

DESIGN, MANUFACTURING, AND SUSTAINABLE PLASTIC WASTE MANAGEMENT THROUGH DECENTRALIZED PYROLYSIS TECHNOLOGY

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Abstract

The exponential growth of plastic waste globally has created an urgent need for sustainable waste management solutions. This study develops and tests a compact, low-cost pyrolysis machine that converts municipal plastic waste into liquid hydrocarbon fuels, mimicking industrial pyrolysis in a small, portable setup for decentralized use.

A mixture of polypropylene (PP) and low-density polyethylene (LDPE) plastic waste was subjected to thermal pyrolysis in a specially designed chamber. The process included controlled heating using a 1000W coil, efficient condensation using a tube-based heat exchanger, and purification through a water and KOH treatment process. A ZSM-5 catalyst was utilized to improve the quality of fuel obtained and reduce the processing temperature. The final liquid products were found to have comparable properties to commercial fuels like diesel and petrol, with a conversion efficiency of approximately 65%.

Experimental analysis demonstrated that optimal yields were achieved at a temperature of $\sim 400^{\circ}\text{C}$, with gasoline-range hydrocarbon content reaching up to 89.1%. The design enables solid fuel production and generates by-products like char and non-condensable gases, which are also utilizable. This compact machine provides a promising step toward community-level plastic recycling and decentralized energy generation, contributing significantly to waste reduction and circular economy goals.

Keywords: Plastic Waste, Pyrolysis, LDPE, ZSM-5 Catalyst, Decentralized Recycling.

1. INTRODUCTION

Plastic waste management is a major global challenge due to the non-biodegradable nature of plastics. Over 400 million tons of plastic are generated annually, and traditional methods like landfilling and open burning lead to significant environmental hazards. Pyrolysis—a thermochemical decomposition in the absence of oxygen—has emerged as a promising solution for converting plastic waste into usable liquid hydrocarbons.

This study explores the design and implementation of a compact pyrolysis system capable of converting household-level plastic waste into fuel components such as diesel, kerosene, and petrol, using a ZSM-5 catalyst and thermal cracking methods.

Table 1. Potential of Pyrolysis Technology: This table highlights the prospective benefits of pyrolysis in tackling key sustainability and environmental issues. It emphasizes the technology's envisioned strengths and long-term potential, while acknowledging that present-day results may still fall short of these future expectations.

Challenge	Contribution of Pyrolysis
Sustainability and Circular Economy	<ul style="list-style-type: none"> – Transforms plastic and biomass waste into valuable fuels and materials – Reduces landfill dependency – Promotes material reuse and supports soil health through biochar application.
Environmental Protection	<ul style="list-style-type: none"> – Reduces harmful emissions from traditional waste disposal – Provides cleaner energy alternatives – Improves local air quality
Marine Ecosystem Preservation	<ul style="list-style-type: none"> – Prevents plastic leakage into oceans; mitigates microplastic formation – Protects marine biodiversity through proper plastic waste diversion.
Climate Action and Carbon Neutrality	<ul style="list-style-type: none"> – Generates renewable energy – Supports CO₂ capture via biochar – Contributes to carbon-negative energy systems.
Energy Accessibility and Decentralization	<ul style="list-style-type: none"> – Offers portable, small-scale systems suitable for remote areas – Improves equitable access to energy.
Support for SDGs	<ul style="list-style-type: none"> – Advances SDG 7 (Clean Energy), SDG 12 (Sustainable Consumption), and SDG 13 (Climate Action) – Aligns with global sustainability targets.
Chemical Resource Recovery	<ul style="list-style-type: none"> – Produces syngas and bio-oil for chemical synthesis – Reduces reliance on fossil-based chemicals – Enables recovery of compounds like benzene and ethylene.

Pyrolysis has the potential to evolve in alignment with future sustainability goals, rather than being judged solely on its current performance.

