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Plastic recycling for liquid fuel production and its use in thermal engines

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ABSTRACT

Pyrolysis is a thermochemical degradation process that has become one of the most promising methods for converting plastic waste into valuable alternative fuels, offering a dual environmental benefit by reducing solid emissions. This review examines the advancements in pyrolysis over the past decade, focusing on the efficiency of different plastics in producing fuels such as diesel, gasoline, and high-calorific-value gases. A systematic analysis is conducted, emphasizing the thermochemical pyrolysis of polypropylene (PP), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polystyrene (PS). Critical parameters evaluated include conversion yields, physicochemical properties of the products, residence times, and reactor configurations. Furthermore, studies comparing the performance and emission characteristics of pyrolysis-derived fuels with conventional fossil fuels are reviewed. Findings indicate that pyrolysis can achieve cumulative yields exceeding 80 wt%, producing fuel products with properties closely resembling those of commercial diesel and gasoline under optimized conditions. Additionally, emission studies suggest that these fuels exhibit environmental performance comparable to conventional fuels, reinforcing pyrolysis as a viable recycling alternative. However, challenges remain in scaling up this technology, primarily due to the variability in plastic feedstock composition and processing conditions, including reactor type and mode of operation, which significantly influence product yield and quality. Addressing these challenges requires further research into process optimization and feedstock pre-treatment. Despite these limitations, pyrolysis represents a promising solution for plastic waste management, contributing to the development of sustainable waste-to-energy strategies aligned with circular economy principles. This review synthesizes findings from multiple studies, bridging existing knowledge gaps while highlighting the critical role of thermochemical conversion in advancing sustainable waste management and alternative fuel development. Unlike previous reviews, this one provides a more comprehensive and nuanced perspective on the subject.

Keywords: pyrolysis, plastic recycling, alternative fuel, thermal degradation.

INTRODUCTION

The advent of plastic materials in the 1940s represented a historic transition point, establishing plastics as a key material in contemporary industries due to their significant contributions to social, technological, and economic advancement. The advantages of plastics include their lightness, durability, flexibility, versatility, corrosion resistance, and low cost. Besides, they are usually applied in various sectors like construction, electronics, automobile manufacturing, textiles, healthcare, and, most specifically, packaging (Al-Salem et al., 2017; Sharuddin et al., 2016; Park et al., 2020a). This extensive utility underscores plastics' indispensable role in modern society. However, high demand and large production volumes raise critical environmental issues primarily due to their short lifespan and very low recycling rates.

Plastics are predominantly derived from fossil and petrochemical resources (Nanda & Berruti, 2021), with approximately 8% of global crude oil consumption rather dedicated to polymer production (Lee et al., 2020). Global plastic production reached approximately 350 million tons in 2017, increasing to 359 million in 2018, with structural growth anticipated (Maafa, 2021; Plastics Europe, 2018). While 20% of plastic waste is typically recycled, 25% is known to be incinerated (Europe, 2018) Thus, 55% of this waste either accumulates in landfills or in the environment, aggravating both pollution and resource depletion more generally.

The recycling and reuse of plastic waste are mandatory in order to preserve natural resources and keep environmental pollution at bay (Maaroufi et al., 2021). Among these concerns are environmental and human health risks associated with the release of harmful pollutants during plastic incineration, including dioxins, NO_x, SO_x, heavy metals, and polycyclic aromatic hydrocarbons (Heidari et al., 2019; Zhang et al., 2019). In addition, total emissions from incineration are predicted to rise to 6.5 gigatons of CO_2 equivalent by 2050 (Zheng & Suh, 2019). As such, incineration should be viewed as a last-ditch solution to waste disposal.

Mechanical recycling is the term for those mechanical treatments where the materials are subjected to grinding so as to restore the material's physical properties without altering its chemical structure and is relatively befitting. Yet the efficiency of mechanical recycling also depends on the actual quality of plastic waste that reflects the effectiveness of sorting processes, which frequently results in limitations in meeting future recycling market demands (Nanda & Berruti, 2021). Plastic waste that cannot be recycled mechanically is sent for incineration or disposed of by landfilling (Agency, 2018). Therefore, with all these limitations, other alternatives have been sought, thus opening the doors for present-day research work focusing on chemicals. Chemical recycling is environmentally sustainable, and therefore can enable plastic valorization (Klemencová et al., 2020). Various chemical recycling technologies such as depolymerization, pyrolysis-gasification, gasification, and hydro-cracking have been developed and thoroughly studied (Grigore, 2017). Among these, pyrolysis stands tall as a promising thermochemical degradation method for plastic recycling.

Pyrolysis is the process of breaking down polymers through the application of heat in an inert or indirectly oxygen-limited environment (Muhammad et al., 2015). This process converts complex polymer chains into simpler monomers, thus yielding materials which can find use in the chemical industry (Mancheno et al., 2016). Pyrolysis products, such as solid, liquid, and gaseous fractions are highly energy rich, which makes them useful in heating processes or other uses, such as energy production via heat engines (Miandad et al., 2017; Sáenz, 2016). Compared to traditional combustion, pyrolysis reduces the volume of gaseous emissions by a factor of five to twenty, and reduces problems associated with storage. Additionally, it is green technology, given that there is minimal impact on water resources and by themselves, by-products may yield energy for use within the pyrolysis facility (Mazlan et al., 2015; Xue et al., 2015).

Process-wise, pyrolysis can be classified into slow or fast based on residence time. Several studies were carried out on waste plastics of different types such as tire waste (Islam et al., 2004; Ucar et al., 2005), electronic waste (Alston et al., 2011), and products for consumer use (Abbas & Saber, 2016; Dutta & Gupta, 2021; Eletta et al., 2017; Honus et al., 2018). Specific polymers studied include polystyrene (Li et al., 2023; Locaspi et al., 2023; Zimmermann et al., 2023), polyethylene (PE) (Sundararajan & Bhagavathi, 2016; Miandad et al., 2017; Ru et al., 2020; Syguła et al., 2021) and polypropylene (Dutta & Gupta, 2021; Eze et al., 2020; Miandad et al., 2017; Farhoud et al., 2022; Thahir et al., 2019). The liquid products recovered from pyrolysis exhibit physicochemical properties comparable to conventional fuels, such as density viscosity and calorific value, making them suitable for use in combustion and thermal engines without adverse effects (Kalargaris et al., 2017a, 2017c, 2018; Miskolczi et al., 2009; Ratio & Engine, 2021).For instance, existing studies have elucidated the major thermochemical processing variables- degradation temperature, heating rate, residence time, reactor type, and pyrolysis mode (thermal or catalytic) – that affect liquid yield and product quality.

The aim of the current review is to compile information on two main topics: thermochemical recycling for heat generation and its potential conversion to useful energy forms. Another key focus in the production of commercially viable fuel substitutes such as diesel-like fuel, gasoline, and high-calorific-value gases. An overview is presented on the effectiveness and feasibility of pyrolysis technology, assessing its thermochemical conversion rates and the fuel yields based on different plastic types, operating parameters, residence time, and the type of reactor configurations. Finally, the last section summarizes studies that have evaluated pyrolysis-derived fuels used in thermal engines, comparing gas emissions with those of conventional fuels. This synthesis highlights the potential of pyrolysis technology for transforming plastic waste into viable alternative energy source.

In general terms, previous research has investigated many aspects of plastic waste pyrolysis wherein thermochemical degradation mechanisms and characterization of pyrolytic end-products and their applications as energy co-products have been distinguished. According to a few representative studies, gasification and pyrolysis of plastics have been analyzed by Shah et al. (2023), detailing the operational constraints of pyrolysis processes, while Zulkafli et al. (2023) have researched co-pyrolysis coupled with biomass, elaborating both the synergistic effects and catalytic roles within bio-oil quality. There are also Pal et al. (2022), concluding a wide-ranged review on pyrolysis advancements with a focus on operating conditions influencing product distribution and its industrial and social context, as finally Laghezza et al. (2024), which, although, did not compare their performance concerning conventional fuels, analyzed the experimental conditions and the industrial scale of alternative fuel generation. This study considers all the above perspectives by relating the pyrolysis process, characterization of the pyrolytic liquid as a fuel, and its performance in thermal engines when compared to diesel and gasoline, focusing on emission, performance, and specific fuel consumption. This perspective actualizes advancements made, textually filling knowledge gaps concerning the use of pyrolytic liquid in producing viable fuel. A schematic representation of the location of this proposal in the existing research landscape is shown in Figure 1.

