OXFORD JOURNAL
OF STUDENT
SCHOLARSHIP

Pyrolysis and Hydrothermal Processing in the Processing of Plastic Waste: a Review and Comparative Analysis

Sunav Adhikari
adhikarisunav@gmail.com

ABSTRACT

Plastic waste pollution is a significant concern in today's society, as only about 10% of global plastic waste is recycled. Chemical recycling technologies may offer solutions to plastic waste management. This review describes and analyzes methods of pyrolysis and hydrothermal processing, which can break down large polymers into valuable products, particularly energy-dense fuels and industrial monomers. Section 2 describes pyrolysis methods, where in fast and flash pyrolysis, electric Joule heating can convert plastics into an olefin-rich gas mixture. Aluminosilicate and metal oxide catalysts promote the formation of gasoline-range hydrocarbons. In slow pyrolysis, spent fluid catalytic cracking (FCC) catalysts can also enhance fuel properties and product yields. Section 3 describes hydrothermal processing methods, which can primarily be divided into subcritical and supercritical water treatments and low-pressure hydrothermal processing (LP-HTP). Supercritical water liquefaction (SCWL) can produce high oil yields (80-100%) and useful fuels, though it requires high pressures of at least 22.1 MPa. Supercritical water oxidation (SCWO) may be able to replace incineration as a cleaner method of energy recovery. LP-HTP can produce similar oil yields to SCWL, though it is less developed. Section 4 analyzes similarities and differences between pyrolysis and hydrothermal processing. SCWL and LP-HTP are most comparable to slow pyrolysis in temperatures and residence times. Mechanisms for the two are similar for addition polymers, though significantly different for the condensation polymer PET. Pyrolysis is significantly more developed industrially, with the plastic pyrolysis oil market having a value of approximately $700 million. Future research in these processes will help to remediate the issue of plastic waste pollution.

INTRODUCTION

Plastics are some of the most useful materials in the world. Their properties, which include high corrosion resistance, low production costs, and low density, make plastics extremely important in everyday life. However, the high production of plastics, which is projected to reach almost 1 billion tons annually by 2050, can cause massive amounts of plastic waste.[1]

Plastic waste contains a wide assortment of different plastics. However, thermoplastics make up the majority of plastic waste, especially polyolefins such as low-density and linear low-density polyethylene

(LDPE and LLDPE, respectively), high-density polyethylene (HDPE), and polypropylene (PP). Combined, polyolefins make up about 54% of total plastic waste.[2]

Unfortunately, about 49% of plastic waste is currently landfilled and 22% of plastic waste is mismanaged, both of which are significantly greater than the 10% of plastic waste that is recycled.[3] Mismanaged plastic waste and landfilled plastic waste can have adverse effects on the environment. Due to their inertness and resistance to degradation, plastics can interact with harmful substances in the environment.[4] When they do degrade, plastics in older landfills and mismanaged plastics frequently contaminate the environment with microplastics, which are plastic particles with dimensions smaller than 5 mm. Microplastics can carry toxic chemicals such as heavy metals, as well as pesticides, antibiotics, and fungicides directly into life forms, which causes them to travel throughout entire ecosystems.[5] Therefore, it is important to consider more effective methods to process plastic waste.

Before examining current plastic waste treatment methods, it is important to consider different types of processing plastic waste. Upcycling is a strategy that repurposes waste into higher-value products such as raw materials, while downcycling is a strategy that repurposes waste into lower-value products, which mechanical recycling commonly falls into. Though upcycling is more appealing due to its capability to improve the quality of a product, downcycling can be more economical and viable for less demanding applications, which makes both strategies important. Recycling generally converts waste into a product of similar quality, though upcycling and downcycling can both commonly be regarded as types of recycling.[6]

The most established methods for treating plastic waste are mechanical recycling and incineration. Mechanical recycling involves melting and resolidifying plastic waste in order to produce cleaner, usable plastic. However, plastics gradually degrade in this process due to heat, light, and other factors, limiting their applications.[7] For example, mechanically recycled plastic is rarely suitable for food packaging.[8] Additionally, the required melting and resolidifying step makes mechanical recycling only suitable for thermoplastics.

Fig. 1 shows the production and the recyclability of the most commonly used plastics in 2019. PET is the most commonly recycled plastic, with a recycling rate almost twice that of HDPE. PP, PS, and PVC are all very rarely recycled, making it crucial to find ways to treat them. Notably, PVC is the only one of these plastics with chlorine, which makes it significantly more difficult to process. In 2019, these 6 plastics contributed to 81.5% of global plastic production.[9]

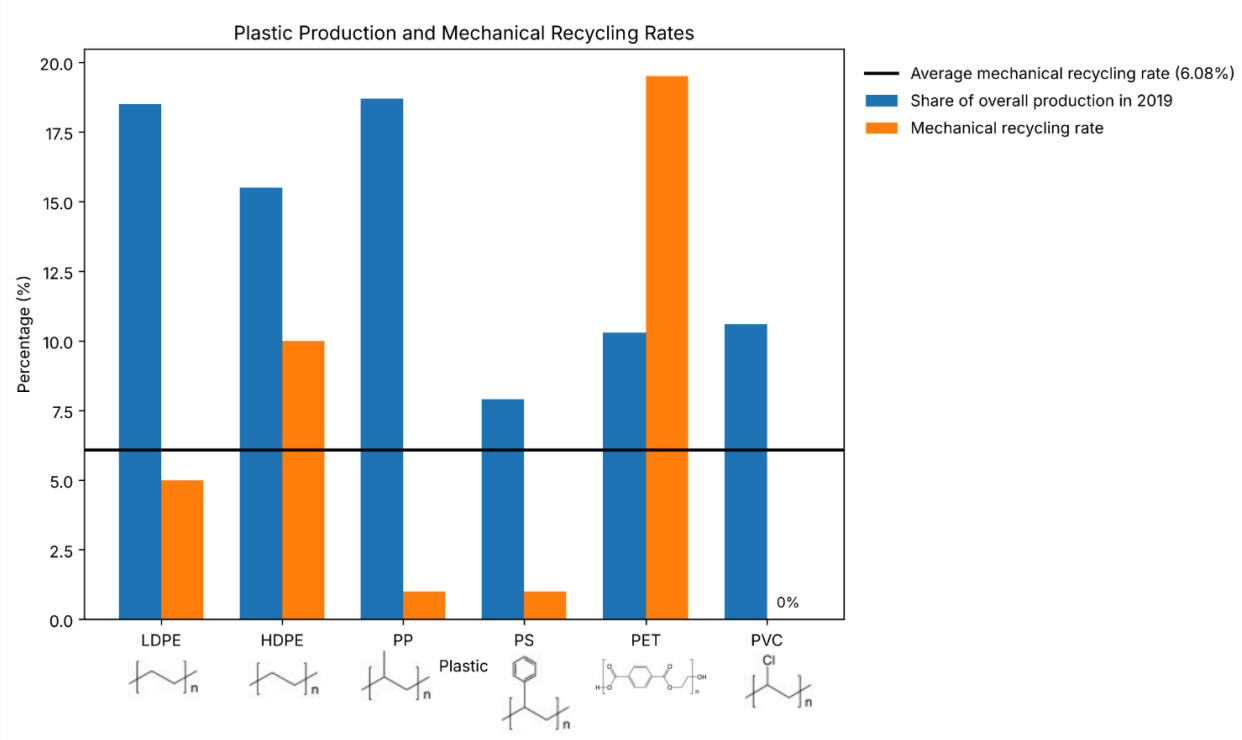


Fig. 1. Percentages of total production and recycling rates for several common plastics. Data in this graph were extracted from Huang et al.[9] Average (black line) was calculated by finding the unweighted arithmetic mean of the plastics' recycling rates.

*abbreviations: PS is polystyrene, PET is polyethylene terephthalate, PVC is polyvinyl chloride

Incineration is a method to treat plastic waste by burning it to recover energy, and was used to treat about 19% of plastic waste in 2023.[3] In particular, hydrocarbon plastics such as PE, PP, and PS have high heats of combustion (>40 MJ/kg), which makes them more suitable for incineration.[10] However, plastics frequently do not burn cleanly. In particular, PVC introduces chlorine into the atmosphere as it burns, polluting the air. Airborne soot from burning plastic is also known to contain polycyclic aromatic hydrocarbons (PAHs), which can cause cancer.[11] Incineration is also energetically inefficient, frequently only yielding about 10-15 MJ/kg of plastic processed, which is only about 20-25% of the calorific value of hydrocarbon plastics.[12–14] These factors make incineration the most undesirable treatment for plastic waste. As such, methods of processing plastics should be developed to completely replace incineration. Ideally, these methods should also be able to process plastics that are incapable of being mechanically recycled.

Chemical recycling is a category of methods that recycles plastics by changing their chemical structures, typically by breaking polymer chains into smaller products.[7,8] A key advantage of chemical recycling is that it is more suitable for plastics that have already been recycled. Because the chemical composition of plastic is not significantly changed during the mechanical recycling process, chemical recycling should remain effective regardless of whether the material has already been mechanically recycled or not.