2. RESEARCH BACKGROUND

The escalating crisis of plastic pollution has driven a global search for sustainable waste management solutions. Annually, over 400 million metric tons of plastic are produced, with a significant portion of this volume, approximately 20 million tons, ending up in our natural environment. Traditional methods like landfilling and incineration are insufficient, leading to calls for a circular economy approach where waste is a resource. Within this framework, advanced recycling technologies, such as pyrolysis, have gained significant attention for their ability to convert plastic waste into valuable products. Pyrolysis is a thermochemical process that breaks down plastics at high temperatures in an oxygen-free environment, yielding liquid pyrolysis oil, combustible gas, and solid char. PS plastic waste showed maximum production of liquid oil (80.8%) along with least production of gases (13%) and char (6.2%) in comparison to other plastic types. Liquid oils from all plastic types contained mostly aromatic compounds with some alkanes and alkenes. Pyrolysis liquid oils found to have ranges of dynamic viscosity (1.77–1.90 mPa s), kinematic viscosity (1.92–2.09 cSt), density (0.91–0.92 g/cm), pour point (–11(–60 °C)), freezing point (–15(–65 °C)), flash point (28.1–30.2 °C) and high heating value (HHV) (41.4 – 41.8 MJ/kg) similar to conventional diesel, thus have potential as an alternative energy source for electricity generation. A key advantage of this technology is its ability to handle a mixed range of plastics, including those that are difficult to recycle mechanically, such as multilayer films. The market for pyrolysis products, particularly pyrolysis oil, is experiencing rapid growth.

The global pyrolysis oil market was valued at approximately USD 2.00 billion in 2025 and is projected to reach USD 4.51 billion by 2034, growing at a CAGR of 9.45%. This growth is driven by the rising demand for renewable fuels, advancements in waste management, and the global transition towards a circular economy. The largest share of this market, in 2024, was attributed to plastic as a feedstock, underscoring its importance to the industry.

3. RESEARCH METHODS

The methodology adopted for the development of the compact plastic-to-fuel conversion machine involved a multidisciplinary approach combining thermal engineering i.e. heat transfer through metallic stainless steel 310 grade cylinder and an insulation layer of glass-wool, mechanical design

and chemical processing. The process was segmented into key stages: selection and preparation of plastic waste, system design and modelling, thermal cracking of plastic with catalytic support, condensation and separation of products, and characterization of the output fuels.

3.1 Feedstock Selection and Preparation

The feedstock, a 1:1 blend of LDPE and PP plastic waste, was prepared by first shredding the plastic into flakes of approximately (50-100mm). As shown in Fig. 3.1, plastic waste management at the Solapur Bio-Energy Plant is illustrated. The flakes were then dried with the help of a dryer at a temperature of 55°C to remove any residual moisture. The physical and chemical properties of this feedstock were characterized prior to pyrolysis. A proximate analysis was conducted to determine the moisture content, volatile matter, fixed carbon, and ash content. The ultimate analysis provided the elemental composition, specifically the percentages of carbon (85.7%), hydrogen (14.3%), nitrogen, and oxygen. The higher heating value (HHV) of the plastic mixture was also determined to quantify its energy content, which was found to be 41.60 MJ/kg. A commercial ZSM-5 zeolite catalyst was utilized to improve the quality of the pyrolysis oil. The catalyst, with a silica-to-alumina ratio of 20:1, was pre-treated by calcination at 400°C for 3 hours to remove impurities and activate its acidic sites. The catalyst was incorporated into the reactor as a fixed bed, positioned to ensure optimal contact with the plastic vapors, thereby promoting the catalytic cracking of the polymer chains.



Fig 3.1 Plastic Waste management at Solapur Bio energy Plant

3.2 Machine Design and Fabrication:

A compact, modular pyrolysis unit was designed using SolidWorks 3D modeling software,

incorporating several key components. The assembly of the compact machine involves systematically integrating components such as the frame, heating coils, electric coil housing, feeding mechanism, and control system. Cooling fans, exhaust systems, and safety features are added to ensure efficient operation and user safety. The process concludes with testing to deliver a fully functional machine capable of converting plastic waste into liquid fuel efficiently as shown in figure 3.2.