Figure 2 is a pictorial representation of the thermochemical degradation recycling of plastic waste. Solid plastic waste is fed into a reactor, where the thermal processing generates three primary outputs: diesel, gasoline, and gases. The

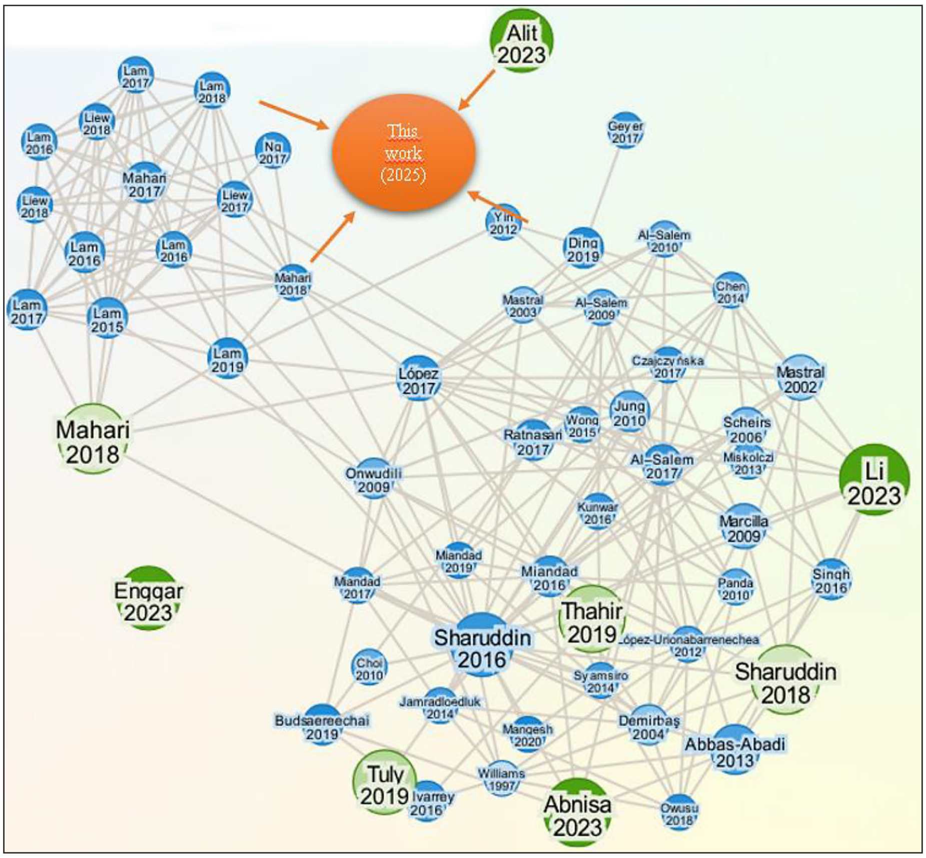

Figure 1. Schematic representation of the literature background and the positioning of this review within the existing research landscape

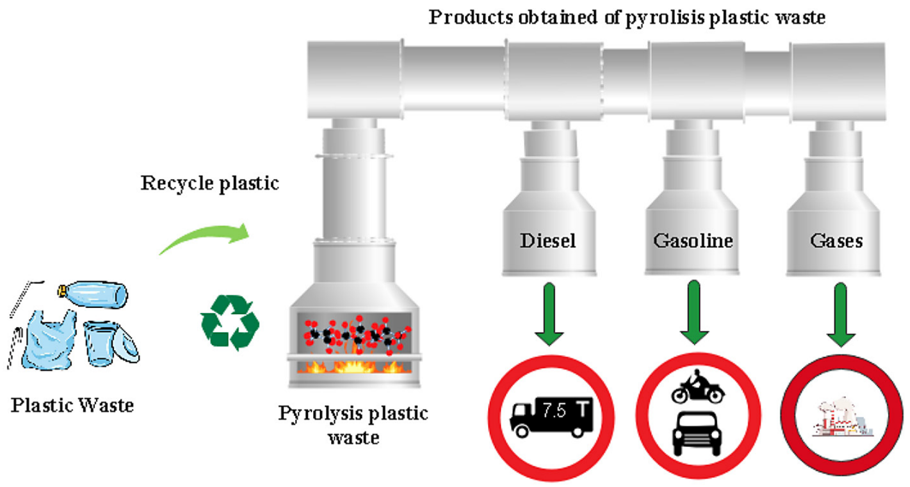

Figure 2. Cycle life for plastics based on a circular economy model involving waste plastics. According to this model can minimize its impact on the environment through its valorization and recovery**.**

diesel produced can be used as fuel for trucks, gasoline can be used for cars or motorcycles, and the gases can be used commercially. This procedure shows how in thermochemical recycling plastic waste can be recreated as an energy-rich resource, which thus leads to sustainable waste management and energy recovery.

Sustainable management of plastics waste: technical viability of thermochemical conversion into fuel products

Although plastic recycling is vexatiously problematic and costly, this arises, generally from certain limitations in the recycling processes, such as contamination with water and ineffective sorting before recycling, which makes the processes specific and complex (Anuar Sharuddin et al., 2016). Although every type of plastic differs distinctly from one another on compositional ground, dictated by their molecular structures and volatile organic compounds (VOCs), these factors work in affecting the yield of liquid hydrocarbons produced during recycling. Ash residue formation is also dictated using process parametric whereby high-functioning types of reactors are operated at high temperatures with rapid heating rates. These would invoke suddenly the bond cleavage and preclude reorganization amongst oligomers, which would lower process efficiency (Zeaiter et al., 2015).

The proximate analysis remains a very important technique through which one may know the different components such as moisture content, ash, fixed carbon and volatile matter. This is very important in determining the fraction of material that is capable of undergoing vaporization or gasification, therefore, a useful table for recycling optimization. The summary of proximate analyses for the dominant plastic types and their comparative values is shown in Table 1. The proximate analysis depicts that all plastics are highly volatized plastics-oft predominantly constituted of carbon and hydrogen when viewed. While it is a common observation that all types of plastic have a little or no ash content and this was mostly rated at 3.55% for PP.

Table 2 also gives the calorific values reported for various types of plastics. It can be seen that a range of 20.83 MJ/kg to 46.6 MJ/kg is comparable to calorific values coming from crude oil and can be noted for its desirability as an energy source. This advantage is substantial when considering the incineration of plastic waste in thermal power plants for electricity generation. Hydrocarbons derived from plastics could also be converted into value-added products for the petrochemical industry, thus increasing economic and industrial usefulness. Options like these increase the likelihood that plastics, far from being considered waste, could actually be treated as strategic materials for the energy industry (Qiao et al., 2018).

Both thermal and catalytic pyrolysis are invariably a means of thermal degradation of long-chain polymers into smaller and less complex molecules. Researchers have shown that with proper conditions at various temperatures, liquid yields exceeding 80% are generally achievable. Nevertheless, the complex parameters involved

Table 1. Proximal analysis of different types of plastics (Cruz et al., 2022)

Type of plastics	Plastics type marks	Moisture (wt%)	Fixed carbon (wt%)	Volatile (wt%)	Ash (wt%)	Ref.
Polyethylene terephthalate (PET)	♳ PET	0.46	7.77	91.75	0.02	[42]
		0.61	13.17	86.83	0.00	[43]
High-density polyethylene (HDPE)	♴ HDPE	0.00	0.01	99.81	0.18	[44]
		0.00	0.03	98.57	1.40	[43]
Polyvinylchloride (PVC)	♵ PVC	0.80	6.30	93.70	0.00	[45]
		0.74	5.19	94.82	0.00	[43]
Low-density polyethylene (LDPE)	♶ LDPE	0.30	0.00	99.70	0.00	[46]
		-	-	99.60	0.40	[47]
Polypropylene (PP)	♷ PP	0.15	1.22	95.08	3.55	[48]
		0.18	0.16	97.85	1.99	[43]
Polystyrene (PS)	♸ PS	0.25	0.12	99.63	0.00	[49]
		0.30	0.20	99.50	0.00	[46]
Polyethylene (PE)	♹ OTHER	0.10	0.04	98.87	0.99	[48]
Acrylonitrile butadiene styrene (ABS)		0.00	1.12	97.88	1.01	[41]
Polyamide (PA) or Nylons		0.00	0.69	99.78	0.00	[41]
Polybutylene terephthalate (PBT)		0.16	2.88	97.12	0.00	[43]

Table 2. High heating value of some typical plastic waste

Polymer (resin)	Calorific value (MJ kg^{-1})	References
High-density polyethylene (HDPE)	43	[51]
Polyethylene (PE)	43.3–46.5	[52]
Polypropylene (PP)	46.50	[52]
Polyvinyl chloride (PVC)	20.83	[53]
Polystyrene (PS)	41.90	[52]
Low-density polyethylene (LDPE)	46.6	[50]
Polyethylene terephthalate (PET)	23.09	[54]
Expanded polystyrene (EPS)	41.29	[54]

in the process-have to be carefully controlled, such as reactor type, temperature, and heating rate, with time, in such a manner so as to fulfill requirements. This flexibility makes pyrolysis a better method of recycling, which could produce high quality usable for different applications. In such a way, products of thermally-decomposed plastics like HDPE, LDPE, and PP should provide liquid, gaseous, and solid substances that carry large energetic values. The light and medium streams evolved by a further fractionation and purification of the liquid part within the temperature ranges below 190 °C and between 180 to 360 °C respectively can serve as fuels for diesel or gasoline thermal engines. The gaseous part which is non-condensable will serve as an auxiliary source of energy in supplying the pyrolysis process with the blaze it generates. The by-product, if any, will only be an ash, which could be diverted into any industrial activities, such as in soils to serve as a possible heat source, in turn improving the overall energy efficiency of that process (Devaraj et al., 2015; Kalargaris et al., 2017c, 2017b; Kassargy et al., 2018; Papari et al., 2021; Sharma et al., 2014). Catalysts need to be introduced to assist in optimizing other plastics involved, such as

PS, PET, PVC, and thermosets. The presence of catalysts improves selectivity toward the formation of specific compounds like benzene, toluene, ethylbenzene, styrene, acetone, and other high-value products that find importance in the chemical industry (Dhahak et al., 2019, 2020; Eze et al., 2020; Kumagai et al., 2015; Li et al., 2021; Park et al., 2020b). This gives results with the degradation temperatures or thermal degradation temperatures are given in Figure 3 with the liquid yields reported in different studies summarized in Table 3. The data indicate that the range of temperature extends from 300 °C to 800 °C, where liquid yields vary between 11 wt% and 91 wt%.

Generally, on the other hand, other contributors to thermal/catalytic degradation are temperature, rate of heating, time of residence, and type of the catalyst, which are considered the four key factors for the explanation of yields of liquid, gaseous, and solid products. In Table 3, results from different research articles were compiled, based mainly on the aforementioned study results. The reported temperatures showed a great variation from 100 °C to 900 °C. However, this greatly disparate range does not mean that plastic resins conventionally degrade or undergo molecular changes at 100 °C. The type of plastic greatly determines the degradation degree along with the activation energy necessary for their transformation. In relation to the liquid yields, it was found that higher yields would be produced from PS, while lower yields are obtained with LDPE and HDPE. It has been discovered that, concerning the compositions of the PS liquids, there are generally high concentrations of aromatic compounds compared to those of linear chain resins. Formulating the conditions for the pyrolysis of plastic mixtures is particularly tough due to the ratios of the various resins, which influence the compound selectivity along with the operational parameters. Research should continue in this area, as results would serve to shed light on the understanding of the corresponding experiments.

Thermochemical degradation of PP Polypropylene (PP) is a polymer consisting of linear chains of hydrocarbon characterized by the presence of only carbon and hydrogen in its virgin state. The molecular structure possesses methyl groups attached to the main chain, with its spatial orientation depending on tacticity. PP is obviously very resistant against chemicals and thermal degradation, being distinguished from other polymers, such as high-density polyethylene (HDPE), by melting points higher than 160 °C when softening.

PP is the world's most widely used plastic since it makes up 19.3% of the yearly plastic production of 390 million tons (Plastics Europe, 2022). This large disposal into the landfill makes it one of the plastics found chiefly in landfills. The lack of ubiquitous global recycling rates for PP has made it difficult to derive numbers; however, it is estimated that roughly 24.3% of landfill plastic waste is from PP, representing almost a quarter of total plastic waste produced (Vijayakumar & Sebastian, 2018). The thermochemical

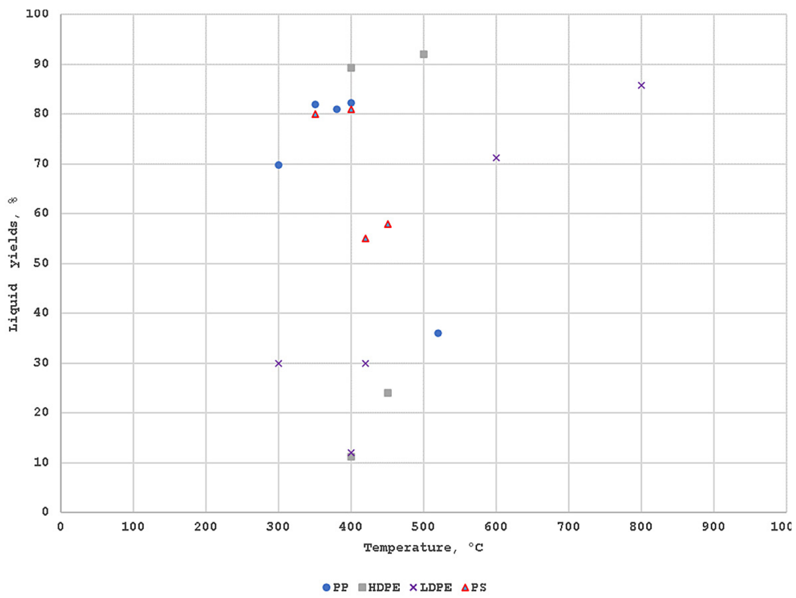

Figure 3. Mapping of different liquid yields according to literature (Table 3)

Table 3. Compilation of studies on the pyrolysis of PP, HDPE, LDPE, PS and MIX

Reference	Plastic type	Temperature	Products		
			Liquid wt%	Gas wt%	Solid wt%
(Mandeel 2013)	PP	250–400 °C	69.82	–	–
Eze et al., (2020)	PP/Catalytic	390 °C	47	–	–
(Lin 2005)	PP/Catalytic	120-550 °C	86–95	2–5	3–10
(Miskolczi 2009)	PP/Catalytic	520 °C	20–48		
(Ali 2011)	PP	100–480 °C	–	–	–
(Dutta 2021)	PP/HDPE	425 °C	55	25	20
(Uebe 2022)	PP/LDPE	350 °C 400 °C	82 (respectly) 82.3 (respectly)	–	–
(Kumar 2011)	HDPE	400–550 °C	11.2-23.96	84.2	–
(Sarker 2012)	HDPE	120-400 °C	89.35	–	–
(Saptoadi 2013; Undri 2014)	HDPE	microwave (1.2–2.7 kW)	12.7	–	–
(Singh 2018)	HDPE/Catalytic	500 °C	92	–	–
(Onwudili 2009)	LDPE	300-500 °C	30	–	–
(Shah 2010)	LDPE	400 °C	12	–	–
(Heriyanti 2018)	LDPE	300 °C	30	–	–
(Akgün 2021)	LDPE/Catalytic	800 °C 600 °C	85.8 (respectly) 71.3 (respectly)	–	–
(Andri 2017)	PS	300–700 °C	91-95	–	–
(Palmay 2023)	PS	400 °C	81	–	–
(Javed 2023)	PS	450 °C	58	–	–
(Amjad 2021)	PS/Catalytic	350-600 °C	94	–	–
(Alston 2011)	Mix	800 °C	70	30	–
(Budsaereechai 2019)	Mix	650–730 °C	36.9	48.4	15.7
(Kyaw 2015)	Mix	380 °C	63.76–67.06	19.92–28.52	–
(Ajibola 2018)	Mix	230 °C	Gasoline [36]; Diesel [32] Residual liquid [12–14]	–	–
(Ghodke 2023)	Mix	473–973 K	64 ~	–	-

degradation of polypropylene is schematically represented in Figure 4. When heat is applied to the molecule of polypropylene, followed by systematic depolymerization, continuous solvolysis occurs. Stage one, termed initiation, involves beta scission whereby heteroconjugating chains can break already existing carbon-carbon bonds. In stage two, termed propagation, there will be molecular reorientation that gives the appropriate attention to the formation of new compounds or radicals. Finally, step three is the almost-exact cessation of chemical reactions that put an end to the formation of either polymer chains or other molecular compounds (Saikrishnan et al., 2020).

Ali et al. (2011) conducted a study on the thermal degradation of PP mixed with petroleum residues or coal while using a cost-effective catalyst, hydrochloric acid (HCl), in a fixed-bed microreactor. Two gaseous streams, nitrogen and hydrogen, were used during the course of the investigation while high fractions of liquid fuels were produced at temperatures up to 480 °C. There were also gaseous products, small amounts of heavy oil, and insoluble residues like gums and carbon produced. This study validated the method as robust to convert polypropylene and waste oil into liquefied fuels as an attractive recycling alternative.

Further study focused on the thermochemical system was conducted within a steel micro-reactor over the temperature interval 250 to 400 °C. At a temperature of 300 °C, that is when the highest liquid fraction yield of 69.82% is gained with a conversion of 98.66 wt%. The temperature was further increased up to 400 °C where there was an insignificant drop in conversion down to 94.3

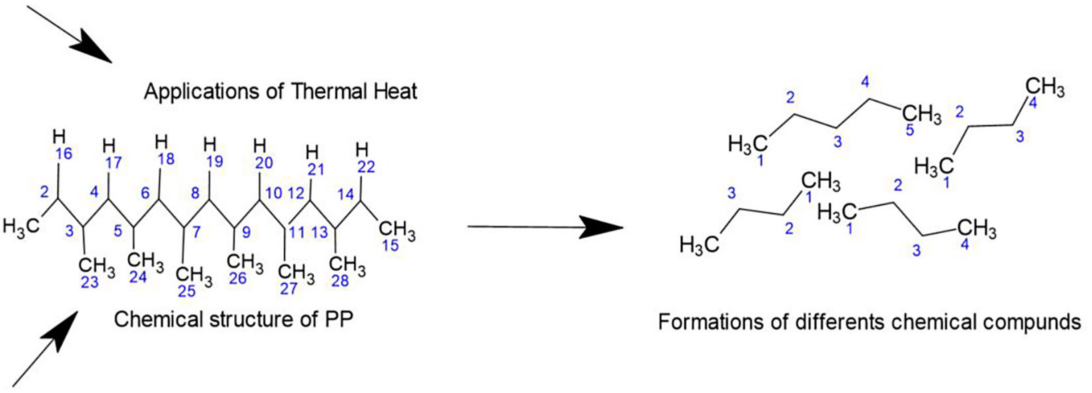

Figure 4. Pyrolysis is one of the thermochemical degradation methods conducted on PP. As far as the process is concerned, there are three main stages; initialization, during which occurs the beta-scission; propagation, producing molecular reorganization and formation of radicals; and termination, where the process finishes with the generation of new polymer chains or molecular compounds

wt% and correspondingly, an increase in solid residue mass (Ahmad et al., 2015).

A study conducted by Eze et al. (2020) Kankara zeolite-Y-based catalyst's performance during pyrolysis of a 13 wt% post-consumer PP-reinforced mixed waste plastic was examined through a batch reactor. The catalytic pyrolysis was performed at 350 °C, with thermal pyrolysis reaching a maximum temperature of 490 °C. In both pyrolyses, the catalyst-to-plastic ratio of 1:10 was maintained, using zeolite-Y, metakaolin, aluminum hydroxide, and sodium silicate. 46.7 wt% Liquid yield during catalytic pyrolysis was found to be optimum, whereas in thermal pyrolysis, it was at a high level of 66.9 wt%. Product characterization showed that oils obtained from catalytic pyrolysis have improved physiochemical properties comparable to standard fuel oils such as diesel and gasoline. The results reflect that, although catalytic pyrolysis runs at lower temperatures, it enhances fuel quality and represents an important potential alternative for sustainable waste-to-energy applications.

According to Dutta & Gupta (2021), packaging comprising HDPE and virgin PP at a 2:1 ratio was processed at 425 °C. The resulting yields included 55% liquid, 25% gas, and 20% solid fractions. Using a limpid silica-alumina catalyst to lower the required reaction temperatures of HDPE to 375 °C and PP to 400 °C, respectively, yielded liquid products containing chemical compounds such as benzene, toluene, xylene, and indene, with a calorific value of 40.9 and 41.1 MJ/kg for HDPE and PP, respectively, indicating their suitability as energy sources. In another related study conducted by Farhoud et al. (2022), 1 kg of PP waste was processed to produce liquid fuel in proportions of grease and gas of 80%, 10%, and 10%, respectively.

Ida Bagus Alit et al. (2022) investigated the production of fuel from PP and LDPE and noted that the yield of the fuel obtained from 1 kg of raw material was found to be in the range of 0.863 to 0.908 kg, with a density between 742 to 761 kg/m^3, and the kinematic viscosity ranged from 1.75 to 1.93 cSt. The recorded flash points were in the range of 1–2 °C, while the fire points were between 8 and 9 °C with an HHV ranging from 44.6 to 46 MJ/kg. The volume of fuel produced from mineral water bottles is notably higher than that from plastic bag waste and has a more prominent calorific value. In parallel, Uebe et al., (2022) recycled polypropylene in a batch reactor without agitation by means of slow pyrolysis at a low temperature. They used both virgin and waste polypropylene as raw materials, in addition to a mixed material that was made up of equal quantities of virgin polypropylene and virgin PP pyrolysis oil at a ratio of 1:1 w/w. The highest liquid yields were 82.0 and 82.3 w/w% when carried out at 350 °C and 400 °C, respectively. The density, viscosity, and calorific value of the gasoline and diesel fractions from the pyrolysis oils met EN228 and EN590 standards, respectively.

Herraprastanti et al. (2024) conducted an investigation into the pyrolytic conversion of PP and HDPE waste collected in Blora Regency, East Java, Indonesia. This experimentation was done when plastic waste surges, particularly during the Eid holiday. Pyrolysis experiments were carried out at varying temperatures and duration of reaction. After conducting the experiments, it was discovered that PP had the highest oil yield on heating at 450 °C for 300 minutes, while HDPE achieves 330 °C for 330 minutes. This study indicates that elevated temperatures augment oil yield while reducing the time of pyrolysis, showcasing the different thermal degradation characteristics of PP and HDPE during pyrolysis. The results substantiate that pyrolysis is effective in converting plastic waste to fuel oil, providing an alternative option for waste management that gives rise to energy resources. However, it is recommended to further optimize and conduct larger scale feasibility studies for improvement in efficiency and the assessment of economic and environmental gains.

Thermochemical degradation of HDPE

High-density polyethylene is an excellent linear polymer, with high linearity and crystallinity. In this way, its chemical structure and formula place it among olefinic polymers, primarily the family of polyethylene. HDPE is a thermoplastic material formed from ethylene monomers with short branches. This further gives way to good mechanical properties that seek its applications in milk containers, detergent bottles, oil containers, and toys (Anuar Sharuddin et al., 2016).