Chemical recycling processes done with high temperatures are broadly called thermolysis. The IUPAC Gold Book defines thermolysis as "the uncatalyzed cleavage of one or more covalent bonds resulting from exposure of a compound to a raised temperature, or a process in which such cleavage is an essential part."[15] For synthetic polymers, this is equivalent to cracking large, high-molecular-weight compounds into smaller molecules that may be more useful. For hydrocarbon polymers such as polyolefins, these processes will frequently yield oils and gases with high hydrocarbon content and heating values, which we will examine throughout this paper. Thermolysis and thermal cracking can be conducted using other substances as well, most commonly water. Using water under high temperatures and pressures can dramatically alter its properties, making it useful in the thermolysis process by impacting yields and qualities of oils, gases, and solids.[7]

Though many reviews on various types of chemical recycling have been done, few have compared methods of anhydrous and hydrous thermolysis for plastic waste.[16–19] Instead, past reviews have focused on specifically anhydrous or hydrous thermolysis, a variety of chemical recycling methods, or mechanical and chemical recycling methods. This review aims to collect key sources to examine and evaluate several types of thermolysis, along with catalytic thermal cracking when applied to plastics. Section 2 will discuss methods of pyrolysis without water, characterized by reaction times and catalysts; this category encompasses both anhydrous thermolysis and catalytic thermal cracking. Section 3 will focus on methods of hydrothermal processing, distinguished by pressures and temperatures used; this category corresponds to hydrous thermolysis. Section 4 will compare and contrast methods of pyrolysis with methods of hydrothermal processing. This review will conclude by discussing future prospects of pyrolysis and hydrothermal processes. Throughout this review, we will focus primarily on the six most widely produced plastics as stated in Fig. 1.

METHODOLOGY

This paper uses a narrative review approach. Relevant sources were found using Google Scholar and Scopus. Keywords included processing methods (such as fast pyrolysis, catalytic slow pyrolysis, or supercritical water liquefaction) and feedstock types (such as specific plastics, mixed plastic waste, or biomass). Biomass was included as a feedstock type because it can undergo similar processing methods to plastic waste. Experimental studies were found by combining keywords to create a query of form, "[processing method] of [feedstock type]," and reviews were found with a query of the form, "a review of the [processing method] of [feedstock type]." Additional sources were found by examining the reference lists of these articles. Priority was given to sources published in the last 15 years (2011 or later); however, older sources were used if they provided valuable information not offered by newer articles.

Studies were included if they offered valuable insights into the processes of pyrolysis and hydrothermal processing of plastic waste. Such valuable sources could include individual plastic processing studies, reviews of these processing methods, applications of these processes on biomass, and life-cycle and techno-economic analyses. Sources were excluded if they focused on unrelated processing methods or

were not available in English. Both experimental and computational studies were considered; however, conference abstracts and preprints were not considered.

PYROLYSIS

The main technique of anhydrous thermolysis is pyrolysis. Pyrolysis is the thermal decomposition of organic matter in an oxygen-free atmosphere, preventing combustion.[20] Though used today for decomposing both biomass and plastic waste, pyrolysis was first applied to plastics in the early 1960s.[21–23] Nitrogen is nearly always used in pyrolysis studies as it is abundant and does not interact with hydrocarbons, even when heated.[24–26] When heated, plastic waste tends to decompose into a solid product, a liquid product, and a gaseous product, though the exact yield of each product may vary depending on the exact temperature, heating rate, plastic used, and other tunable factors.[24] Gaseous products generally consist of hydrogen, carbon oxides, and small paraffins and olefins (C_1-C_4), most of which can be used as raw materials or burned. Solid pyrolysis products generally consist of char composed of carbon and ash, which can sometimes be converted into useful products such as nanomaterials. Liquid products consist of hydrocarbon mixtures that can be distilled in a manner similar to crude oil.[24,25,27] The goal of pyrolysis is usually either to turn plastic waste into fuels such as gasoline and diesel or to upcycle plastic waste into gaseous monomers, making the formation of liquid and gaseous products most favorable.[14,24,28] Catalysts can also be used in pyrolysis to enhance product selectivity and lower reaction temperatures, with highly porous aluminosilicate materials and metal oxides (which can be found in pyrolysis ash) being popular options.[29–33] The variety in catalysts makes catalytic pyrolysis a widely researched topic, and many reviews tend to focus on a specific product, and then describe the propensities of various catalysts to produce that product.[34–37] This review will examine both catalytic and non-catalytic (thermal) pyrolysis methods and how catalysts can enhance product selectivity.

Fig. 2 shows a pyrolysis process flow diagram. Before pyrolysis, plastic waste is sorted and shredded. After shredding, plastics enter a pyrolysis reactor, where they are decomposed at high temperatures into solids and volatile products under an inert atmosphere. Volatile products then travel through a condenser, where condensable vapors turn into oil, and noncondensable vapors travel into another container. Pyrolysis product gases can also be burned to create electricity for the pyrolysis process. It should be noted that this figure simplifies the uses of each product, and we will examine how the solid, liquid, and gaseous pyrolysis products can be used throughout Sections 2.1 and 2.2. In catalytic pyrolysis, catalysts may be placed in different positions based on whether in-situ or ex-situ catalysis is intended.[33,38] In-situ catalysis is when the catalyst is directly mixed with the feedstock, while ex-situ catalysis is when the catalyst is located downstream, and only interacts with volatile pyrolysis products.[31] The specific mechanisms associated with catalysts are outside the scope of this review, though we will summarize how catalysts may impact the yield of certain functional groups and fractions.

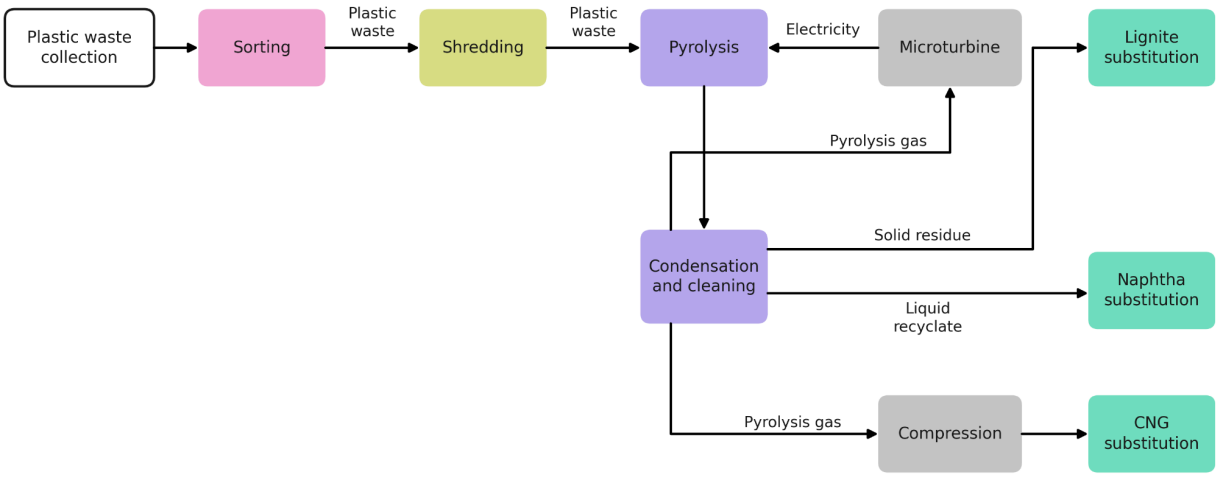


Fig. 2. Process flow diagram for the pyrolysis of plastic waste. Adapted from Trecáková et al.[39]

Types of pyrolysis can be identified based on their heating rate and temperature used. Slow pyrolysis uses the lowest temperatures and slowest heating rates, while fast pyrolysis uses higher temperatures and heating rates. Flash pyrolysis uses extremely high temperatures and heating rates with very short residence times. Higher temperatures and heating rates also require more finely divided particles, which is an important practical consideration.[40] Categories of pyrolysis are not standardized based on their heating rates or residence times, and different studies may categorize types of pyrolysis differently, with the boundary between flash pyrolysis and fast pyrolysis being unclear. Previous reviews of pyrolysis have classified flash pyrolysis as having a residence time shorter than 500 milliseconds and fast pyrolysis as having a residence time of 0.5-10 seconds, and slow pyrolysis having a residence time longer than 5 minutes,[14,40] though individual fast and flash plastic pyrolysis experiments are frequently inconsistent with these conventions.[30,41] Therefore, for the purpose of this review, flash pyrolysis and fast pyrolysis will be considered together, and will encompass any study that processes plastic with shorter residence times shorter than 5 minutes. Experiments with residence times longer than 5 minutes will be considered slow pyrolysis.

Fast and flash pyrolysis

Fast pyrolysis and flash pyrolysis are methods of pyrolysis requiring the fastest heating rates, most finely divided particles, and shortest residence times. These methods can use temperatures ranging from 450°C to 2800°C, which makes research relatively scattered as temperature is one of the primary determinants of product yield and composition.[27,41] Early flash pyrolysis studies suffered from relatively low conversion rates (<70%) and low oil or monomer yields.[42,43] This prompted the need to attempt to enhance product selectivity by manipulating reaction conditions or adding catalysts.

One way to manipulate reaction conditions is by using electric Joule heating. Luo et al. commented that Joule heating favors primary reactions and minimizes secondary ones, enhancing product selectivity. At a

temperature of 1250°C, in less than 1 second, 80.1% of LDPE was converted into an olefin-rich gas mixture consisting of 35.60% ethylene, 17.70% propylene, and 7.28% butadiene. The flash pyrolysis of HDPE notably yielded carbon nanospheres with tunable sizes, nanomaterials with wide usage in lithium-ion battery anodes and adsorption materials.[27] Niu et al. used indirect Joule heating to convert PE and PS into gases with residence times as short as 2.5 seconds and temperatures up to 2300°C. At 2300°C, PE and PS yielded gases that were 70% and 99% hydrogen by volume, respectively. At lower temperatures, this did not occur, and the pyrolysis gases and oils consisted of mainly olefins. Additionally, char could be upgraded into graphene, though this required direct flash Joule heating and temperatures of about 2600°C. This turbostratic graphene significantly outperformed commercial graphene in corrosion resistance, showing its potential for use in protective coatings.[41] These studies demonstrate the potential of electric heating to be used for synthesizing valuable gases such as ethylene, propylene, and butadiene, which are known to be important industrial monomers, and hydrogen, which is an emerging energy carrier. They also demonstrate that the solid pyrolysis product, which is typically undesired, can also be useful.