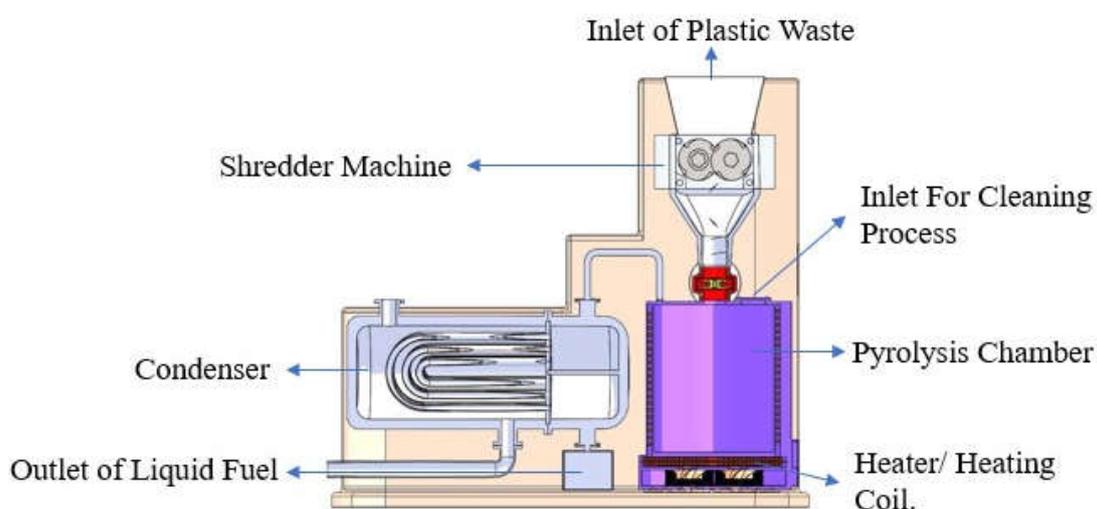


Fig.3.2 Pyrolysis unit -Sectional Front View

The pyrolysis reactor was a cylindrical stainless-steel chamber measuring 60 cm in diameter and 90 cm in height, equipped with an internal heating coil. The heating system consisted of a 1000W electric coil to provide uniform heating throughout the reactor. A ZSM-5 zeolite catalyst was introduced to enhance the breakdown of polymer chains and lower the required operational temperature. The setup included a condenser unit, designed as a copper-tube based heat exchanger, to effectively condense the pyrolyzed vapours into liquid fuel. Cooling fans were installed to maintain optimal operating temperatures and assist in condensing volatile hydrocarbons. Finally, a collection tank was provided to store the resulting fuel oil and solid residue (char).



Fig 3.3 Experimental Setup for Prototype of Pyrolysis Reactor

The entire setup was thermally insulated and mounted on a portable trolley, making the system suitable for community-level deployment as shown in figure 3.3.

3.3 Pyrolysis Process

The cleaned and shredded plastic was loaded into the pyrolysis chamber. The reactor was heated gradually from ambient temperature to 400°C in an oxygen-free environment to prevent combustion. The process involved thermal decomposition, where long polymer chains were broken down into shorter hydrocarbon molecules, followed by catalytic cracking using ZSM-5, which facilitated dehydrogenation and aromatization to produce high-quality liquid hydrocarbons. The volatile products generated during pyrolysis exited the reactor and were directed into a condenser, where the cooling system condensed them into liquid hydrocarbons (plastic fuel). Meanwhile, non-condensable gases were either flared off or reused as a heat source for the process. Each pyrolysis cycle was completed in approximately 2.5 to 3 hours for a plastic load of 600 grams.

3.4 Product Purification and Characterization

The condensed liquid fuel was subjected to a purification process to remove acidic residues. First, it was mixed with water and allowed to settle for 5 to 7 hours. Then, its pH was adjusted to neutral by treating it with potassium hydroxide (KOH). Following this, the fuel was separated from the water-acid layer by decantation. The purified fuel was then tested for various properties: its viscosity was measured using a Saybolt viscometer; the flash and fire points were determined using

the Cleveland Open Cup tester; its calorific value was assessed using a bomb calorimeter; and the emission characteristics—including HC, CO, CO₂, and NO_x—were analysed using an AVL DIGAS 444 D gas analyser.