According to Plastics Europe (2022), HDPE accounts for 12.5 % of global plastic demand in respect to resin type, ranking third place in consumption; and thus, with increased use, the emphasis has now focused on HDPE recycling to properly lay the environmental burdens that come with its disposal. Then there is the higher interest from research on HDPE due to its specific ability to pyrolyze hydrocarbons and other unrelated compounds such as phenols and DPA from waste by-product. Figure 5 illustrates the thermal degradation of HDPE. Upon heat application, the polymer shows a beta-scission mechanism that results in a sequential breaking of carbon-carbon bonds. Formation of the lower molecular weight chains occurs, optionally transforming the polymer into HDPE oligomers. The alkane and alkene products are mainly paraffins and olefins, with smaller alkynes because of hydrogen rearrangement and transfer (Vicente 2009; Hamad 2013).

Modeling and simulation studies, such as the ones carried out by Eidesen et al. (2018), developed mathematical models addressing key reactions of HDPE pyrolysis, including beta-scission, hydrogen abstraction, and chain scission. Kabir et al. (2015) validated these models against experimental data and were able to predict with reasonable accuracy the degradation of HDPE at 420 °C. The catalytic burning process was examined. Singh et al. (2018) conducted catalytic pyrolysis with nickel in a conical fluidized bed reactor. At 500 °C, this method achieved liquid yields of 92 wt.% and the chemical composition was comparable to diesel fuel. These results illustrate a wide array of methodologies and conditions affecting the production of liquid fuel from HDPE, including the influence of temperature, catalysts, microwave-assisted techniques, and computational modeling.

Fanani et al. (2020) and Surma et al. (2020) evaluated HDPE pyrolysis using varied conditions to show the influence of the temperature and the type of catalyst on product yield and composition. Fanani et al. (2020) sought out catalytic pyrolysis by applying a natural zeolite catalyst at 500° Celsius for which 44.36% with 10,230.295 cal/g as its calorific value was recovered when 5% by mass of the catalyst was added. Surma et

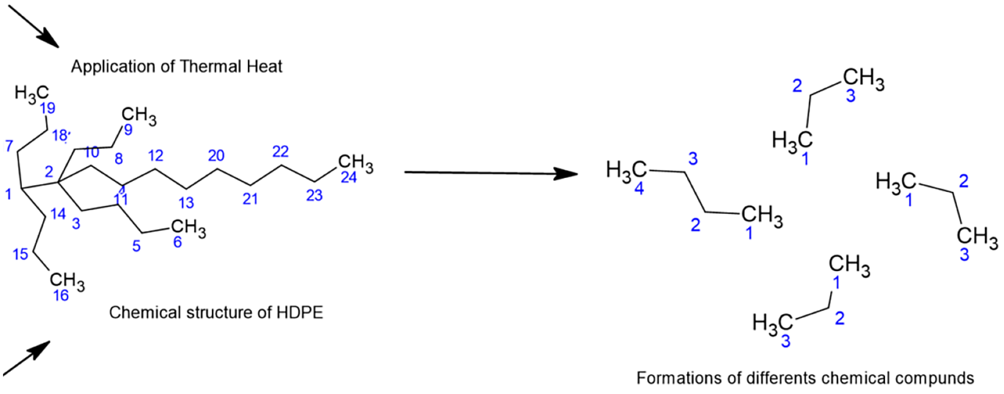

Figure 5. Pyrolysis is a thermal degradation process of HDPE. In this mechanism, carbon-carbon bonds are cleaved through a beta-scission process ceasing to polymerize because it is a mechanism that involves the breakup of other lower molecular weight chains: hence, alkanes, alkenes, and small amounts of alkanes

al., (2020) initiated low-temperature pyrolysis (150–250 °C) with the use of an FCC catalyst and concentrated on the production of aliphatic gaseous hydrocarbons (C_1-C_9), with concentrations of hydrocarbons ranging from 84.3969 to 526.4070 ppm depending on temperature and catalyst-to-sample ratio. This suggests that at elevated temperatures and using zeolites as catalysts, they could maximize liquid fuel production while lowering temperatures and FCC catalysts to enhance gaseous fuel generation. The results spell out that catalyst selection and reaction conditions are crucial in optimizing HDPE pyrolysis targeting specific energy products requiring more work in refining process parameters and bettering conversion efficiency.

Thermochemical degradation of LDPE

On the contrary to HDPE, LDPE visibly manifests a striking difference in the spacing of intermolecular chains. The structure variation and intermolecular chain distribution confer ductility to LDPE but increase its brittleness. Conversely, HDPE features better hardness and mechanical properties. Their easy processing and fantastic resistance to water have made LDPE a vital processing material in the field of packaging, such as plastic bags, wrappers for confectionery goods, and garbage bags. Indeed, LDPE products abound in everyday life, creating further evidence of their versatility and importance (Ahmad et al., 2015).

LDPE made up 14.4% of the total plastic resin production worldwide, according to Plastics Europe (2022). It has found its major application in packaging. Yet, specific figures on LDPE recovery are unavailable. On average, 2.9% of totally plastic-derived packaging waste is recycled. Most probably, such waste sits unnoticed in various landfills, worsening the environmental problems they cause due to the short use of these products. Figure 6 shows the thermochemical degradation of LDPE. LDPE deteriorates when subjected to heat through beta-scission, which is the cleavage of carbon-carbon bonds in the polymer chains. This may result in the formation of low molecular weight compounds, or LDPE oligomers, or the manufacturing of heavier molecules via cross-linking, which would explain the presence of a waxlike material in the liquid fraction obtained upon degradation.

There have been many studies on thermal degradation of LDPE that stress temperature, catalyst, and the nature of the products formed. Onwudili et al. (2009) applied a batch reactor under nitrogen for temperatures ranging from 350 to 500 °C. With the increase of temperature up to 425 °C, the liquid yield decreased, while the carbon content increased. The liquid fraction (i.e 30 wt %) was largely composed of aliphatic hydrocarbons, with lower levels of aromatic compounds, which increased slightly with increased temperature and longer times. Shah et al. (2010) performed thermochemical degradation of LDPE at different temperatures and analyzed the effect of different catalysts. The highest liquid yield (12 wt %) was reported by them for 400 °C with physical and chemical properties very close to those of conventional diesel and gasoline. Similarly, Heriyanti et al., (2018) studied LDPE degradation at 300 °C with approximately 30 wt% liquid yield and higher calorific values than the commercial diesel.

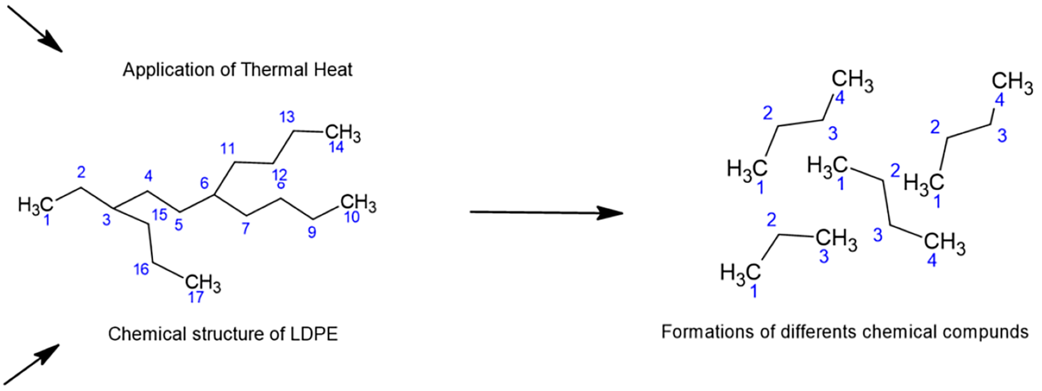

Figure 6. Comparative analysis of LDPE resin and degradation of LDPE via a thermochemical degradation process. LDPE, which has longer intermolecular chains, and it is more brittle when compared with HDPE, which exhibits superior hardness and mechanical strength. When heated, LDPE will more often undergo beta-scission, forming lower weight oligomers and, through cross-linking, heavier molecules.

Akgün et al. (2021) studied the degradation of LDPE single and mixed with aluminum under various heating rates and heating temperatures. Maximum liquid yields were found to be at 800 °C for pure LDPE (85.87 wt%) and at 600 °C for LDPE mixed with aluminum (71.3 wt%). In catalytic pyrolysis of LDPE with magnesium bentonite performed by Pradeep & Gowthaman, (2022), the liquid yield was 77.97 wt% with 1% catalyst. A noteworthy improvement in quality was observed of the liquid upon the application of 2% catalyst, comparable to that of the commercial diesel. These observations show the impacts of operational conditions, catalyst, and processing techniques upon yield and composition of produced liquid products from LDPE pyrolysis, paving the way for enhanced viability gleaning fuel and sustainable waste management approaches long into the future.

Thermochemical degradation of PS

PS is an aromatic polymer obtained from petroleum and comes into play from the era of the 1930s onwards. It polymerizes with some additives from styrene monomers obtained from petrochemical liquids (Nanda & Berruti, 2021). The molecular formula of PS is $(C_8H_8)n$, and according to the International Union of Pure and Applied Chemistry (IUPAC), its name is poly(1-phenylene). While it is naturally colorless, PS can be dyed with pigments. It is valued for its physical properties: heat-resistant, immensely durable, and lightweight. These features make it more advantageous than other plastics.

Polystyrene has its application in packaging industries and industries such as food, electronics, automotive, and construction (Pramudia et al., 2020). This increase in PS production is virtually juxtaposed with the other factors of population growth and its many applications. As put forth by Plastics Europe (2022), PS contributes about 6.1% of the total 390 million tons of global plastic consumption each year, which corresponds to about 23.8 million tons. Among thermoplastics, PS is the fourth most produced polymer in the world, after PE, PP, and polyvinyl chloride (PVC) (Inayat et al., 2021). Moreover, global demand for plastics is growing at about 4% per annum (Volk et al., 2021).

Several studies have investigated the mechanism by which polystyrene degrades. Researchers such as (Albor et al., 2023; Kunwar et al., 2016; Zhou et al., 2016) attributed it primarily to beta-scission, unzipping (end-chain beta-scission), and hydrogen transfer reactions, both inter- and intramolecular. Among these, the unzipping mechanism is envisioned as the most important in degradation of polystyrene to styrene monomers (Park et al., 2020b). Figure 7 shows a general schematic depiction of thermochemical degradation of polystyrene. The process begins with the unzipping mechanism via lateral elimination (end-chain scission) and proceeds via beta-cleavage that breaks composite-carbon bonds, resulting in reduced molecular mass compounds and styrene monomers. In contrast, PS produces aromatic substances at lower temperatures than polyethylene. The lateral elimination pathway contributes to the high intense styrene monomer concentration in the pyrolytic products (Singh et al., 2019).

One research avenue addressed within the PS thermal pyrolysis framework has been concerned

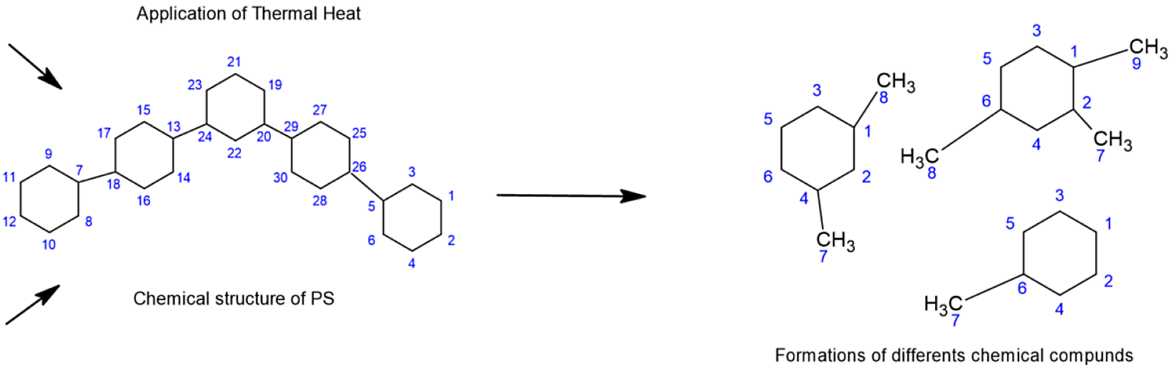

Figure 7. Schematic representation of polystyrene (PS) thermochemical degradation processes. The first lateral elimination (end-chain scission) follows beta cleavage, breaking carbon-carbon bonds to produce lower molecular weight compounds and styrene monomers. The unzipping mechanism being the primary route for degradation followed, therefore, as expected from the kinetics, at comparatively lower temperatures than polyethylene, producing a fairly high concentration of styrene monomers in the pyrolytic products

with processes and conditions employing catalysts intent upon liquid product recovery as a potential alternative fuel. As a case study, Andri (2017) studied PS degradation in washed and unwashed forms using a fluidized bed reactor at levels between 300 and 700 °C. The thermochemical conversions for unwashed PS yield 95% and for washed PS 91%, whereby the higher yield in the unwashed samples can be postulated along the same line as concerning residual biological matter. Liquid products included hydrocarbons within the C_{10}-C_{40} range. The liquid percent obtained from the pyrolysis of PS has the potential to be analyzed and tested as an additive for industrial fuel oil, according to Palmay et al. (2023). The liquid yield of up to 81 wt% was achieved at 400 °C. The kinematic viscosity was 1.026 mm^2/s, the relative density was 0.935, the flashpoint was 24 °C, and specific heat was 48.5 MJ/kg. The properties of the liquid fraction show the possibility of its application in enhancing fuel oil formulations.

Thermal degradation of PS was carried out at 450 °C, leading to a liquid yield of 58 wt% and a high calorific value of 46.2 MJ/kg, according to Javed et al. (2023). Hydrocarbon contents of PS are in the range of C_9–C_{17}, which indicates that this material is suitable for light liquid fuel production. The catalytic pyrolysis of PS has also been explored by Budsaereechai et al. (2001). Bentonite was used to obtain three fractions of products, while Amjad et al. used NiO/ZrO_2 catalysts to achieve a thermal conversion yield of 94 wt%. Results from these studies point to the role of catalysts in enhancing the selectivity of compounds and optimizing the degradation of PS. The thermal degradation of PS offers capacities for the sustainable management of plastic waste while propounding for energy production.

Thermochemical degradation a plastic mixture

Pyrolysis of composite plastic wastes, like HDPE, PP, LDPE, and PS polymers, has emerged as a promising process to tackle the burden of plastic waste management by investigating renewable energy options. This process can treat a wide range of plastics and offers a diversified option for sustainable waste management and energy recovery. Presently, efforts by researchers are focused on improving pyrolysis conditions to maximize yield and reduce the environmental burden with consideration to facilitate the emergence of a circular low-carbon economy. Among thermo-chemical recycling, pyrolysis has shown possibly better sustainability allowing the recovery and reuse of a substantial fraction of the materials' original compounds. Consequently, this technique has become a focus of numerous studies.

In one study carried out by Alston et al., (2011), pyrolysis of municipal solid waste with a mixed deposit of plastic materials was performed. The raw materials consisted of acrylonitrile-butadiene-styrene, high-impact polystyrene, and high-density polymers such as polyvinylchloride, polycarbonate, polyphenylene oxide, and polymethyl methacrylate, with considerable additive contents. The study was conducted in a batch reactor at 800 °C, and more than 70 wt% conversion was obtained, with 30 wt% being gaseous products and 46 wt% liquid fractions. Interestingly, the gas phase mainly contained methane, along with carbon monoxide, ethane, and ethene, while the liquid phase contained benzene, toluene, styrene, and other unidentified.

Thermal pyrolysis with gas, liquid, and solid fractions of 36.9/48.4/15.7 wt% at 650 °C and 42.4/45.47 wt% at 730 °C. Catalytic pyrolysis liquid yields of 89.0 wt% at 500 °C and 41.9 wt% at 650 °C yield mainly olefins (Budsaereechai et al., 2019). More recent investigations have focused on converting plastic waste blends into liquid fuels. Kyaw et al., (2015) studied pyrolysis of mixed plastics, including HDPE, LDPE, PS, PP, and PET, at 380 °C with various catalysts. Their experiments yielded liquid fractions of 63.76-67.06 wt% and gas fractions of 19.92–28.52 wt%, with the liquid products exhibiting properties similar to commercial fuels.

In a different area of research, Coniwanti et al. (2020) studied the pyrolysis of HDPE and LDPE in the presence of activated zeolite. By varying the percentages of HDPE and LDPE (0:100, 30:70, 50:50, 70:30, 100:0) with temperature intervals (300–450 °C or 573.15-723.15 °K), the study found that a mixture of HDPE and LDPE in a 70:30 ratio produced maximum results, yielding 83 mL of liquid product. The GC-MS analysis identified hydrocarbons in the C_8–C_{20} ranges and strongly advocated that zeolite is a potent catalyst. Ajibola et al., (2018) subjected HDPE and LDPE to pyrolytic experiments at 230 °C, whereby 50 separate compounds were singled out for each of the polymers. The yield for HDPE consisted of 36% gasoline, 32% diesel, 14% residual liquid, and 18% non-hydrocarbons, while LDPE produced 36% gasoline, 34% diesel, 12% residual liquid, and 18% non-hydrocarbons. Ghodke et al. (2023) have been looking into the possibilities of the pyrolysis of HDPE, LDPE, PP, plastic blends, and household waste at temperature ranges from 473 to 973 °K. Liquid yields of 64.6 wt%, 62.2 wt%, 63.1 wt%, 68 wt%, and 64.6 wt% were obtained at 773 K, and the products contained hydrocarbons in a range of C_8–C_{20}. The physical and chemical properties of the liquids determined by different ASTM standards resembled commercially available gaseous fuels.

PYROLYTIC LIQUID TESTS IN THERMAL ENGINES

Rinaldini et al., (2016) studied an interesting proposal consisting of the production of a liquid similar to diesel through the pyrolytic liquid produced from waste since, through the pyrolytic process of plastics, hydrocarbon mixtures can be obtained, which are a combination of petroleum, diesel, kerosene, and gasoline (Frigo et al., 2014). This in turn generates a double advantage, the first of which is energy recovery from waste, and the second is the mitigation of waste disposal problems. There exist some studies and projects which have been focused on converting WP into fuel (Naima & Liazid, 2013). Furthermore, several of them include detailed investigations of the combustion parameters of diesel engines. Diesel engines are generally preferred for use in power plants or large cars due to their high thermal efficiency; however, an important disadvantage of some of them is the release of high amounts of nitrogen oxides and smoke, which leads to effects on human health. In addition, a high diesel fuel demand for vehicles in the transport sector tends to quickly make this problem worse (Das et al., 2020). For this reasons, great efforts are being made to innovate in the production of alternative fuels from plastic waste.

Mani et al. (2009) made a comparison between the physical and chemical properties of the compound obtained from plastic waste, which tend to be very similar between the pyrolytic liquid and commercial diesel, as shown in Table 4.

Due to the similarities between the physical and chemical properties of pyrolytic oil and commercial diesel, several studies have been carried out on the engine performance (Fig. 8), as well as on the polluting emissions related to the use of fuel obtained from plastic waste.

Kalargaris et al. (2017c) conducted a study that consisted of measuring emissions (NOx, CO, HC) from the use of waste pyrolytic oil (WPO) obtained from plastic waste vs. commercial diesel. The pyrolytic fuel was obtained by thermochemical degradation at temperatures of 700 and 900 °C. For the experimental phase, a turbocharged direct injection four-cylinder diesel engine coupled to a cooling water system was used, and it was driven at a speed of 1500 rpm at three different loads, 75%, 85%, and 100%. The results showed that in terms of emissions such as NOx, CO, and HC, there was an increase compared to diesel. This is due to the density of waste pyrolytic oil (WPO) since it is slightly higher than traditional diesel, producing a more significant amount of mass entering the cylinder, i.e., there is a greater amount of burned mass. On the other hand, the thermal efficiency (BTE) was slightly lower due to the lower calorific value

Table 4. Comparison of fuel properties from waste plastic oil and diesel fuel

Property	Waste plastics oil	Diesel
Density at 30 °C in gm/cc	0.83	0.840
Ash content, %	0.00023	0.045
Kinematic viscosity, Cst at 40 °C	2.52	2.0
Gross calorific value (kJ/kg)	44.34	46.50
Cetane number	51	55
Flashpoint, °C	42	50
Firepoint, °C	45	56
Carbon residue, %	82.49	26
Sulfur content	0.030	0.045
Distillation temperature, °C at 58%	344	328
Distillation temperature, °C at 95%	362	340

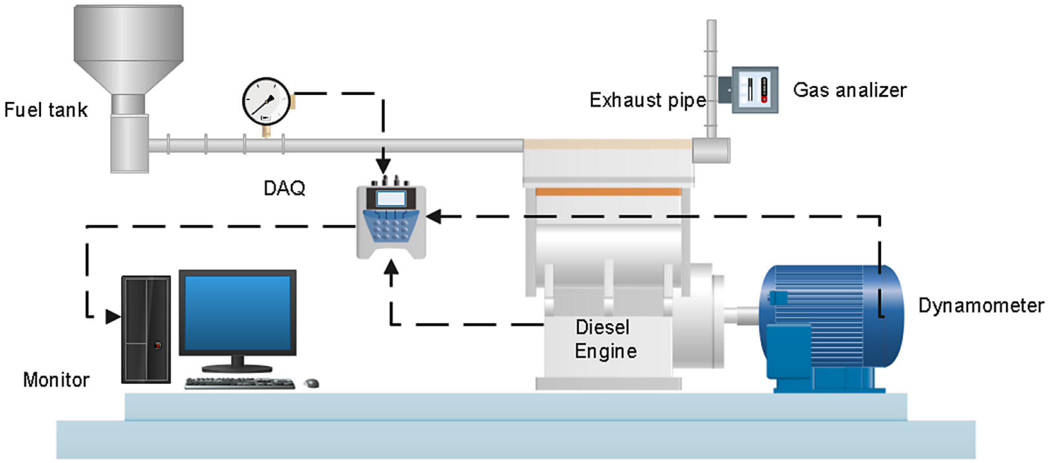

Figure 8. A schematic diagram of the experimental installation used in different works

that WPO presented. Regarding the comparison between the pyrolytic liquids, it was found that the one obtained at a temperature of 700 °C was higher than that of 900 °C, but without a mixture with commercial diesel, it tends to have delays in the ignition time.

Devaraj et al. (2015) evaluated the emissions and performance of WPO in the combination of 5% and 10% with commercial diesel. The engine used in the experimental phase was a 4-stroke mono-cylinder water-cooled and coupled to an eddy current dynamometer; also, the measured emissions from combustion, such as CO, CO_2, HC, O_2, and the thermal efficiencies of the motor (Bsfc) were calculated. The physical-chemical characterization of the WPO showed a slightly lower density of 0.798 compared to the diesel (0.840). In terms of the flash point, a value of 42 °C (WPO) and 50 °C for the diesel was recorded. The cetane number was higher in WPO than in diesel. Regarding the results of the studies on the engine, it was found that WPO showed a higher specific consumption and a higher thermal efficiency.

Kalargaris et al. (2017b) evaluated and compared the use of different pyrolytic liquids obtained from LDPE and ethylene-vinyl acetate (EVA). The engine used for the tests was a 4-cylinder turbocharged direct injection with a cooling system. The liquid obtained from pyrolysis was characterized, and different engine operating parameters were measured, such as NOx, CO, CO_2, HC emissions, specific fuel consumption, and thermal efficiency. The results showed a slight delay in the ignition time both for the EVA pyrolytic liquid obtained at 900 °C and for the mixture of EVA with diesel. Regarding the thermal efficiency of combustion of LDPE pyrolytic oil, it showed a certain similarity with diesel, but the fuel obtained from blends of EVA with diesel was slightly lower. On the other hand, NOx was higher for EVA and its blends with diesel than for LDPE fuel and commercial diesel. This is due to the longer ignition times of EVA fuel and its blends with diesel fuel, which lead to higher local temperatures in the compression cylinder than those obtained with LDPE and diesel fuel. On the other hand, UHC emissions were higher for EVA and its blends. CO_2 was slightly higher for diesel and its blend with EVA and lower for LDPE and pure EVA fuel, i.e., they had complete combustion, causing higher local temperatures in the cylinder than those obtained with LDPE and diesel.

Mangesh et al. (2020) studied pyrolytic plastic oil in a diesel engine with exhaust gas recirculation as a coolant. The engine was a 4-stroke single-cylinder diesel engine. The pyrolytic liquid was characterized, and very similar characteristics to diesel were observed. On the other hand, various parameters were measured with the specific fuel consumption (BSFC) and thermal efficiency (BTE), and in terms of emissions, carbon oxides were taken into account. NOx, CO, unburned hydrocarbons (HC), and smoke The results showed that pyrolytic oil has a higher specific consumption, the thermal efficiency decreased, and in terms of emissions, both nitrogen oxides, carbon monoxide, unburned hydrocarbons, and smoke increased compared to commercial diesel. Mani et al. (2010) evaluated the use of mixtures of diesel with pyrolytic oil in different portions, from 10% to 70%. The engine was a 4.4 kW air-cooled 4-stroke diesel cylinder at 1500 rpm interconnected to a dynamometer. Operating parameters were taken into account, ignition time, thermal efficiency, and regarding emissions were measured NOx, CO, unburned HC, CO_2, and smoke The results showed that the ignition time was more significant in the pyrolytic liquid and its mixtures with diesel compared to commercial diesel. The thermal efficiency turned out to be more significant in the pyrolytic liquid and its mixtures. In terms of emissions were more remarkable for the oil pyrolytic and its combinations with diesel.

The reformulation of the pyrolytic liquid through hydrogenation through catalysts has also been studied, which allows improving the performance of the liquid fuel, as shown by Mani et al. (2011). A 4-cylinder, direct injection, 4-stroke engine with a maximum power of 70 kW was used for the tests. Specific consumption and thermal efficiency were considered as operating parameters. In terms of emissions, NOx, CO, HC, and smoke were measured, and the results showed that all emissions were higher compared to commercial diesel. However, there was a slight decrease in hydrogenated pyrolytic liquid compared to pure pyrolytic liquid. Das et al. (2020) studied a diesel engine's operating parameters and emissions using pyrolytic liquid mixed with commercial diesel as fuel. A 4-cylinder, 4-stroke, water-cooled diesel engine with a power of 5.2 kW at 1500 rpm was used. The parameters considered were specific fuel consumption and thermal efficiency. In the emissions of NOx, CO, unburned hydrocarbons (HC), and smoke were taken into account. It was obtained that the specific fuel consumption was lower for the pyrolytic liquid alone, and in all its mixtures, the thermal efficiency was higher in the pyrolytic liquid. In terms of emissions, there was an increase in all cases compared to commercial diesel.

Mangesh et al. (2020) evaluated the use of pyrolytic liquid obtained from plastic waste as an alternative fuel to commercial diesel. A 4-cylinder, 4-stroke, turbocharged diesel engine interconnected to a cooling system with a power of 70 kW was used. The operating parameters considered for the study were the specific fuel consumption and thermal efficiency. In addition, NOx, CO, HC, and Smoke were taken into account for emissions. The results showed that the thermal efficiency was higher with lower specific fuel consumption. Regarding the other emissions, it was observed that there was an increase compared to commercial diesel. In Table 5, a comparison among emission studies is presented.

Table 5. Summary of diverse investigations on using the pyrolytic liquid from plastic wastes in diesel engines vs diesel fuel

Diesel engine specifications	Types of fuel	Performance		Combustion		Emissions				Reference
		BSFC	BTE	PCI	RoHR	NOx	CO	HC	Smoke	
AKSA-A4CRX46TI, 4-cylinder, 4-stroke, 68 kW at 1500 rpm	WPO	–	↓	↑	↑	↑	↑	↑	–	[40]
Kirloskar AV1, 1 cylinder, 4-stroke, 3.7 kW at 1500 rpm	WPO	↑	↑	↑	↑	↑	↑	↑	↑	[55]
AKSA-A4CRX46TI, 4-cylinder, 4-stroke, 69 kW at 1500 rpm	WPO	↑	↓	↑	↑	↑	↑	–	↑	[56]
4JA1, DI, 4-cylinder, 4-stroke, 68 kW at 1500 pm	WPO	↑	↓	↓	↑	↑	↑	↑	↓	[117]
Kirloskar TAF1,DI, 1-cylinder, 4-stroke,4.4 kW at 1500 rpm	WPO	↓	↑	–	–	↑	↑	↑	–	[118]
Eicher E483, DI, 4-cylinder, 4-stroke, power 70 kW	WPO	↓	↑	↑	↑	↑	↑	↑	↑	[119]
Kirloskar TV1, DI, 4-cylinder, 4-stroke, 5.2 at 1500 rpm	WPO	↓	↑	–	–	↑	↑	↑	↑	[116]
DI-Turbocharger, 4-cylinder, 4-stroke, 70 kW	WPO	↓	↑	↑	↑	↑	↑	↑	–	[120]

Note: RoHR: rate of heat release, PCI: in-cylinder pressure.

DISCUSSION TRENDS AND PROSPECTS

The thermochemical degradation of plastics is an alternative method to traditional recycling since it allows solid waste that is contaminated or cannot be recycled by other means to be transformed into products with a high energy value, such as PP, LDPE, HDPE, and PS, in turn, according to some authors, it has been reported that its use in diesel or gasoline thermal engines, can allow the product obtained to be an alternative energy source. According to studies, some of the highest-rated plastics for thermochemical conversion are such straightforward chain polymers as PP, HDPE, and LDPE. The structure of polyethylenes requires high-energy input, whereas PP has the lowest energy barriers for conversion. Considerable amounts of aromatic compounds have been reported to be present in PS, and therefore, might result in generating toxic substances when used in thermal engines. To ensure sustainable and safe use, reformulating the fuel from PS may be preferable if deemed necessary. The physical-chemical properties of the pyrolytic liquid have characteristics similar to those of commercial diesel, such as density (0.835 gm/cc), calorific value (44.3 kJ/kg), kinematic viscosity (2.52 Cst), cetane number (51), flash point (42 °C), fire point (45 °C).

Regarding emissions, almost all studies show a higher amount of NO_x, CO, and HC. This may be due to the increase in specific fuel consumption in some cases since its lower density requires a larger amount of fuel. Therefore, using pyrolytic liquid as an alternative fuel is one of the most viable ways since it offers the opportunity of an energy source and, in turn, a solution to the problems in the disposal of urban solid waste. Such studies show, without a care for controversy, the technical viability for both thermochemical conversion and the application of its energy in thermal engines. Nevertheless, it must be highlighted that there is an urgent need for the scientific community to enhance this research into energy recovery from plastics, linking technical feasibility with legal aspects.

CONCLUSIONS

This review effectively assimilates the current perspectives and advancements on the thermochemical degradation of plastic wastes through pyrolysis. The findings lend credence to the assertion that pyrolysis is a technically and economically feasible method, for example, obtaining diesel-like liquids and high calorific gases from wastes such as PP, HDPE, LDPE, and PS. This paper stands to be among the few that provide insights into potential applications of fuels from pyrolysis in thermal engines by systematically evaluating yields, their physicochemical properties, and emissions characteristics. Overall, the PP, HDPE, and LDPE yielded rather high efficiencies of conversion with low energy demands, while PS compound-rich aromatics posed challenges for conversion. The present review seeks to fill the void by a detailed comparison of the conversion performances, different reactor designs, and relevant fuel properties in relating to process optimizations and operational efficiencies. Additional consideration was also made of some of the issues of large-scale processing, notably feedstock variability and regulatory matters, in light of gaining wider industrial acceptance. Thus, future studies should focus on further optimization of pyrolysis processes and coupling them with emission-control strategies to conform to the standards of environmental regulations.

Summarizing, the results substantiate pyrolysis as an option for recycling plastics, providing a two-pronged benefit for combating plastic pollution and yet providing a source of energy that can be sustainable. Future efforts must surround the integration of technical feasibility with regulatory dynamics to allow the prior execution of pyrolysis, which can support principles of a circular economy while also promoting sustainable waste management strategies.

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