Klaimy et al. investigated various aluminosilicate materials and found that high acidity caused greater decomposition of PE, with pure silica being ineffective for PE decomposition. High olefin yields came from low-acidity catalysts and thermal flash pyrolysis, though only an amorphous aluminosilicate catalyst had both a high olefin and small hydrocarbon (C_3-C_5) yield, presenting a potentially viable option for upcycling. Still, no catalyst was able to produce a predominant fraction of wax, oil, or gas, respectively.[32] In a different study, the natural aluminosilicate kaolin was used ex situ to produce an oil composed of 87% gasoline-range (C_5-C_{12}) hydrocarbons.[29]

Metal oxides, particularly calcium oxide, can also be used in catalytic fast pyrolysis. Dong et al. used CaO in the pyrolysis of PVC, which decreased the concentration of benzene derivatives but increased the concentration of naphthalene derivatives. Still, PVC overwhelmingly converts to aromatics, which constituted 89.5% of the products without a catalyst and 93.5% of the products with the catalyst.[44] Alves et al. pyrolyzed PE-based packaging waste and found that low-cost cement kiln dust composed primarily of calcium oxide could act as an effective catalyst to yield gasoline-range hydrocarbons. After calcination, catalytic flash pyrolysis yielded 76.2% hydrocarbons in the gasoline range compared to the 18.5% yielded using thermal flash pyrolysis. The catalyst specifically decreased the concentrations of olefins, paraffins, and oxygenated compounds while increasing concentrations of cyclics and aromatics.[31]

Slow pyrolysis

Slow pyrolysis decomposes plastic with a slower heating rate and longer residence time (>5 min) than fast and flash pyrolysis. Recent studies focus on both catalyzed and uncatalyzed methods, as both can be viable. The intended product is typically an oil that can be distilled to use as fuel or chemical feedstock. It usually contains primarily paraffins and olefins, though manipulating the temperature can drastically change the composition of the oil.[45–47] Higher temperatures result in smaller hydrocarbons but more aromatics and naphthenes. To simply maximize oil yield from mixed waste, studies show that the optimal temperature for slow thermal pyrolysis is 500°C.[24,25] Among polyolefins, PP tends to degrade at lower

temperatures than PE due to its less stable methyl side group.[47] A review by Tetičkovič et al. found that HDPE, LDPE and PP all degrade through radical mechanisms, starting with homolytic cleavage. Then, processes such as β-scission and hydrogen abstraction occur. In HDPE and LDPE, processes such as secondary cracking and aromatization are more likely to occur. In PP, homolytic cleavage is more likely to create highly reactive methyl radicals, which cause more hydrogen abstraction.[48]

When PET degrades via slow thermal pyrolysis, it creates compounds such as paraldehyde, ethylene glycol, and benzoic acid, though this process has not been researched as deeply as processes that react PET with alcohols or water (see Section 3.1). The proposed degradation pathway involved the conversion of PET to vinyl alcohol through β-scission, which was quickly converted to acetaldehyde. Acetaldehyde tends to trimerize into paraldehyde, which was the largest component in the oil product. Another proposed mechanism involved the cleavage of the ester C-O bond, followed by hydrogen abstraction to create ethylene glycol and carbon monoxide.[49] A more recent study proposed a variety of competing pathways creating small aldehydes, carbon oxides, benzoic acid, and benzene.[50] Nevertheless, pyrolysis pathways of PET are not well established, and more research should be conducted in order to do so.

PVC degradation by slow pyrolysis starts with dehydrochlorination via a "zipper" elimination mechanism. This creates a conjugated polymer (called polyene in other studies[48,51]) along with hydrogen chloride, which can be neutralized by weak base products in co-pyrolysis with PET. Then, it reacts through Diels-Alder cyclization and dehydrogenation to form aromatics, yielding up to 83% benzene.[50] When not neutralized, hydrogen chloride can corrode reactors and add back to olefins, creating chloroalkanes.[48,52]

PS degradation by slow pyrolysis was found to create almost exclusively aromatic compounds. Among these was the monomer styrene, which accounted for over half of the oil at all tested temperatures, as well as alkylbenzenes and PAHs.[53] An older study was able to convert PS into oil with a high yield of up to 96.4%, with 65-75% of the oil being composed of styrene.[54]

Catalytic slow pyrolysis is generally conducted with similar catalysts as fast and flash pyrolysis, including aluminosilicates and metal oxides. For instance, Zhang et al. investigated both the in-situ and ex-situ pyrolysis of LDPE using various zeolites modified with Ga and P. They found that adding Ga and P to the zeolites significantly increased yields of BTEX (benzene, toluene, ethylbenzene, xylene) and total aromatics, as well as hydrogen in the gas product with ex-situ catalysis. The authors commented that other studies using metal-modified zeolites also achieved high aromatic yields, demonstrating their potential.[55] In another study, various Ni/ZSM-5 catalysts were used in-situ to pyrolyze a 50-50 mixture of LDPE and HDPE. Under different conditions, they reached up to 87.7% aromatics in the oil and 58% hydrogen in the gas. Solid yields were kept low (<10%); however, both of these studies struggled with total oil yields below 50%.[38] In the ex-situ catalytic pyrolysis of electronic equipment waste, López et al. investigated ways to dehalogenate oils using metal-modified zeolites. After investigating several catalysts, they selected Fe/ZSM-5 as the optimal catalyst to avoid halogenation in oils, as well as deactivation. With the catalyst, they found that halogen contaminants in plastic waste primarily end up in the solid char

product after pyrolysis (66.4% and 92.6% for Cl and Br, respectively), with a significant amount of Cl (32%) being removed simply by washing the sample.[20] The aluminosilicate bentonite, which has a similar composition to kaolin, was also used in the catalytic pyrolysis of polyolefin and PS waste. The presence of the catalyst increased the yields (about 85-90%) and calorific values of the oils for all types of plastic (43-45 MJ/kg), though the compositions of the oils did not appear to change drastically.[26]

Fluid catalytic cracking (FCC) catalysts can also catalyze pyrolysis in situ. A 2023 study found that a spent FCC catalyst could convert HDPE waste to oil with up to an 88.8% yield at 500°C. The oils had high calorific values (>40 MJ/kg) and characteristics similar to gasoline, diesel, and kerosene.[56] Another study used a spent FCC catalyst to pyrolyze plastic mixtures of PET/LDPE and LDPE/PA6 (polyamide 6). They found that FCC was effective in deoxygenation of oils, but ineffective in denitrification for PA6.[57] However, most plastics, including all of the 6 most common plastics in Section 1, lack nitrogen as a fundamental part of their structure. Moreover, of these 6 plastics, only PET contains oxygen. Overall, aluminosilicate and FCC catalysts are effective in removing undesirable elements and enhancing oil properties and yields. Using spent FCC catalysts can also be considered a form of reusing waste products, as FCC catalysts could otherwise be disposed of after use.

A recent study by Yun et al. investigated the pyrolysis of PP using a basic catalyst composed of pyrolytic carbon and calcium hydroxide. They were able to achieve a high oil yield, with most of it being composed of olefins. The pyrolysis temperature was 480°C,[58] which is lower than most polyolefin thermal pyrolysis studies, showing another benefit of the catalyst in potentially reducing energy costs.[46] However, this could be offset by the costs to synthesize and maintain effective catalysts, though such costs will vary widely.

Overall, slow pyrolysis methods present promising solutions to process plastic waste. Though thermal slow pyrolysis can be scattered in products, similar to fast and flash pyrolysis, adding a catalyst can help to improve oil quality and selectivity of specific products. Unlike fast and flash pyrolysis, slow pyrolysis tends to produce lower amounts of gas, instead primarily producing liquid and solid compounds. Therefore, fast and flash pyrolysis are generally more effective for upcycling plastics into olefin monomers, while slow pyrolysis is generally more effective in producing oils to use as fuels.

Outlooks on the industrialization of pyrolysis

The primary challenges that are constantly associated with pyrolysis are costs. Most slow pyrolysis experiments in this review have used temperatures of 450-700°C,[38,57,59] while fast and flash pyrolysis experiments have generally used temperatures of 600-2000°C.[27,30] It requires an immense amount of energy to heat plastics to these temperatures, especially on an industrial scale.

In a life-cycle assessment (LCA), Gracida-Alvarez et al. investigated the impact of using pyrolytic oil in the production of HDPE and LDPE by substituting naphtha for pyrolytic oil in steam cracking, where olefins such as ethylene are produced. This resulted in a roughly 20% decrease in GHG emissions when pyrolytic oil completely replaced naphtha in the steam cracker feedstock, where steam cracker feedstock is about 6% naphtha. However, these benefits were almost completely eliminated when considering the

possibility of pyrolytic oil replacing gases in steam cracker feedstock (ethane, propane and butane). This is due to the energy-intensive step of purifying the pyrolytic oil to decrease chlorine content. Overall, considering the lower amount of plastic that would be incinerated, industrial plastic pyrolysis would significantly decrease GHG emissions across the United States and Europe.[60] Another LCA by Das et al. compared the possibilities of pyrolytic oil as fuel with the above pathway to convert naphtha to LDPE. They assumed that pyrolytic oil was 100% naphtha and that, unlike in the LCA above, no purification was required to dechlorinate the oil. They found that plastic-to-plastic pathways were found to have lower GHG emissions when compared to plastic-to-fuels; however, plastic-to-fuel pathways were more effective in decreasing reliance on fossil fuels. The authors commented that, although plastic-to-plastic methods may generate fewer GHGs, plastic-to-fuel methods can also be highly effective in areas where plastics are frequently incinerated or mismanaged, as is common in the EU and US, respectively.[61]

Moreover, the wide variety in catalysts, temperatures, and heating methods makes studies relatively scattered, particularly for fast and flash pyrolysis studies where temperatures vary more widely. When examining the effectiveness of a specific catalyst, temperature, or heating rate, this may result in a fundamental lack of research. However, for slow pyrolysis, which operates at a much smaller range of temperatures, this is not as much of an issue, though there are still a large number of catalysts that can be used. Because research is scattered, further research into existing catalysts and heating methods should help to reveal the most effective pyrolysis methods.

Current research also focuses heavily on lab-scale technologies, which at some point must be scaled to process larger amounts of feedstock to be viable. Therefore, future research into established pyrolysis methods should aim to use larger feedstocks of at least 1 kg to better represent industrial pyrolysis.[26] Nevertheless, industrial pyrolysis plants exist, with fast and flash pyrolysis holding 75% of market share and slow pyrolysis holding 25%. Fuel applications hold 48% of the market, with chemical feedstocks holding about 32%. Notably, pyrolysis oils from polyolefins contribute nearly 80% of market share. Still, plastic pyrolysis technologies are expected to grow significantly in market share, with an estimated compound annual growth rate of 5.56%.[62]

HYDROTHERMAL PROCESSING

Hydrous thermolysis techniques fall under hydrothermal processing. Hydrothermal processing (HTP) uses heat and pressure to alter the properties of water, making it more useful for breaking down plastics.[63] As the temperature of water increases, its properties change dramatically; in particular, its dielectric constant drops.[12] As such, under high pressure and high temperature, water behaves more as a nonpolar solvent, capable of dissolving otherwise hydrophobic compounds. Numerous studies have been conducted to examine the interactions of plastic with supercritical water (SCW), subcritical water (SubCW) and superheated steam (SHS) [12,63,64]. Similar to pyrolysis, reactors are usually filled with inert nitrogen gas to prevent oxidation and promote cracking.[13,63,65]

Supercritical and subcritical water treatments

Supercritical water liquefaction (SCWL) uses water above its critical point of approximately 374°C and 22.1 MPa (221 bar) to convert polymers primarily into oils.[66,67] Studies generally show that, in this phase, water can act as a reaction medium, reactant, and catalyst.[12,68] Compared to pyrolysis, SCWL tends to produce significantly lower quantities of solid (coke) product, resulting in a greater yield of oil.[65,67] For instance, using a temperature of 450°C and pressure of 22 MPa, after 60 minutes, Mathew et al. were able to convert PS, PP, and LDPE into oil with high oil yields (>96%) and very low solid (coke) yields (<1.5%). It is important to note that gas formation can increase the pressure in a reactor significantly, which made the final pressure reach up to 33 MPa in that study.[66] In a different study, Mathew and coworkers investigated the effects of adding PET plastic, which decreased oil yield and increased CO_2 and methane yields. High concentrations of PET also increased the amount of solid terephthalic acid, which would cause concentrations of PET above 30% in feedstock to be problematic due to blockages in pipelines.[69] Generally, liquefaction of PET into fuel is not suitable as PET contains significant amounts of oxygen. These oxygen atoms would create a fuel that is partially oxidized, which would result in a lower heating value than fuels of hydrocarbon polyolefins.

Table 1 shows the yield and potential uses of oil resulting from several SWCL studies, especially polyolefins. The yield ranged from 80% to 100%, with a median of about 90%. In studies that specifically specified fractions in their oils, the resulting oil tended to correspond to transportation fuels such as gasoline, kerosene, and diesel. Temperatures of 450°C generally produced higher oil yields, though the optimal conditions for the liquefaction of each type of plastic will vary in practice. For example, Čolnik et al. identified experimentally that PP degrades faster in SCW than PE, with PP degrading under lower temperature conditions and shorter residence times. They attributed this to a difference in structure, where PP's side methyl group has a lower C-C dissociation energy. This makes it possible for PP to degrade with milder conditions.[63]

Table 1. Oil properties and conditions in previous SCWL studies

Type of plastic(s)	Conditions	Yield of oil	Fractions of crude oil after distillation	Reference
LLDPE	425 °C for 120 min	83%	NS	12
PP	450 °C for 15 min	95%	NS	63
HDPE	425 °C for 150 min	87%	gasoline, diesel	65
PS	450 °C for 60 min	98.2%	NS	66
PP	450 °C for 60 min	97.5%	NS	66
LDPE	450 °C for 60 min	97.8%	NS	66

1 PS: 1 PP: 1 LDPE	450 °C for 60 min	96.4%	NS	66
LLDPE	400 °C for 60 min	87.04%	kerosene, diesel, lubricant, gasoline	67
PP	400 °C for 60 min	86.42%	kerosene, diesel, lubricant	67
1 LLDPE: 1 PP	400 °C for 60 min	~90%	kerosene, diesel, lubricant	67
HDPE	475 °C for 120 min	~80%	NS	70

*NS = not specified

Uses for the resulting oil may also vary. As was presented in Table 1, the most common use would be as a fuel, particularly for transportation. However, there are other uses. For example, Lu et al. investigated the use of SCWL to create aromatics such as BTEX from ocean-bound HDPE to use in the synthesis of various polymers. They found that more extreme conditions (higher temperatures and longer residence times) significantly increased aromatic content and BTEX yield,[70] a finding that aligns with other literature.[12,63]

PVC may also be able to be processed by SCWL. PVC has historically been difficult to chemically recycle due to its high chlorine content (about 57% by mass), which limits its ability to create hydrocarbon fuels compared to polyolefins. Additionally, the chlorine generally turns into corrosive hydrogen chloride when decomposed, which can damage equipment. Chlorinated hydrocarbons are also dangerous and are strictly limited in oils under petrochemical specifications.[71] Mechanistically, Čolnik and coworkers proposed that a "zipper" reaction occurs to convert PVC into polyene and hydrogen chloride, therefore removing chlorine from the polymer and making the degradation pathway similar to that of polyolefins (see Fig. 1). However, unlike polyolefins, as residence time increased, chlorine was reintroduced into the oil phase, making up to 15% chloroalkanes in the oil phase. Though they only yielded 26% oil,[51] it is important to consider that only about 43% (by mass) of PVC is made of carbon and hydrogen. In an earlier study, Takeshita et al. found that chlorine was released with the same mechanism, but rather than traveling into the oil, it traveled into the solid product.[72] Tito et al. used SubCW to convert PVC into polyene, and then supercritical water to liquefy polyene with the goal of avoiding reintroducing chlorine into the oils. After the first step of processing with SubCW at 325°C, they were able to remove about 99% of chlorine in the PVC while retaining about 94% of carbon. However, oil formation was quite limited, peaking at only about 10%.[73] Overall, there is not a significant amount of research concerning SCWL of PVC; however, existing research does point to SCWL being a promising method to degrade PVC.

Fig. 3 summarizes how PE, PP, and PVC generally decompose in SCW. As discussed earlier, PVC undergoes dechlorination, where it then forms polyene, with a structure that is similar to PE and therefore degrades similarly. Then, PE, PP, and polyene undergo homolytic bond cleavage to form various radicals. Though not specifically reflected in the figure, PP's methyl side groups tend to degrade before the main chain due to their lower dissociation energies, as previously discussed. The radicals then undergo competing processes of β-scission and hydrogen abstraction, both of which produce new radicals along with unsaturated olefins and saturated paraffins, respectively. Paraffins can undergo secondary cracking and other reactions to form smaller gases, while the more reactive olefins may participate in other reactions. If hydrogen chloride from the dehydrochlorination of PVC is present, it may add to olefins to produce chloroalkanes. Similarly, water may add to olefins to produce alcohols. However, olefins will mainly form cyclics, which under high temperatures and long residence times, form alkylbenzenes. Over time, these alkylbenzenes may polymerize to form PAHs.

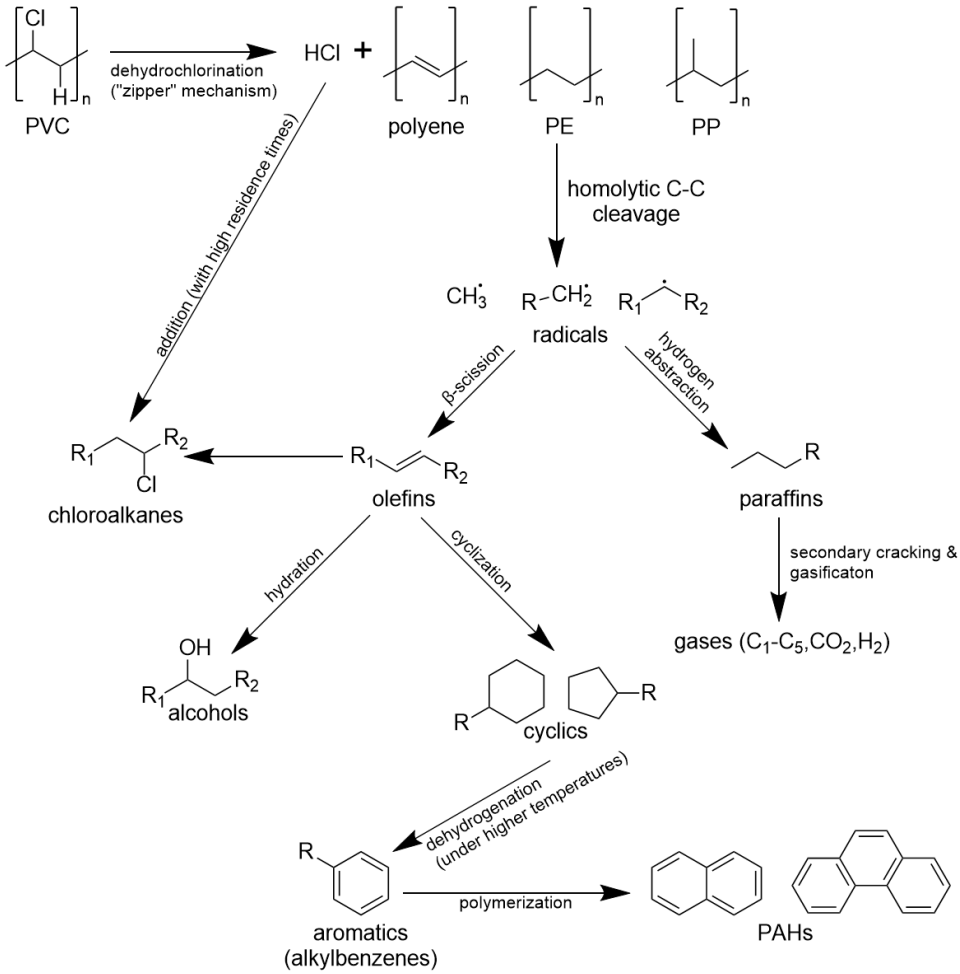


Fig. 3: Degradation pathways of PE, PP, and PVC in supercritical water. Data for pathways was compiled from [51,63,67,70]

PET can also be processed using SCWL. However, instead of converting it into energy-dense fuels, studies focus on upcycling it into its monomers of terephthalic acid and ethylene glycol through hydrolysis. Terephthalic acid yields of 85-90% have been produced from colored and colorless PET waste, though using SubCW water at 300°C and a pressure of about 9 MPa.[64] Because terephthalic acid is a direct product of PET hydrolysis, extreme conditions such as supercritical water treatments are not required to yield it. In fact, research shows that intense, high temperature and supercritical conditions cause terephthalic acid to be decarboxylated and form benzoic acid.[64,74] Though terephthalic acid can have a high yield, ethylene glycol tends to decompose more quickly, producing toxic VOCs such as acetaldehyde and crotonaldehyde that may pose health concerns if HTP is implemented, showing a need for greater research in this area.[75] Additionally, terephthalic acid is notoriously difficult to purify, which makes it costly to use terephthalic acid from hydrolysis to create food-grade PET.[49]

Supercritical water oxidation (SCWO) uses SCW with an oxidant (such as molecular oxygen, hydrogen peroxide, or nitrates) to convert organic matter into water and carbon dioxide, similar to combustion.[76] SCWO has primarily been applied to wastewater, where it excels in removing pollutants such as PFAS and azo dyes;[77–79] however, biomass has also been used as SCWO feedstock.[76] Unlike incineration, SCWO generally does not produce toxic pollutants such as nitrogen oxides and fully oxidizes carbon into carbon dioxide instead of carbon monoxide.[78] Residence times under a second can be achieved by using hydrothermal flames, which also increase energy recovery. Additionally, similar to combustion, these processes are exothermic (particularly for hydrocarbon polyolefins), which makes them more self-sufficient energetically than SCWL.[76] Problems may stem from the massive carbon dioxide emissions from oxidizing millions of tons of plastic, though SCWO should still be a more environmentally friendly method of energy recovery than incineration due to the lack of toxic pollutants released. Still, there is a clear lack of research on the SCWO of plastics compared to the amount of SCWO of wastewater above.

Though SCWL presents a promising method of chemical recycling, some limitations and challenges must be addressed. Primarily, the energy cost of operating at high temperatures and pressures is quite high.[80] Additionally, additives in plastic waste may decompose and degrade into other chemicals, corroding reactors and complicating the process, though this phenomenon should be researched in greater depth.[81] Salts that dissolve well in water at room temperature and pressure tend to precipitate out of SCW, creating solid residue and plugging reactors.[76,81]

Low-pressure hydrothermal processing

When applied to plastics, low pressure hydrothermal processing (LP-HTP) is a newer technique that uses high temperature water (similar temperatures to SCWL) at lower pressures to create superheated steam.[12,80,82] In a pioneering study in 2021, Jin et al. used LP-HTP to convert polyolefin waste into oil with 86-87% yield and minimal (<0.5%) char formation, using water at 450°C and 1.55 MPa for 45 minutes. The authors also commented that this method results in significantly lower capital and energy costs, as well as significantly less greenhouse gas (GHG) emissions when compared to other recycling methods such as pyrolysis and mechanical recycling.[13]

Degradation pathways for LP-HTP have been found to be nearly identical to those of SCWL in Fig. 3. Homolytic cleavage is followed by β-scission and hydrogen abstraction, which create olefins and paraffins. Paraffins may degrade into gases by secondary cracking reactions, while olefins can go through a variety of reactions such as cyclization followed by dehydrogenation and polymerization into BTEX or PAHs, as well as hydration.[12,13]

Various studies find that oil from LP-HTP, similar to SCWL, may be usable as fuel. Jin et al. found that distilled oils from PE waste could be used as gasoline blendstock and No. 1 ultra-low sulfur diesel. Waste from PP was distilled into high-quality gasoline and marginal-quality diesel.[13] Though they did not specifically distill or test their oils' combustion properties, Harisankar et al. found that oils from PE and PP waste contained 80-100% hydrocarbons with 25 carbons or less.[83] Therefore, these oils could likely be used as blendstocks for gasoline (C_4-C_{12}) or diesel (C_{12}-C_{20}).[84] However, the conditions in this study used high pressures slightly below the supercritical region (~20 MPa), which are higher than most other LP-HTP studies. Un et al. found that non-woven face masks made of PP could be liquefied into oil with 87% yield. Roughly 80-85% of the oils were distilled into naphtha (C_4-C_{13}) or middle distillate (C_{14}-C_{25}), which roughly correspond to gasoline and diesel, respectively.[85]

Gentilcore et al. used continuous feeding of PS into a reactor at 397°C and atmospheric pressure to convert 99% of PS into oil. 88% of the oil was composed of styrene monomers, dimers, and trimers. The authors also commented that their use of atmospheric pressure LP-HTP is simpler and more cost-effective than reactors using pressures of 2-3 MPa.[86] This study demonstrates the potential of LP-HTP to be used not only for conversion into fuels but for upcycling into monomers.

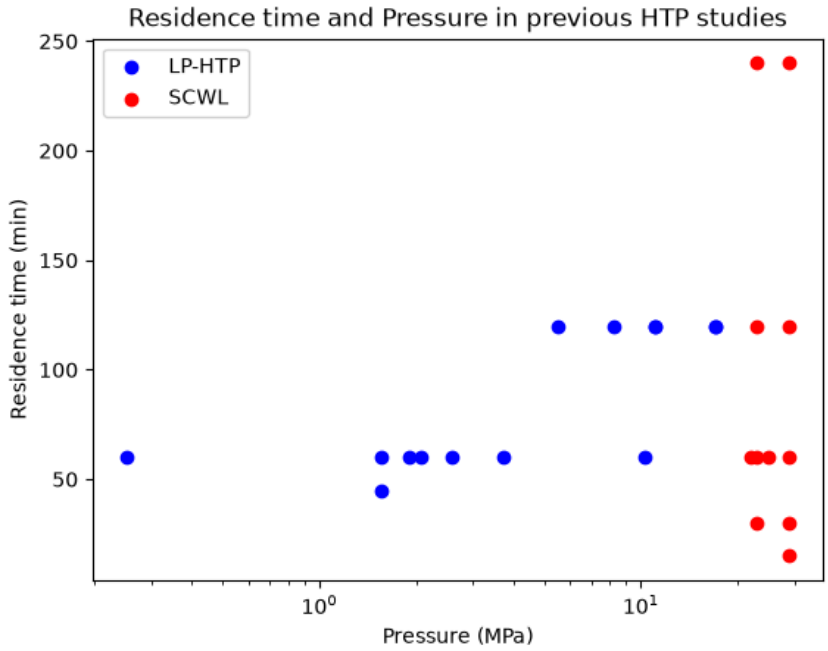


Fig. 4. Conditions used in previous hydrothermal processing studies. Data used for this plot were extracted from [12,13,87] (LP-HTP, blue) and [12,63,65–67,70] (SCWL, red).

Though LP-HTP is a very promising method of plastic processing, certain challenges must be addressed. Primarily, LP-HTP is a newer technique, and therefore there is a lack of research on its effectiveness. Most LP-HTP and SCWL studies use temperatures of 400-450°C;[12,13,63,66] however, pressures and residence times in LP-HTP studies vary widely, which makes existing research relatively scattered in conditions (temperature, pressure, residence time) compared to SCWL, which can be observed in Fig. 4. Similar to SCWL, LP-HTP research concerning the interactions of additives with superheated steam has not been conducted, marking a crucial gap. Additionally, when directly comparing LP-HTP and SCWL using PE feedstock, Lachos-Perez et al. found that the latter produced higher oil yields and better suppressed char formation.[12] Nevertheless, LP-HTP presents a possibly viable, lower-cost alternative to SCWL; however, more research should be done to confirm its effectiveness.

COMPARISON OF METHODS FOR PYROLYSIS AND HYDROTHERMAL PROCESSING

Now that we have reviewed various forms of pyrolysis and hydrothermal processing for plastics, we will compare the two. Both pyrolysis and HTP decompose plastic in a non-oxidative atmosphere. However, hydrothermal processing techniques generally operate at high pressures and always use water, while pressures in pyrolysis are typically not monitored and only increased by gas formation.[24,45] Temperatures for both processes vary; however, as seen in Table 1 and the entirety of Section 3, HTP almost always

uses lower temperatures of 300-500°C, with supercritical water and superheated steam processes using temperatures of 400-500°C. Meanwhile, temperatures for pyrolysis vary widely. In this review, fast and flash pyrolysis studies used temperatures of 500-3000°C[29,41] and slow pyrolysis studies used temperatures from 300-800°C.[38,54] Conditions for HTPs can most precisely be compared to slow pyrolysis, as temperatures for the two processes are similar, and both have residence times longer than 5 minutes. As such, this comparison section will primarily focus on these processes.

Table 2 summarizes the similarities and differences between the SCWL and slow pyrolysis processes. Slow pyrolysis generally uses slightly higher temperatures than SCWL. SCWL uses water and high pressures, which can significantly increase its energy costs; however, this can also save costs relative to pyrolysis because pyrolysis cannot tolerate significant moisture, typically requiring an extra drying step.[81] The primary advantages of SCWL and LP-HTP are that they both result in very low char yields.[13,65] On the other hand, pyrolysis can frequently yield high amounts of char, especially slow pyrolysis.[40] Char is generally unideal for pyrolysis, as olefins and liquid oils are usually more useful. Excessive char can also deactivate catalysts.[20] However, char can be used as a carbon source, and flash pyrolysis studies have created useful nanomaterials from char.[27,41] Though hydrothermal processes do not yield significant amounts of char, similar effects to coking could be observed due to how salts soluble in ambient water precipitate out of SCW, potentially plugging reactors.[76,81] Both processes operate at high temperatures, which means that they will both need high amounts of energy. Exact energy requirements vary by study, as variations in the temperatures and concentrations of water used can affect energy cost in pyrolysis and HTP. However, pyrolysis tends to have higher energy costs, though the conditions (particularly high pressure and the corrosive nature of SCW) make it likely for SCWL to have higher capital costs, as it requires specialized, highly corrosion-resistant materials.[81] This is less likely for LP-HTP, as Jin et al. stated that it required significantly lower capital and energy costs compared to SCWL.[13]

Table 2. A summary of the processes and products of slow pyrolysis, SCWL, and LP-HTP

	Thermal and catalytic slow pyrolysis	Supercritical water liquefaction	Low-pressure hydrothermal liquefaction
Uses water	No	Yes	Yes
Temperature (°C)	300-800	400-500	350-450
Pressure (MPa)	Usually not reported	>22.1	Varies widely, typically 0.1-17
Typical oil yields	50-97%	80-100%	75-99%
Energy requirements [13,81,85]	3.0-5.8 MJ/kg	2.8-3.2 MJ/kg*	~1.5 MJ/kg

*Energy consumption in HTP can vary widely depending on the amount of water used. Higher concentrations of water can cause heating to consume up to 7.04 MJ/kg in SCWL[13]

Mechanistically, slow pyrolysis and HTPs proceed through similar pathways, especially for polyolefins. As we investigated degradation pathways in Sections 2.2 and 3.1, we found that PE, PP, and PVC degraded similarly. In both slow pyrolysis and SCWL, PVC was first dechlorinated through the "zipper" mechanism, producing polyene and HCl. This step could also be completed using SubCW, which could be the more desirable option when considering the capital costs required for SCWL. After dehydrochlorination, the resulting polyene proceeded through similar pathways to polyolefins, starting with homolytic C-C bond cleavage, and then competing processes of β-scission and hydrogen abstraction to create olefins and paraffins. Notably, higher temperatures increased yields of aromatics in both processes due to cyclization and dehydrogenation reactions, showing a relatively consistent and viable way to produce valuable BTEX building blocks in both processes.[47] SCW can participate in hydration reactions, creating alcohols; however, this process is generally not enough to significantly lower the calorific values of oils. For PS, both slow pyrolysis and HTP yielded large amounts of styrene monomers, though this yield was higher for HTP. Additionally, PS could be converted into high-styrene oil at atmospheric pressure in LP-HTP, eliminating the need for high-pressure infrastructure.[86]

Major differences arise primarily when analyzing PET. As PET is a condensation polymer, water can play a more direct role in its degradation through hydrolysis, producing terephthalic acid and ethylene glycol.[64] SubCW was a better reaction medium than SCW, as the intense conditions in SCWL decarboxylated terephthalic acid, creating benzoic acid. However, pyrolysis lacks water entirely, causing PET to break down through a distinct pathway, creating compounds such as acetaldehyde, ethylene glycol, benzoic acid, and benzene (see Section 2.2).

The current state of research is very different for pyrolysis compared to HTP. As we examined in Section 2.3, numerous LCAs concerning pyrolysis have been conducted, and they showed positive environmental effects. Pyrolysis of mixed plastic waste is generally more established and researched than SCWL,[24,25,30] with SCWL research focusing primarily on the processing of specific plastics.[51,63,65] Pyrolysis technologies have also been more widely industrialized, with plastic pyrolysis oil having a global market value of about $700 million, showing a clear advantage compared to HTP which lacks such plants.[62] However, recently, a pilot plant was created by the University of Amsterdam to convert mixed plastic waste into naphtha utilizing catalytic solvothermal liquefaction.[88] This process is similar to SCWL; however, it uses organic solvents such as ethanol, toluene, and acetone instead of water. Though precise analyses are outside the scope of this review, the lower critical points of these solvents generally result in lower energy costs.[89] Nevertheless, liquefaction of plastics using organic solvents represents a step forwards in terms of creating a circular economy.

CONCLUSION

In this review, we analyzed and compared methods of anhydrous and hydrous thermolysis and catalytic thermal cracking, particularly for LDPE, HDPE, PP, PS, PET, and PVC. In Section 2, we examined pyrolysis, where catalysts could frequently be utilized to create both gaseous monomers and energy-dense fuels. In Section 3, we delved into hydrothermal methods, which could be categorized into subcritical and supercritical water liquefaction, as well as low-pressure hydrothermal processing. HTP studies in this review focused on producing oils to be used as fuels, as well as producing plastic monomers and BTEX building blocks. In Section 4, we analyzed similarities and differences between pyrolysis and HTP.

In Section 2, in fast and flash pyrolysis, electric Joule heating helped to yield monomers, creating gas mixtures containing up to 60% olefins. Aluminosilicates and metal oxides mainly helped to yield products in the gasoline range. In slow pyrolysis, aluminosilicates and FCC catalysts helped to remove elements such as Cl, Br, and O, improving oil quality, as well as yielding more aromatics. In Section 3, in SCWL, numerous studies reported oil yields above 80% with hydrocarbon mixtures usable as blendstocks for fuels. LP-HTP provided a viable, more cost-effective way to yield similar results to SCWL, also producing usable fuels. In analyzing thermal and hydrothermal methods, comparisons were drawn between slow pyrolysis, SCWL and LP-HTP. All methods were similar in temperatures, residence times, and product yields, usually operating at around 400-600°C for at least 5 minutes to yield mostly oil products. Mechanistic similarities were also observed in all addition polymers, where homolytic cleavage was followed by competing processes of β-scission and hydrogen abstraction. All processes had higher aromatic yields with higher temperatures due to enhanced cyclization and dehydrogenation reactions. Pyrolysis is the more established technique; it has been researched to a significantly greater depth, and several pilot pyrolysis plants exist.

Limitations in pyrolysis are primarily energy costs, which usually exceed those of SCWL and LP-HTP. Other issues stem from halogen and oxygen contamination in oils. Limitations in HTP include corrosion of reactors and salt precipitation from SCW, along with high energy costs. For both slow and fast catalytic

pyrolysis, future research should aim to replicate existing studies and verify the effectiveness of specific catalysts. For HTP, future research should aim to analyze the interactions of SCW and superheated steam with common additives in plastic waste. Life cycle assessments and pilot plants are also necessary to further advance both SCWL and LP-HTP.

Overall, pyrolysis and HTP present distinct but similar ways to process plastic waste, and more research can advance both processes. Furthermore, research in these areas may move society towards a circular economy, where waste is constantly reused and repurposed instead of landfilled and incinerated.

REFERENCES

(1) Nayanathara Thathsarani Pilapitiya, P. G. C.; Ratnayake, A. S. The World of Plastic Waste: A Review. *Clean. Mater.* **2024**, *11*, 100220. https://doi.org/10.1016/j.clema.2024.100220
(2) Wojnowska-Baryła, I.; Bernat, K.; Zaborowska, M. Plastic Waste Degradation in Landfill Conditions: The Problem with Microplastics, and Their Direct and Indirect Environmental Effects. *Int. J. Environ. Res. Public. Health* **2022**, *19* (20), 13223. https://doi.org/10.3390/ijerph192013223
(3) Guha, F.; Abser, Md. N.; Mondal, B. K. Fate of Waste Plastics: A Review. *Res.* **2025**, *2* (2), 100338. https://doi.org/10.1016/j.nexres.2025.100338
(4) Li, P.; Wang, X.; Su, M.; Zou, X.; Duan, L.; Zhang, H. Characteristics of Plastic Pollution in the Environment: A Review. *Bull. Environ. Contam. Toxicol.* **2021**, *107* (4), 577–584. https://doi.org/10.1007/s00128-020-02820-1
(5) Zhou, G.; Li, J.; Chen, Y.; Cui, Y.; Wang, Y.; Zheng, L.; Zhang, D.; Luo, T. Size-Dependent Toxicological Effects of Microplastics: A Review. *Ecotoxicol. Environ. Saf.* **2026**, *311*, 119831. https://doi.org/10.1016/j.ecoenv.2026.119831
(6) Ogwu, M. C.; Kosoe, E. A. Innovative Approaches to Recycling, Upcycling, and Downcycling for Sustainable Waste Management. *CleanMat* **2025**, *2* (3), 242–261. https://doi.org/10.1002/clem.70013
(7) Ragaert, K.; Delva, L.; Van Geem, K. Mechanical and Chemical Recycling of Solid Plastic Waste. *Waste Manag.* **2017**, *69*, 24–58. https://doi.org/10.1016/j.wasman.2017.07.044
(8) Schade, A.; Melzer, M.; Zimmermann, S.; Schwarz, T.; Stoewe, K.; Kuhn, H. Plastic Waste Recycling─A Chemical Recycling Perspective. *ACS Sustain. Chem. Eng.* **2024**, *12* (33), 12270–12288. https://doi.org/10.1021/acssuschemeng.4c02551
(9) Huang, J.; Veksha, A.; Chan, W. P.; Giannis, A.; Lisak, G. Chemical Recycling of Plastic Waste for Sustainable Material Management: A Prospective Review on Catalysts and Processes. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111866. https://doi.org/10.1016/j.rser.2021.111866
(10) Nagy, Á.; Kuti, R. The Environmental Impact of Plastic Waste Incineration. *Acad. Appl. Res. Mil. Public Manag. Sci.* **2016**, *15* (3), 231–237. https://doi.org/10.32565/aarms.2016.3.3
(11) Verma, R.; Vinoda, K. S.; Papireddy, M.; Gowda, A. N. S. Toxic Pollutants from Plastic Waste- A Review. *Procedia Environ. Sci.* **2016**, *35*, 701–708. https://doi.org/10.1016/j.proenv.2016.07.069
(12) Lachos-Perez, D.; Jan, K.; Yu, E.; Patil, A.; Chen, W.-T. Hydrothermal Processing of Polyethylene in Superheated Steam and Supercritical Water into Fuels and Chemicals. *Energy Convers. Manag.* **2025**, *325*, 119355. https://doi.org/10.1016/j.enconman.2024.119355

(13) Jin, K.; Vozka, P.; Gentilcore, C.; Kilaz, G.; Wang, N.-H. L. Low-Pressure Hydrothermal Processing of Mixed Polyolefin Wastes into Clean Fuels. *Fuel* **2021**, *294*, 120505. https://doi.org/10.1016/j.fuel.2021.120505

(14) Papari, S.; Bamdad, H.; Berruti, F. Pyrolytic Conversion of Plastic Waste to Value-Added Products and Fuels: A Review. *Materials* **2021**, *14* (10), 2586. https://doi.org/10.3390/ma14102586

(15) *The IUPAC Compendium of Chemical Terminology: The Gold Book*, 4th ed.; Gold, V., Ed.; International Union of Pure and Applied Chemistry (IUPAC): Research Triangle Park, NC, 2019. https://doi.org/10.1351/goldbook

(16) Chin, M. T.; Diao, T. Industrial and Laboratory Technologies for the Chemical Recycling of Plastic Waste. *ACS Catal.* **2024**, *14* (16), 12437–12453. https://doi.org/10.1021/acscatal.4c03194

(17) Boel, M. J.; Wang, H.; Al Farra, A.; Megido, L.; González-LaFuente, J. M.; Shiju, N. R. Hydrothermal Liquefaction of Plastics: A Survey of the Effect of Reaction Conditions on the Reaction Efficiency. *React. Chem. Eng.* **2024**, *9* (5), 1014–1031. https://doi.org/10.1039/D2RE00510G

(18) Kijo-Kleczkowska, A.; Gnatowski, A. Recycling of Plastic Waste, with Particular Emphasis on Thermal Methods—Review. *Energies* **2022**, *15* (6), 2114. https://doi.org/10.3390/en15062114

(19) Silva, R. J. D. O.; Graf, K.; Leite Ribeiro Okimoto, M. L. Plastic Waste Recycling: An Overview of the Mechanical, Chemical, and Thermal Technologies. *J. Eng. Appl. Sci.* **2025**, *72* (1), 251. https://doi.org/10.1186/s44147-025-00799-2

(20) López, J.; Amodio, L.; Del Mar Alonso-Doncel, M.; Cueto, J.; Hernando, H.; Mazur, M.; Čejka, J.; Pizarro, P.; Serrano, D. P. Enhanced Oil Dehalogenation during Catalytic Pyrolysis of WEEE-Derived Plastics over Fe- and Ca-Modified Zeolites. *J. Environ. Chem. Eng.* **2024**, *12* (1), 111790. https://doi.org/10.1016/j.jece.2023.111790

(21) Baena-González, J.; Santamaria-Echart, A.; Aguirre, J. L.; González, S. Chemical Recycling of Plastic Waste: Bitumen, Solvents, and Polystyrene from Pyrolysis Oil. *Waste Manag.* **2020**, *118*, 139–149. https://doi.org/10.1016/j.wasman.2020.08.035

(22) Gautam, R.; Kulkarni, S. R.; Zaini, I. N.; Han, H.; Sarathy, S. M.; Dally, B. B.; Roberts, W. L. A Review on Interactions and Reactor Implications during Pyrolysis of Biomass- and Plastic-Based Waste. *Appl. Energy Combust. Sci.* **2026**, *26*, 100507. https://doi.org/10.1016/j.jaecs.2026.100507

(23) Varma, A. K.; Thakur, L. S.; Shankar, R.; Mondal, P. Pyrolysis of Wood Sawdust: Effects of Process Parameters on Products Yield and Characterization of Products. *Waste Manag.* **2019**, *89*, 224–235. https://doi.org/10.1016/j.wasman.2019.04.016

(24) Singh, R. K.; Ruj, B.; Sadhukhan, A. K.; Gupta, P. Impact of Fast and Slow Pyrolysis on the Degradation of Mixed Plastic Waste: Product Yield Analysis and Their Characterization. *J. Energy Inst.* **2019**, *92* (6), 1647–1657. https://doi.org/10.1016/j.joei.2019.01.009

(25) Singh, R. K.; Ruj, B. Time and Temperature Depended Fuel Gas Generation from Pyrolysis of Real World Municipal Plastic Waste. *Fuel* **2016**, *174*, 164–171. https://doi.org/10.1016/j.fuel.2016.01.049

(26) Budsaereechai, S.; Hunt, A. J.; Ngernyen, Y. Catalytic Pyrolysis of Plastic Waste for the Production of Liquid Fuels for Engines. *RSC Adv.* **2019**, *9* (10), 5844–5857. https://doi.org/10.1039/C8RA10058F

(27) Luo, B.; Zhang, W.; Hu, S.; Liu, K.; Cheng, L.; Gu, J.; Yuan, H.; Chen, Y. Product Regulation Mechanism in Joule Flash Pyrolysis of Polyethylene for Low Carbon Olefins and Carbon Nanospheres. *J. Anal. Appl. Pyrolysis* **2025**, *186*, 106963. https://doi.org/10.1016/j.jaap.2025.106963

(28) Matthiesen, K.; Plessing, L.; Luinstra, G. A. Fast Pyrolysis Product Analysis of Commercial Polyethylenes. *Energy Fuels* **2024**, *38* (16), 15543–15559. https://doi.org/10.1021/acs.energyfuels.4c02296

(29) Lopes, V. F. D.; Alves, J. L. F.; Da Silva, E. R.; Marques, J. D. A. O.; Melo, D. M. D. A.; Melo, M. A. D. F.; Braga, R. M. Catalytic Flash Pyrolysis for Recovery of Gasoline-Range Hydrocarbons from Electric Cable Residue Using a Low-Cost Natural Catalyst: An Analytical Py–GC/MS Study. *Waste Manag.* **2024**, *186*, 188–197. https://doi.org/10.1016/j.wasman.2024.06.013

(30) Tokmurzin, D.; Nam, J. Y.; Lee, T. R.; Park, S. J.; Nam, H.; Yoon, S. J.; Mun, T.-Y.; Yoon, S. M.; Moon, J. H.; Lee, J. G.; Lee, D. H.; Ra, H. W.; Seo, M. W. High Temperature Flash Pyrolysis Characteristics of Waste Plastics (SRF) in a Bubbling Fluidized Bed: Effect of Temperature and Pelletizing. *Fuel* **2022**, *326*, 125022. https://doi.org/10.1016/j.fuel.2022.125022

(31) Alves, J. L. F.; Silva, E. R. D.; Junior, J. O. D. D.; Marques, J. D. A. O.; Silva, L. N. R.; Melo, D. M. D. A.; Braga, R. M. Upcycling of Post-Industrial Multilayer Plastic Packaging Waste through Gasoline-Equivalent Hydrocarbon-Targeted Pyrolysis by an Environmentally Friendly Catalyst. *Chem. Eng. Sci.* **2025**, *304*, 121040. https://doi.org/10.1016/j.ces.2024.121040

(32) Klaimy, S.; Ciotonea, C.; Dhainaut, J.; Royer, S.; Casetta, M.; Duquesne, S.; Tricot, G.; Lamonier, J. Flash Catalytic Pyrolysis of Polyethylene over (Alumino)Silicate Materials. *ChemCatChem* **2020**, *12* (4), 1109–1116. https://doi.org/10.1002/cctc.201901819

(33) Dai, L.; Zhou, N.; Li, H.; Wang, Y.; Liu, Y.; Cobb, K.; Cheng, Y.; Lei, H.; Chen, P.; Ruan, R. Catalytic Fast Pyrolysis of Low Density Polyethylene into Naphtha with High Selectivity by Dual-Catalyst Tandem Catalysis. *Sci. Total Environ.* **2021**, *771*, 144995. https://doi.org/10.1016/j.scitotenv.2021.144995

(34) Dong, T.; Bai, B.; Wang, Q.; Qi, J.; Zhang, Y.; Zhang, Y.; Wang, P.; Hao, Z. Catalytic Pyrolysis of Plastic Waste: A Sustainable Approach for Liquid Oil and Carbon Black Production. *Chin. Chem. Lett.* **2026**, 113106. https://doi.org/10.1016/j.cclet.2026.113106

(35) Xie, X.; Wang, X.; Chang, W.; Xing, L.; Li, H.; Liu, M.; Miao, L.; Huang, Y. Recent Progresses in Catalytic Pyrolysis of Polypropylene Using Core-Shell Catalysts for Conversion of High-Value Carbon Nanotubes: A Review. *Waste Biomass Valorization* **2026**, *17* (10), 5323–5350. https://doi.org/10.1007/s12649-025-03380-3

(36) Mishra, R.; Kumar, A.; Singh, E.; Kumar, S. Recent Research Advancements in Catalytic Pyrolysis of Plastic Waste. *ACS Sustain. Chem. Eng.* **2023**, *11* (6), 2033–2049. https://doi.org/10.1021/acssuschemeng.2c05759

(37) Peng, Y.; Wang, Y.; Ke, L.; Dai, L.; Wu, Q.; Cobb, K.; Zeng, Y.; Zou, R.; Liu, Y.; Ruan, R. A Review on Catalytic Pyrolysis of Plastic Wastes to High-Value Products. *Energy Convers. Manag.* **2022**, *254*, 115243. https://doi.org/10.1016/j.enconman.2022.115243

(38) Zhang, Y.; Li, A.; Zhang, Y. S.; Xie, W.; Liu, C.; Peng, Y.; Zhang, H.; Kang, Y.; Qu, B.; Ji, G. In-Situ Catalytic Pyrolysis of Polyethylene to Co-Produce BTX Aromatics and H2 by Ni/ZSM-5 in the

Rotary Reactor with Solid Heat Carriers. *Fuel* **2024**, *371*, 131950. https://doi.org/10.1016/j.fuel.2024.131950

(39) Trecáková, T.; Paulu, A.; Harasymchuk, I.; Brunhoferová, H.; Kočí, V. The Effects of the Technological Setup of Plastic Waste Pyrolysis on Its Environmental Performance. *Environ. Sci. Adv.* **2025**, *4* (11), 1796–1809. https://doi.org/10.1039/D5VA00182J

(40) Maqsood, T.; Dai, J.; Zhang, Y.; Guang, M.; Li, B. Pyrolysis of Plastic Species: A Review of Resources and Products. *J. Anal. Appl. Pyrolysis* **2021**, *159*, 105295. https://doi.org/10.1016/j.jaap.2021.105295

(41) Niu, X.; Chen, T.; Zong, H.; Sun, H.; Chen, B.; Li, X.; Yan, J.; Sun, C. Aromatic Plastic-Driven High-Selectivity Hydrogen Production and Carbon Sequestration via Electrified Flash Pyrolysis. *Chem. Eng. J.* **2025**, *524*, 169769. https://doi.org/10.1016/j.cej.2025.169769

(42) Karaduman, A.; Şimşek, E. H.; Çiçek, B.; Bilgesü, A. Y. Flash Pyrolysis of Polystyrene Wastes in a Free-Fall Reactor under Vacuum. *J. Anal. Appl. Pyrolysis* **2001**, *60* (2), 179–186. https://doi.org/10.1016/S0165-2370(00)00169-8

(43) Del Remedio Hernández, M.; García, Á. N.; Marcilla, A. Catalytic Flash Pyrolysis of HDPE in a Fluidized Bed Reactor for Recovery of Fuel-like Hydrocarbons. *J. Anal. Appl. Pyrolysis* **2007**, *78* (2), 272–281. https://doi.org/10.1016/j.jaap.2006.03.009

(44) Dong, J.; Tang, Y.; Hu, Y.; Wang, S.; Zhou, Z.; Shi, Y.; Liu, C.; Wang, F. Effect of CaO Addition on Fast Pyrolysis Behavior of Solid Waste Components Using Py GC/MS. *J. Anal. Appl. Pyrolysis* **2025**, *188*, 107055. https://doi.org/10.1016/j.jaap.2025.107055

(45) Das, P.; Tiwari, P. Valorization of Packaging Plastic Waste by Slow Pyrolysis. *Resour. Conserv. Recycl.* **2018**, *128*, 69–77. https://doi.org/10.1016/j.resconrec.2017.09.025

(46) Das, P.; Tiwari, P. The Effect of Slow Pyrolysis on the Conversion of Packaging Waste Plastics (PE and PP) into Fuel. *Waste Manag.* **2018**, *79*, 615–624. https://doi.org/10.1016/j.wasman.2018.08.021

(47) Shi, X.; Xu, Z.; Chen, Z.; Wang, J.; Pan, Z.; Hu, Z.-T.; Hu, M. Polyolefins Pyrolysis: Quantitative Structure-Thermal-Reactivity Relationships for Selective High-Value Fuels and Chemicals Production. *Chem. Eng. J.* **2026**, *527*, 171974. https://doi.org/10.1016/j.cej.2025.171974

(48) Tetičkovič, T.; Klinar, D.; Rižnar, K.; Pečar, D. Mechanistic Pathways and Product Selectivity in Pyrolysis of PE, PP and PVC: A Foundation for Applied Chemistry in Europe. *Molecules* **2026**, *31* (2), 202. https://doi.org/10.3390/molecules31020202

(49) Straka, P.; Bičáková, O.; Šupová, M. Slow Pyrolysis of Waste Polyethylene Terephthalate Yielding Paraldehyde, Ethylene Glycol, Benzoic Acid and Clean Fuel. *Polym. Degrad. Stab.* **2022**, *198*, 109900. https://doi.org/10.1016/j.polymdegradstab.2022.109900

(50) Wang, Y.; Ding, Z.; Chai, D.; Han, W.; Wang, C.; Yin, F.; Chen, H. Study on Kinetics and Products of Co-Pyrolysis of Polyvinyl Chloride and Polyethylene Terephthalate. *Therm. Sci. Eng. Prog.* **2025**, *67*, 104126. https://doi.org/10.1016/j.tsep.2025.104126

(51) Čolnik, M.; Kotnik, P.; Knez, Ž.; Škerget, M. Degradation of Polyvinyl Chloride (PVC) Waste with Supercritical Water. *Processes* **2022**, *10* (10), 1940. https://doi.org/10.3390/pr10101940

(52) Qureshi, M. S.; Oasmaa, A.; Pihkola, H.; Deviatkin, I.; Tenhunen, A.; Mannila, J.; Minkkinen, H.; Pohjakallio, M.; Laine-Ylijoki, J. Pyrolysis of Plastic Waste: Opportunities and Challenges. *J. Anal. Appl. Pyrolysis* **2020**, *152*, 104804. https://doi.org/10.1016/j.jaap.2020.104804

(53) Albor, G.; Mirkouei, A.; McDonald, A. G.; Struhs, E.; Sotoudehnia, F. Fixed Bed Batch Slow Pyrolysis Process for Polystyrene Waste Recycling. *Processes* **2023**, *11* (4), 1126. https://doi.org/10.3390/pr11041126

(54) Kim, Y. S.; Hwang, G. C.; Bae, S. Y.; Yi, S. C.; Moon, S. K.; Kumazawa, H. Pyrolysis of Polystyrene in a Batch-Type Stirred Vessel. *Korean J. Chem. Eng.* **1999**, *16* (2), 161–165. https://doi.org/10.1007/BF02706830

(55) Zhang, J.; Ma, M.; Chen, Z.; Zhang, X.; Yang, H.; Wang, X.; Feng, H.; Yu, J.; Gao, S. Production of Monocyclic Aromatics and Light Olefins through Ex-Situ Catalytic Pyrolysis of Low-Density Polyethylene over Ga/P/ZSM-5 Catalyst. *J. Energy Inst.* **2023**, *108*, 101235. https://doi.org/10.1016/j.joei.2023.101235

(56) Aisien, F. A.; Aisien, E. T. Production and Characterization of Liquid Oil from the Pyrolysis of Waste High-Density Polyethylene Plastics Using Spent Fluid Catalytic Cracking Catalyst. *Sustain. Chem. Clim. Action* **2023**, *2*, 100020. https://doi.org/10.1016/j.scca.2023.100020

(57) Wang, P.; Qiao, L.; Wang, W.; Yu, J. Catalytic Pyrolysis of Waste Composite Plastics with Waste FCC Catalyst. *J. Energy Inst.* **2023**, *110*, 101338. https://doi.org/10.1016/j.joei.2023.101338

(58) Yun, K.; Lian, X.; Wang, S.; Shan, R.; Yuan, H.; Chen, Y. High Value Olefins from Polypropylene by in Situ Catalytic Pyrolysis. *J. Energy Inst.* **2025**, *123*, 102279. https://doi.org/10.1016/j.joei.2025.102279

(59) Chaudhary, A.; Lakhani, J.; Dalsaniya, P.; Chaudhary, P.; Trada, A.; Shah, N. K.; Upadhyay, D. S. Slow Pyrolysis of Low-Density Poly-Ethylene (LDPE): A Batch Experiment and Thermodynamic Analysis. *Energy* **2023**, *263*, 125810. https://doi.org/10.1016/j.energy.2022.125810

(60) Gracida-Alvarez, U. R.; Benavides, P. T.; Lee, U.; Wang, M. Life-Cycle Analysis of Recycling of Post-Use Plastic to Plastic via Pyrolysis. *J. Clean. Prod.* **2023**, *425*, 138867. https://doi.org/10.1016/j.jclepro.2023.138867

(61) Das, S.; Liang, C.; Dunn, J. B. Plastics to Fuel or Plastics: Life Cycle Assessment-Based Evaluation of Different Options for Pyrolysis at End-of-Life. *Waste Manag.* **2022**, *153*, 81–88. https://doi.org/10.1016/j.wasman.2022.08.015

(62) *Plastic Waste Pyrolysis Oil Market Size, Share & Analysis, 2034*. https://www.fortunebusinessinsights.com/plastic-waste-pyrolysis-oil-market-112760 (accessed 2026-09-15)

(63) Čolnik, M.; Kotnik, P.; Knez, Ž.; Škerget, M. Chemical Recycling of Polyolefins Waste Materials Using Supercritical Water. *Polymers* **2022**, *14* (20), 4415. https://doi.org/10.3390/polym14204415

(64) