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Waste Plastic to Fuel Conversion Unit

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Abstract: The exponential increase in plastic production and consumption has caused a serious global environmental challenge due to the non-biodegradability and long persistence of polymeric materials in ecosystems. Conventional methods of waste plastic management such as landfilling, incineration, and mechanical recycling are no longer sufficient to handle the growing volume and diversity of plastic waste streams. Consequently, alternative approaches that integrate environmental sustainability with energy recovery have become imperative. One of the most promising strategies is the conversion of waste plastic into liquid fuel through controlled pyrolysis, a thermochemical decomposition process that occurs in the absence of oxygen. This paper presents an extensive study and engineering development of a Waste Plastic to Fuel Conversion Unit, integrating thermochemical analysis, process design, catalyst optimization, and artificial intelligence (AI)-based control modeling. The research emphasizes the influence of process variables—temperature, residence time, catalyst selection, and feedstock composition—on fuel yield and quality. Additionally, a computationally aided process optimization framework employing artificial neural networks (ANN) and genetic algorithms (GA) has been developed to predict and enhance fuel conversion efficiency. Experimental and simulation results confirm that the optimized process achieves a conversion yield of up to 82%, producing a hydrocarbon-rich liquid fuel with calorific values comparable to commercial diesel. The proposed unit demonstrates an economically viable, environmentally safe, and scalable pathway for converting non-recyclable plastic waste into useful energy resources.

Keywords: *Plastic Waste Management, Pyrolysis, Renewable Fuel, Process Optimization, Waste-To-Energy, Catalyst, Artificial Intelligence, Sustainability.*

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I. INTRODUCTION

➢ *Global Plastic Crisis and Motivation*

Plastics are an indispensable part of modern civilization due to their low cost, durability, versatility, and ease of fabrication. They have replaced traditional materials in packaging, construction, automotive, electronics, and healthcare industries. However, the same chemical stability that makes plastics durable also renders them resistant to natural degradation. According to a 2023 report by the United Nations Environment Programme (UNEP), global plastic production surpassed 400 million metric tons annually, of which less than 10% is effectively recycled. The remainder accumulates in landfills, oceans, and urban environments, leading to severe ecological damage and threats to human health.[1-4]

In many developing countries, the absence of advanced waste management infrastructure exacerbates the problem. Uncontrolled dumping and open burning of plastic waste release toxic gases such as dioxins, furans, and polyaromatic hydrocarbons (PAHs), contributing to air pollution and greenhouse gas emissions. Landfills, on the other hand, occupy large tracts of valuable land and pose risks of leachate contamination in soil and groundwater. The need for a sustainable, closed-loop system to manage and valorize plastic waste is therefore an urgent global priority.[5-9]

➢ *Transition to Waste-to-Energy (WTE) Concepts*

The concept of converting waste into energy (WTE) is based on the idea that waste materials contain intrinsic energy, which can be recovered through thermal, biological, or chemical processes. Among these, pyrolysis—the thermal decomposition of materials in an oxygen-free environment—has emerged as one of the most promising technologies for plastic waste management. The process converts high-molecular-weight polymers into smaller hydrocarbon chains that can be refined into usable fuels such as diesel, kerosene, and gasoline. This approach not only reduces the environmental burden of plastic waste but also contributes to energy generation, thus aligning with the principles of circular economy and sustainable development.[10-14]

➢ *Rationale for Waste Plastic to Fuel Conversion*

Plastic-to-fuel (PTF) conversion offers a unique dual advantage: environmental remediation and renewable energy recovery. Unlike incineration, which involves combustion and produces CO_2 and toxic residues, pyrolysis prevents oxidation and yields cleaner fuels. Moreover, since most plastics are derived from petroleum-based feedstocks, the

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energy content of plastics is comparable to fossil fuels. Polyethylene (PE) and polypropylene (PP), which constitute over 60% of global plastic waste, have calorific values of around 43–46 MJ/kg, close to that of commercial diesel. Harnessing this energy through pyrolysis can therefore provide a renewable substitute for fossil fuel sources.[15]

➢ *Objectives of the Study*

The main objectives of this study are to design, develop, and optimize a Waste Plastic to Fuel Conversion Unit based on pyrolysis technology. The research focuses on the following goals:

- To analyze the thermochemical behavior of various plastic feedstocks during pyrolysis.
- To design and fabricate a scalable batch-type pyrolysis reactor capable of processing mixed plastic waste.
- To evaluate the effect of temperature, residence time, and catalyst on fuel yield and composition.
- To develop AI-based predictive and optimization models for process enhancement.
- To perform comparative characterization of the produced fuel with standard petroleum fuels.

The comprehensive approach integrates engineering design, materials science, computational modeling, and sustainability assessment to establish a complete framework for waste-to-fuel conversion.[16-22]

II. LITERATURE REVIEW

➢ *Historical Evolution of Plastic Pyrolysis*

The concept of pyrolytic decomposition dates back to the mid-20th century when early researchers investigated the cracking of polymer chains to produce gaseous hydrocarbons. However, systematic exploration of plastic pyrolysis as a waste management and energy recovery method began in the late 1980s. Early investigations focused on the thermal degradation behavior of polyethylene (PE) and polypropylene (PP) in laboratory-scale reactors. Researchers such as Williams and Williams (1999) demonstrated that pyrolysis temperatures between 400°C and 600°C yielded substantial quantities of liquid hydrocarbons. Subsequent studies introduced catalysts such as silica-alumina, zeolite Y, and HZSM-5 to enhance the conversion rate and modify product selectivity toward lighter fractions.[23-29]

Over the last two decades, advances in material characterization and reactor design have significantly improved process efficiency. Studies by Uddin et al. (2010) and Marcilla et al. (2015) showed that the introduction of catalysts reduces reaction time, energy consumption, and coke formation, resulting in higher liquid yields. With the emergence of computational tools, researchers have also begun to employ machine learning models to predict and optimize process outcomes, marking a shift toward intelligent, data-driven pyrolysis systems.[30-32]

➢ *Thermochemical and Catalytic Mechanisms*

Pyrolysis involves the thermal breakdown of long polymer chains into smaller hydrocarbon molecules through free radical mechanisms. The process typically proceeds in three stages: initiation, propagation, and termination. During initiation, heat energy breaks C–C and C–H bonds in the polymer backbone, generating free radicals. These radicals propagate chain scission reactions, leading to smaller molecules such as alkanes, alkenes, and aromatics. In the termination stage, the radicals recombine or stabilize, forming liquid, gaseous, or solid (char) products.

Catalysts such as zeolites and metal oxides play a crucial role in lowering activation energy, enhancing selectivity, and improving liquid fuel yield. Zeolite-based catalysts, particularly ZSM-5, provide acidic active sites that favor cracking and aromatization reactions, producing high-octane aromatic hydrocarbons. However, catalyst deactivation due to coke deposition remains a challenge, necessitating periodic regeneration through controlled oxidation.[33-38]

➢ *Role of Artificial Intelligence in Pyrolysis Optimization*

Recent developments in AI and computational modeling have revolutionized process optimization in chemical engineering. Techniques such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Genetic Algorithms (GA) are now applied to model nonlinear relationships between process variables and outputs. These models can predict yield, energy consumption, and product composition based on historical data, reducing experimental trial requirements. Hybrid ANN-GA systems have been particularly effective in identifying optimal combinations of reactor temperature, heating rate, and catalyst load to maximize yield.[39, 40]

Furthermore, the integration of computational fluid dynamics (CFD) with AI algorithms allows for advanced simulation of heat and mass transfer phenomena within the reactor. This combined approach enables real-time process control and dynamic adjustment of parameters, ensuring consistent quality and efficiency.

➢ *Research Gap*

Despite substantial progress, several research gaps persist. Many previous studies have been limited to laboratory-scale setups with homogeneous feedstocks, whereas real-world waste plastics are highly heterogeneous. Moreover, most designs lack integrated control systems and sustainability assessments. The current study addresses these limitations by developing a practical, scalable conversion unit incorporating AI-based optimization, catalyst reuse strategies, and environmental impact evaluation.

III. EXPERIMENTAL METHODOLOGY

The waste plastic to fuel conversion unit operates on the principle of thermal pyrolysis under controlled heating conditions. The methodology involves several sequential stages—collection and preprocessing of plastic waste, shredding and cleaning, reactor design and fabrication,

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heating mechanism development, condensation system design, and product analysis.

- *Feedstock Preparation:*

The feedstock comprises commonly available waste plastics such as LDPE, HDPE, PP, and PS. The materials are cleaned to remove dirt, labels, and moisture before being shredded into uniform granules (5–10 mm). This ensures consistent heating and reaction kinetics within the pyrolysis reactor.

- *Reactor Design and Operation:*

A batch-type cylindrical reactor made of stainless steel (SS316) is used due to its high-temperature resistance and corrosion durability. The reactor is designed with a capacity of 10 kg per batch and is equipped with a temperature controller, thermocouple sensors, and safety valves. The heating system uses electrical coils and ceramic insulation to maintain temperatures between 350°C and 500°C, optimized for maximum liquid yield. The reactor operates in an oxygen-free atmosphere, achieved by nitrogen purging prior to heating.

- *Condensation and Collection System:*

The vaporized hydrocarbon gases are directed into a condensation chamber through a heat-resistant steel pipe. The chamber consists of a series of water-cooled condensers arranged in parallel to separate liquid fuel, waxes, and non-condensable gases. The liquid fraction is collected in a storage tank, while the gaseous fraction is re-circulated to fuel the heating process, improving energy efficiency.

- *Analytical Testing:*

The liquid fuel is subjected to laboratory analysis, including density, viscosity, flash point, calorific value, and gas chromatography–mass spectrometry (GC–MS). The obtained properties are compared with commercial diesel standards to evaluate performance viability.

- *Computational and AI-based Optimization:*

A multilayer neural network model is employed to predict yield and fuel quality based on operational parameters such as temperature, feed composition, and heating rate. Genetic algorithms (GA) optimize the process for maximum fuel yield and energy efficiency. Simulation tools such as ANSYS Fluent are used for heat transfer and flow analysis within the reactor.

IV. RESULTS AND DISCUSSION

The developed waste plastic to fuel conversion unit achieved successful conversion of mixed plastic waste into hydrocarbon fuel. The total liquid yield ranged from 60% to 80% depending on temperature and catalyst type. Optimal performance was observed at 450°C using a zeolite catalyst, producing light hydrocarbon fuel with a calorific value of approximately 43 MJ/kg, closely comparable to conventional diesel (45 MJ/kg).

GC–MS analysis indicated the presence of alkanes, alkenes, and aromatic hydrocarbons, with a carbon chain distribution primarily between C8 and C20. The resulting fuel exhibited a viscosity of 2.9 cSt and a density of 0.82 g/cm³, well within the acceptable range for diesel engines. Combustion tests demonstrated smooth engine operation with minor emissions, indicating the feasibility of the produced fuel as an alternative energy source.

AI-based optimization results revealed that temperature and residence time are the most significant factors influencing yield. Genetic algorithm optimization predicted an ideal combination of 460°C and 45-minute retention time, achieving an 82% liquid yield while minimizing energy input. The re-utilization of non-condensable gases as a heating source further enhanced the system's thermal efficiency, reducing external energy demand by 18%.

V. CONCLUSION AND FUTURE WORK

The study successfully demonstrates that waste plastic can be efficiently converted into fuel through controlled pyrolysis in a properly designed conversion unit. The produced fuel exhibits physicochemical characteristics similar to commercial diesel and can serve as a potential substitute in power generation and industrial heating applications. The process not only mitigates plastic waste pollution but also provides a sustainable pathway for energy recovery and circular economy integration.

Future work will focus on scaling the process for continuous operation, improving catalyst reusability, and integrating automated AI-based control systems for adaptive process regulation. Additionally, life-cycle and techno-economic assessments will be performed to evaluate large-scale commercial viability and environmental impact.

The fusion of AI-driven process control, catalytic chemistry, and sustainable engineering ensures that waste plastic to fuel conversion will continue to evolve as a cornerstone technology in the pursuit of a cleaner, greener future.

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