3.5 Safety and Environmental Considerations

The design ensured containment of gases and safe handling of hot components. Emission levels from fuel combustion were monitored to verify environmental compliance. All processing was done in a controlled lab environment with ventilation.

4. RESULTS AND DISCUSSION

The compact pyrolysis machine was tested with a controlled blend of LDPE and PP plastic waste under various thermal and catalytic conditions. The results are discussed in terms of fuel yield, quality of liquid products, performance characteristics, and environmental impact.

4.1 Fuel Yield and Conversion Efficiency

The pyrolysis process yielded approximately 65% by weight of liquid hydrocarbon fuel when operating at an optimal temperature of 400°C. The remaining by-products included:

- a) Solid char (~15%) – usable as a solid fuel or carbon source
- b) Non-condensable gases (~20%) – composed mainly of methane, ethane, and propane

The liquid fuel yield varied depending on several factors. The heating rate played a significant role, as gradual heating up to 400°C ensured efficient breakdown of polymer chains. The type of plastic also influenced the yield; both LDPE and PP provided high yields due to their long-chain aliphatic structure. Additionally, the presence of the ZSM-5 catalyst enhanced the process by increasing the breakdown of long polymer chains into more valuable shorter-chain hydrocarbons.

4.2 Composition of Pyrolysis Oil

The pyrolysis oil collected showed physical and chemical properties comparable to conventional diesel and petrol.

The presence of ZSM-5 catalyst in the process improved the quality of fuel by:

- i. Increasing the aromatic content

- ii. Lowering the average molecular weight
- iii. Enhancing the gasoline-range fraction
- iv. NMR and distillation analysis confirmed a high percentage of C5–C12 hydrocarbons, which are suitable for use as motor fuels after refining.

4.3 Emission Characteristics

Blends containing 20% and 40% plastic-derived fuel (referred to as PF20 and PF40) were tested on a compression ignition (CI) engine, and the emission results were analyzed using the AVL DIGAS 444 D analyzer. The findings indicated that CO and HC emissions were slightly higher for pure plastic fuel, primarily due to incomplete combustion at lower engine loads. However, NO_x emissions remained comparable to conventional diesel when the fuel was pre-treated with potassium hydroxide (KOH). Additionally, the absence of Sulphur in the plastic feedstock led to lower SO₂ emissions. Overall, these results suggest that plastic-derived fuel, when blended with diesel, is clean-burning and environmentally favorable.

4.4 Performance Analysis

Engine performance tests conducted using plastic fuel blends demonstrated several key observations. The blends exhibited brake thermal efficiency (BTE) comparable to that of diesel, particularly at medium and high engine loads. There was a slight increase in specific fuel consumption (SFC), more noticeable in the PF40 blend, attributed to lower combustion efficiency. Despite this, the engine showed stable ignition and consistent power output, provided the fuel was properly filtered and neutralized. These findings affirm the practical usability of plastic-derived liquid fuels in diesel engines with only minimal modifications required.

4.5 Economic and Operational Insights

The system offers several economic and operational advantages. The material cost is significantly reduced by using plastic waste, which serves as a nearly zero-cost feedstock for fuel production. The energy input is also minimal, as the process utilizes low-power 1000W electric heating coils. Furthermore, the compact size of the machine ensures portability and makes it suitable for decentralized applications, such as use in small communities or waste transfer stations.

4.6 Limitations and Observations

- i. PVC plastics were excluded due to high chlorine content and corrosive nature.
- ii. Condensation setup required optimization to improve recovery of lighter hydrocarbons.
- iii. Fuel purification required proper pH control to avoid acidic damage to engine components.

5. CONCLUSION

The developed compact pyrolysis machine offers a viable small-scale solution for managing plastic waste and producing valuable fuel. It is cost-effective, environmentally friendly, and can be easily deployed in urban and rural areas. Further optimization and scaling may increase its commercial viability.

6. FUTURE SCOPE

- i. Integration with solar thermal heating.
- ii. Automation for feeding, monitoring, and fuel collection.
- iii. Testing with a wider variety of plastic waste (e.g., PET, PVC).
- iv. On-site deployment in small communities or municipal waste yards.

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