquid, and gaseous products. It is an ancient method primarily used for charcoal production, and vapors can be continuously removed as they are formed. Fast pyrolysis is characterized by higher temperatures (850–1250 K) for tar production at low temperatures and gas production at high temperatures (1050–1300 K). Currently, the preferred technology is fast or flash pyrolysis, which occurs at high temperatures with very short residence times. Fast pyrolysis, more accurately referred to as thermolysis, rapidly heats materials like biomass to high temperatures in the absence of oxygen.

Mechanism of Thermal Degradation: Cullis and Hirschler proposed a detailed study on the mechanisms of thermal degradation of polymers. Four different mechanisms of degradation are:

1. End-chain scission (or unzipping)
2. Random-chain scission/fragmentation
3. Chain stripping/elimination of side chains
4. Cross-linking

The decomposition mode primarily depends on the type of polymer and its molecular structure.

$$\mathrm{M}_n^* \longrightarrow \mathrm{M}_{n-1}^* + \mathrm{M} \quad \textbf{(1)}$$

$$\mathrm{M}_{n-1}^* \longrightarrow \mathrm{M}_{n-2}^* + \mathrm{M} \quad \textbf{(2)}$$

$$\mathrm{M}_n \longrightarrow \mathrm{M}_x + \mathrm{M}_y \quad \textbf{(3)}$$

Equations (1) and (2) describe the thermal degradation process, while equation (3) represents the random degradation pathway during polymer pyrolysis. The fourth mechanism, cross-linking, frequently occurs in thermosetting plastics when exposed to high temperatures. In this process, two adjacent "stripped" polymer chains can bond, forming a network structure and resulting in higher molecular weight species, such as char formation.

Catalytic Degradation: Catalytic degradation involves the use of a suitable catalyst to facilitate the cracking reaction [10]. The presence of the catalyst lowers both the reaction temperature and time. This process results in a narrower product distribution, with a peak at lighter hydrocarbons, and occurs at lower temperatures. To enhance the economic feasibility of this method, further cost reductions are necessary. Optimizing catalyst use by reusing catalysts and employing more efficient catalysts in smaller quantities can improve the overall process. This approach has the potential to become a cost-effective solution for commercial polymer recycling, addressing the environmental challenges posed by plastic waste disposal. Additionally, catalytic degradation offers higher plastic cracking efficiency and results in lower concentrations of solid residues in the product.

Mechanism of Catalytic Degradation: The catalytic degradation of polyolefins using Thermogravimetric Analysis (TGA) has shown that the presence of a catalyst reduces the apparent activation energy. Several mechanisms, including ionic and free radical mechanisms, have been proposed for plastic pyrolysis. In the carbonium ion reaction mechanism, various steps occur, including H-transfer, chain/beta-scission, isomerization, oligomerization/alkylation, and aromatization, all of which are influenced by the acid site strength, density, and distribution. Solid acid catalysts, such as zeolites, are known to promote hydrogen transfer reactions due to the large number of acid sites they contain. These acid sites are typically either Bronsted or Lewis types, which determine the acid strength of the solid acids. Bronsted acid sites, in particular, facilitate the cracking of olefinic compounds. The majority of these acid sites in crystalline solid acids, such as zeolites, are located within the material's pores. The microporosity of such solid acids plays a critical role in determining the level of polyolefin cracking during catalytic degradation. The carbonium ion mechanism for the catalytic pyrolysis of polyethylene can be described as follows:

1. Initiation: The process begins at defect sites on the polymer chains. For example, an olefinic linkage can be converted into a carbonium ion through proton addition, initiating the cracking process.

$$-CH_2CH_2CH = CHCH_2CH_2^{-} + HX \longrightarrow CH_2CH_2^{+}CHCH_2{-}CH_2CH_2 + X^{-} \quad \textbf{(4)}$$

The polymer chain may be broken up through β-emission:

$$-CH_2CH_2^{+}CHCH_2{-}CH_2CH_2^{-} \longrightarrow CH_2CH_2CH = CH_2 + {}^{+}CH_2\,CH_2^{+} \quad \textbf{(5)}$$

Table 4 List of catalysts in use.

S.	Catalyst	Pore size (nm)	Commercial name
1	USY	0.74	H-Ultrastabilised, Y-zeolite
2	ZSM-5	0.55 × 0.51	H-ZSM-5 zeolite
3	MOR	0.65 × 0.70	H-Mordenite
4	ASA	3.15	Synclyst 25 (silica-alumina)
5	MCM-41	4.2–5.2	—
6	SAHA	3.28	Amorphous silica-alumina
7	FCC-R1	—	Equilibrium catalyst
8	Silicalite	0.55 × 0.51	Synthesized in house

Initiation may also take place through random hydride-ion abstraction by low-molecular-weight carbonium ions (R+):

$$-CH_2CH_2CH_2CH_2CH_2{-} + R^{+} \longrightarrow -CHCH_2^{+}CHCH_2CH_2^{-} + RH \quad (6)$$

The newly formed on-chain carbonium ion then undergoes β-emission.

(2) Depropagation: The molecular weight of the polymer chains can be reduced through successive attacks by acidic sites or other carbonium ions, leading to chain cleavage and the formation of an oligomer fraction (approximately C30–C80) [11]. Further cleavage of the oligomer fraction, likely by direct β-emission of chain-end carbonium ions, results in gas formation on one hand and a liquid fraction (approximately C10–C25) on the other.

(3) Propagation: The hydrocarbon radical decomposes to produce lower hydrocarbons, such as propylene, followed by β-scission and the abstraction of hydrogen radicals from other hydrocarbons. This leads to the formation of a new hydrocarbon radical:

$$CH_2=CH{-}CH_2{-}CH_2{-}CH_3 \xrightarrow{H^+} CH_3\ {}^+CH{-}CH_2{-}CH_2{-}CH_3 \xrightarrow{\overset{+}{H}} CH_3{-}CH=CH{-}CH_2{-}CH_3 \qquad (7)$$

(4) Isomerization: The carbonium ion intermediates can undergo rearrangement by hydrogen- or carbon-atom shifts, leading to double-bond isomerization of an olefin.

$$R_1^+ + R_2CH=CH{-}CH_2CH_2CH_2CH_2CH_3 \longleftrightarrow R_1H + R_2CH=CH{-}CH_2CH_2CH_2\,{}^+CHCH_3 \quad (8)$$

The carbonium ion can undergo intramolecular attack on the double bond. A free radical mechanism for the catalytic degradation of polypropylene (PP) using an Fe/activated carbon catalyst has been proposed [12]. During the degradation process, methyl, primary, and secondary alkyl radicals are formed, leading to the production of methane, olefins, and monomers through hydrogen abstraction and recombination of the radical units.

The various steps in catalytic degradation are as follows:

1). Initiation: Random breakage of the C–C bonds in the main chain occurs under heat, producing hydrocarbon radicals.

$$R_1{-}R_2 \longrightarrow R_1^{\bullet} + R_2^{\bullet} \qquad (9)$$

2). Propagation: The hydrocarbon radical decomposes to produce lower hydrocarbons, such as propylene. This is followed by β-scission and the abstraction of hydrogen radicals from other hydrocarbons, leading to the formation of a new hydrocarbon radical [13].

$$R_1^{\bullet} \longrightarrow R_3^{\bullet} + C_2 \text{ or } C_3 \qquad (10)$$

$$R_2^{\bullet} + R_4 \longrightarrow R_2 \text{ or } R_4^{\bullet} \qquad (11)$$

3). Termination: Disproportionation or recombination of two radicals occurs.

$$R_5^{\bullet} + R_6^{\bullet} \longrightarrow R_5 + R_6^{\bullet} \qquad (12)$$

$$R_7^{\bullet} + R_8^{\bullet} \longrightarrow R_7{-}R_8 \qquad (13)$$

During catalytic degradation with Fe-activated charcoal in a hydrogen (H_2) atmosphere, hydrogenation of the hydrocarbon radicals (olefins) and the abstraction of hydrogen radicals from hydrocarbons help generate new radicals, thus enhancing the degradation rate. At temperatures lower than 400°C or reaction times shorter than 1 hour, many macromolecular hydrocarbon radicals exist in the reactor, and recombination happens readily due to the slower movement of these radicals. However, in the presence of Fe-activated carbon in a H_2 atmosphere, these radicals undergo hydrogenation, which suppresses recombination. As a result, the decomposition of the solid product, including low polymers whose molecular size exceeds the catalyst's pore size, is promoted.

Gasification: Gasification is a process in which biomass undergoes partial combustion to produce gas and char in the initial stage. The product gases, primarily carbon dioxide (CO_2) and water (H_2O), are then reduced by charcoal into carbon monoxide (CO) and hydrogen (H_2). Depending on the reactor design and operating conditions, the process may also generate methane and other higher hydrocarbons (HCs). Broadly, gasification refers to the thermochemical conversion of solid or liquid carbon-based materials (feedstocks) into a combustible gaseous product (combustible gas) using a gasification agent (a gaseous compound). This agent facilitates the rapid conversion of the feedstock into gas through various heterogeneous reactions. If gasification occurs without the use of an oxidizing agent, it is termed indirect gasification, requiring an external energy source [14]. This method can increase the hydrogen content of the combustible gas, making it a promising option. A gasification system consists of three main components: (1) the gasifier, which produces the combustible gas; (2) the gas cleanup system, which removes harmful compounds from the gas; and (3) the energy recovery system. Additionally, subsystems are included to control environmental impacts such as air pollution, solid waste production, and wastewater management. Gasification presents a promising alternative to waste incineration for the thermal treatment of homogeneous carbon-based waste and pretreated heterogeneous waste.

4. Conclusion

In conclusion, this study evaluates three methods for converting plastic waste into fuel: pyrolysis, catalytic degradation, and gasification, each with distinct advantages and limitations. Pyrolysis, operating at temperatures between 370°C and 420°C, effectively reduces waste volume by 50-90%, producing liquid, gaseous, and solid fuels. It allows for the production of energy from renewable sources like municipal solid waste, with fast pyrolysis being the most efficient due to its high temperatures and short residence times. Catalytic degradation, using solid acid catalysts like zeolites and silica-alumina, lowers activation energy, facilitating cracking at lower temperatures and improving the yield of lighter hydrocarbons. This process has potential for commercial polymer recycling, though further optimization of catalyst use is necessary for cost-effectiveness. Gasification, which involves partial combustion of plastic waste, generates syngas and other gaseous hydrocarbons, offering an alternative to waste incineration with higher energy recovery and reduced environmental impact. All three methods were optimized by varying key parameters such as temperature, catalyst type, and particle size to enhance fuel production and minimize environmental harm. Overall, the study highlights the feasibility of these processes in addressing plastic waste and contributing to sustainable fuel production, with room for further optimization to improve efficiency and reduce costs.

iFuture Scope

- This study evaluates three plastic waste-to-fuel methods: pyrolysis, catalytic degradation, and gasification, each offering unique advantages and challenges.
- Pyrolysis efficiently reduces waste volume by 50-90%, producing liquid, gaseous, and solid fuels at temperatures between 370°C and 420°C, with fast pyrolysis being the most efficient.
- Gasification, which generates syngas and other hydrocarbons through partial combustion, offers higher energy recovery and lower environmental impact than traditional waste incineration.

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