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Pyrolysis of Plastics Waste to Diesel Engines Oil: A Review

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Abstract
Port Harcourt, a major city in Nigeria's Niger Delta region, faces severe environmental challenges, including oil spills, air pollution from industrial activities, gas flaring, and inadequate plastic waste management. With the rising consumption of plastic, there is an urgent need to curb plastic littering. Despite these challenges, Rivers State lacks Waste-to-Energy facilities for converting plastic waste into energy, and there are limited studies on the characteristics and potential applications of different plastic waste types as energy recovery feedstock. This study reviewed various technologies for converting plastic waste into oil for use in diesel engines. The findings indicate that pyrolysis is a viable method for transforming municipal plastic waste—an increasing environmental threat—into diesel engine oil. Pyrolysis presents an environmentally sustainable alternative to incineration and inefficient landfilling. Consequently, this study proposes a pilot reactor for converting plastic waste into diesel engine oil at a production temperature of 600°C.

Keywords: Pyrolysis Oil, Plastic Waste Eradication, Trash to Wealth Schemes, Renewable Energy

Introduction
Plastic, a byproduct of crude oil, is widely utilized in various aspects of daily life. With the increasing demand for packaged products, plastic consumption continues to rise. Nigeria ranks among the leading plastic producers in Africa, generating approximately eight (8) million metric tons of plastic annually (Anjum et al., 2016). Globally, plastic consumption is escalating at an alarming rate of 40% per year due to its durability, lightweight nature, and cost-effectiveness (Miandad et al., 2016a), leading to significant waste generation. In 2011, the global production of plastic waste was estimated at approximately 280 million tons (Sriningsih et al., 2014). Sadly, this waste may continue to expand or increase most especially in the developing countries because of increase in population and economic expansion. The discovery and commercialization of synesthetic plastics in the early 1950s has immensely advanced human evolution technologically which includes health care delivery Systems, automobile industries car batteries, dashboards, computer chips, and accessories amongst numerous other applications that are currently being deployed in our society (Eze et al., 2021a). Plastic waste has become a significant component of municipal solid waste (MSW), consisting of various plastic products primarily made from low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET). Among municipal plastic waste (MPW), polyethylene (PE) and polystyrene (PS) are the most prevalent types (Onwudili et al., 2009). Effective and urgent waste management strategies are essential to prevent further environmental degradation. This study focuses on reviewing the conversion of plastic waste into liquid oil through the pyrolysis process. It examines various technologies, methodologies, and findings from previous research on this conversion method.

Plastic Waste to Energy Technologies: - Conceptual View
There are six primary Waste-to-Energy (WTE) technologies used globally: incineration, pyrolysis and/or gasification, plasma arc gasification, refuse-derived fuel (RDF), anaerobic digestion (AD), and transesterification (Nizami et al., 2015a). The selection and operation of these technologies depend on factors such as the type of waste, capital and operational costs, technological complexity, labor skill requirements, plant location, and overall efficiency of the

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chosen technology. Developing a WTE facility requires a scientific approach, beginning with laboratory and pilot-scale studies before commercial implementation. The selection and design of a WTE system for specific or mixed waste types depend on accurate baseline data. However, there is limited data on municipal solid waste (MSW) characterization in Nigeria. Therefore, locally generated data from research institutions using indigenous MSW is crucial for designing feasible WTE plants.Pyrolysis, a widely studied WTE technology, can be classified into slow and fast pyrolysis based on the heating rate (Nizami et al., 2015b; Zaman et al., 2017a). Slow pyrolysis has a longer vapor residence time, while fast pyrolysis achieves a higher peak temperature in a shorter duration. Additionally, pyrolysis can be categorized based on the reaction medium: hydrous pyrolysis occurs in the presence of water, and hydro-pyrolysis takes place in the presence of hydrogen (Zaman et al., 2017a).

The environmental consequences of various plastic waste disposal methods underscore the need for an efficient, eco-friendly, and cost-effective approach to waste management. Current plastic waste management methods include reusing, recycling, WTE conversion, and landfill disposal (Ouda et al., 2016; Sadef et al., 2016). Conventional mechanical recycling techniques, which involve sorting, grinding, washing, and extrusion, are limited in effectiveness, recycling only 15–20% of all plastic waste types (Nizami et al., 2015a). This highlights the necessity for advanced waste management technologies to enhance sustainability and resource recovery. Plastics have a wide range of applications across various industries. In the global fight against the COVID-19 pandemic, plastics have played a crucial role in the production of personal protective equipment (PPE). Additionally, plastics have significantly contributed to advancements in technology, including computers, cell phones, lightweight automobile parts, roofing, and ceiling materials (Vandecasteele et al., 2007). The fight against COVID-19 would have been nearly impossible without PPE, which is largely composed of plastic components.

Abnisa et al. (2014) further stated that plastics exhibit excellent insulating and dielectric properties, making them essential in the electrical and electronics industries. Due to their increasing applications, plastics have become an integral part of modern life, with a significant portion being single-use items (Ecarnot et al., 2015; Bharti et al., 2016). In recent decades, the production and consumption of plastics have surged. Eze et al. (2021) reported that between 1950 and 2015, approximately 8,300 million tons (Mt) of virgin plastics were produced globally, generating around 6,300 Mt of plastic waste. Of this waste, only 9% has been recycled, 12% incinerated, while 79% has accumulated in landfills. Consequently, the volume of post-consumer plastic waste (PCPW) continues to rise. Global plastic production is estimated at around 300 million tons per year and is increasing annually (Zaman et al., 2017a). This review was conducted by searching and analyzing various electronic databases, including ScienceDirect, PubMed, ResearchGate, Google Scholar, and Google, for relevant journal articles and studies on pyrolysis published between 2010 and 2021.

Conventional methods of plastic waste management

It is obvious that plastic waste is a menace, there is therefore need for urgent attention to save the environment. A number of researchers have looked into various means for addressing plastic waste. Figure 1 describes conventional plastic waste management methods

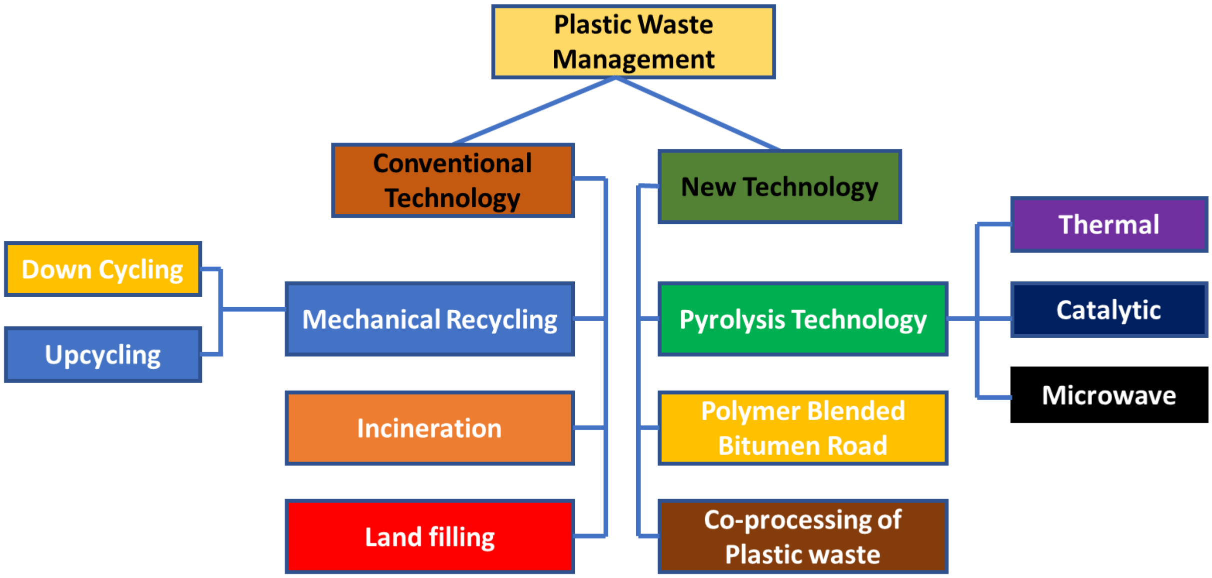

Figure 1. **Conventional and New Technologies for Plastic Waste Management.**

The conventional plastic waste methods include the following;

Land filling:

Landfilling remains the most common conventional waste management approach in many countries. However, rapid population growth and urbanization have led to a scarcity of available landfill space. Plastic waste landfilling is now considered the least favorable waste management option due to increasing environmental and public health concerns. A major issue associated with plastic waste in landfills is the presence of toxic chemicals, which have the potential to leach into groundwater, posing significant risks to public health (Rehan et al., 2017). Given these concerns, alternative and more sustainable waste management strategies are necessary to mitigate the environmental impact of plastic waste.

Incineration or Open Burning of Plastics fraction in Municipal Solid Waste:

Incineration, also known as the open burning of municipal solid waste (MSW), is an age-old practice still widely used, especially in underdeveloped and developing countries. The open burning of plastic waste is a major source of air pollution, with plastics constituting approximately 12% of MSW. Globally, around 40% of waste is burned, releasing toxic gases such as dioxins, furans, mercury, and polychlorinated biphenyls (PCBs) into the atmosphere. These emissions pose significant risks to vegetation, human health, and animal life (Anuar Sharuddin et al., 2016).

Landfilling, another common disposal method, results in the irreversible loss of valuable raw materials and energy. The incomplete combustion of polyethylene (PE), polypropylene (PP), and polystyrene (PS) during open burning generates high concentrations of carbon monoxide (CO) and other harmful emissions, while polyvinyl chloride (PVC) produces dioxins, carbon black, and aromatic compounds such as pyrene and chrysene (Abnisa & Wan Daud, 2014). Additionally, plastic combustion releases airborne particulate emissions (soot) and solid residue ash, primarily composed of black carbonaceous materials (Khuenkaeo et al., 2021). Studies have shown that soot and solid residue ash contain hazardous pollutants, including volatile organic compounds (VOCs), semi-VOCs, particulate-bound heavy metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzofurans (PCDFs), and dioxins, all of which have severe health and environmental consequences (Valkenburg et al., 2008). In many cities, landfills and dumpsites pose increasing threats, as plastic waste is often burned alongside other materials. A concerted effort is necessary to raise awareness about the dangers of this practice and its long- and short-term impacts on health and the environment (Lopez-Urionabarrenechea, 2012; Armenise et al., 2021).

Mechanical recycling Mechanical recycling of plastics

Mechanical recycling involves processing plastic waste into secondary raw materials or products without significantly altering its chemical structure (Aremu & Vijay, 2016). In principle, all types of thermoplastics can undergo mechanical recycling with minimal quality degradation, although the quality may diminish with repeated recycling cycles. The addition of additives and blending with virgin plastic can help improve the properties of the recycled material.
Currently, mechanical recycling is the predominant form of plastic recycling worldwide, accounting for over 99% of recycled plastic (Abnisa & Wan Daud, 2014). However, the high costs associated with collection, sorting, transportation, and recycling operations often make the process economically unviable. As a result, many plastic processing companies prefer using virgin materials, contributing to environmental degradation.
Mechanical recycling of plastic waste can be categorized into two main types: downcycling and upcycling. Downcycling involves converting plastic waste into lower-quality products, while upcycling enhances the properties of recycled plastics to create higher-value products (Nizami et al., 2015).

Downcycling of plastic waste Downcycling

Downcycling refers to the recycling of plastic waste into lower-quality materials with reduced functionality compared to the original product (Bharti et al., 2016). Unlike materials such as glass and metal, which can be continuously recycled without significant degradation, plastics tend to lose essential properties—such as mechanical integrity, optical clarity, and other inherent characteristics—after multiple recycling cycles. This deterioration makes them unsuitable for their initial applications. For example, a plastic water bottle may be downcycled into artificial turf or plastic furniture rather than being reused to manufacture another water bottle. In general, mechanical recycling of plastics through heating and remolding leads to downcycling over time, as the material eventually becomes unsuitable for applications requiring stringent engineering properties (Abnisa & Wan Daud, 2014; Anuar Sharuddin et al., 2016).

Upcycling of plastic waste Upcycling

Upcycling, also known as creative reuse, is the process of transforming waste plastic materials into new products with perceived higher value, whether in terms of artistic, functional, or environmental benefits (Násner et al., 2017). Unlike downcycling, which results in lower-quality materials, upcycling repurposes plastic waste into innovative and aesthetically valuable items. For instance, plastic bottles can be upcycled into flower pots, bird feeders, garden sprinklers, green parking canopies, chandeliers, Christmas trees, children's toys, and more. However, as previously discussed in Section 2.3.1, if the process involves heating and remolding, the plastic material may gradually degrade, ultimately leading to downcycling. Upcycling of both single and mixed plastic waste can also be achieved through thermo-chemical processes. Among these, pyrolysis is gaining significant attention as a promising technique for converting plastic waste into valuable products (Zaman et al., 2017b; Rehan et al., 2017).

Pyrolysis

Pyrolysis is the thermal degradation of plastic waste at high temperatures (300–900°C) in the absence or near-absence of oxygen, producing liquid and gaseous fuels (Nizami et al., 2015; Zaman et al., 2017b). Instead of burning, the plastic feedstock undergoes thermal depolymerization, breaking down into simpler hydrocarbons. Since plastics are composed of monomers formed through polymerization, pyrolysis essentially reverses this process, converting discarded plastics back into valuable resources such as monomers, fuel, and other useful chemicals (Armenise et al., 2021).

Pyrolysis offers several advantages over conventional plastic waste management approaches (Khuenkaeo et al., 2021). Unlike mechanical recycling, where plastics gradually lose essential properties such as clarity, strength, and flexibility, pyrolysis does not involve remelting and remolding, which often leads to downcycling (Armenise et al., 2021). Additionally, the costly and labor-intensive steps of sorting, washing, and blending—common in mechanical recycling—are largely absent in pyrolysis (Rehan et al., 2017).Another key advantage is that pyrolysis can process both thermoset and thermoplastic materials, making it suitable for handling a wider range of plastic waste, including composite materials that are increasingly replacing traditional materials in engineering applications (Bharti et al., 2016). The yield and composition of pyrolysis products depend on several factors, including the type of feedstock, process conditions (temperature, heating rate, reaction gas), and whether the process is conducted with a catalyst (catalytic pyrolysis) or without one (thermal pyrolysis). By adjusting these parameters, pyrolysis can be optimized to produce specific products such as high-quality fuel or valuable chemical feedstocks.

Selected results of some researchers on pyrolysis
Numerous researchers as well as scholars have carried out extensive on the use of Pyrolysis as a sustainable and viable option to replace dwindling fossil fuel dependence globally. Table 1 describes various types of pyrolysis, retention time, rate of heating and the resulting products obtained.

Table 1: Different types of the pyrolysis processes and products

Pyrolysis types	Retention time	Rate of heating	Final temperature (°C)	Products
Fast	<2 s	Very high	500	Bio-oil
Flash	<1 s	High	<650	Bio-oil, chemicals and gas
Ultra-rapid	<0.5 s	Very high	1000	Chemical and gas
Vacuum	2–30 s	Medium	400	Bio-oil
Hydro-pyrolysis	<10 s	High	<500	Bio-oil
Carbonization	Days	Very low	400	Charcoal
Conventional	5–30 min	Low	600	Char, bio-oil, and gas

Source (Zaman et al, 2017)

Bezegianni et al. (2017) reported on the alternative diesel from plastics, they considered the recovery of Engine oil alternative using the optimal combination of obtained pyrolysis oil from plastic with Catalytic Hydrotreatment.
It was revealed that the two-step process for converting plastic waste to Pyrolysis yielded quality product after upgrading the mid -distillate Pyrolysis oil. It was concluded that the hydro-processed mid-distillate fraction of Pyrolysis oil came out with an excellent ignition quality oil that meets the standard of EN590 Standard for Automotive Diesel. Maceiras, (2016) reported on diesel to fuel from plastics and postulated that the major gains in the process include the following:

a. Making productive use of otherwise problematic urban byproducts
b. Providing consistent base load power from reliable local fuel sourcing
c. Utilizes waste that can create land use problems
d. Effectively addressing waste management needs in rapidly growing urban areas

From all the literature reviewed it is obvious that diesel fuel from plastic waste which is free from Lead, Sulphur, or Nitrogen could be obtained via from plastic through Pyrolysis. This oil anticipated through this pyrolysis process could be used as an alternative fuel for diesel engines in the future, having two benefits: to recover energy from waste and reduce the environmental problems caused by this Plastic waste.

Gaps Identified in using pyrolysis to convert plastic to diesel oil
From this review, it is evident that knowledge gaps still exist in this technique, hence the need for further research which this work would further to close up. Table 2 present the various gaps identified in this review.

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Table 2: Identified gaps in the review of pyrolysis

S/N	
1.	Even though a number of research work has been done on the pyrolysis of plastics to diesel oil. Recovering catalyst used in this process and its cost has not yet been adequately addressed. There is need to closely and carefully address this concern to make the pyrolysis fuel good for use.
2.	Most research work on pyrolysis specially the oil obtained through thermal and catalytic process has issue of delayed ignition and in some instances release of higher heat with No_x substance. This in essence may not be too suitable for diesel engine, hence the need to address them.
3.	In most of the literatures, there are no adequate research directed towards reducing the hydrocarbons in the oil obtained from pyrolysis. This is a major area that need to be addressed to avoid black suit in the atmosphere when the oil is combusted.
4.	From literature, there are no adequate focus on the product of liquid pyrolysis when used as fuel. The components are complex hence a closer look at it is necessary for a safer environment without pollution.

Conclusion

Significant advancements have been made in the field of pyrolysis, with various techniques such as thermal, catalytic, and microwave-assisted pyrolysis being explored. However, microwave pyrolysis has received relatively little attention compared to the other methods. Most research agrees that both thermoset and thermoplastic materials can serve as suitable feedstock for pyrolysis. A common consensus in the reviewed literature is that the liquid product obtained from pyrolysis can be used as diesel oil. However, further research is necessary to evaluate the fuel's performance comprehensively. It is essential to investigate its efficiency, emissions, and long-term effects to prevent unintended environmental consequences. Comparative studies between pyrolysis-derived fuel and conventional diesel are needed to assess viability, optimize performance, and ensure sustainability.

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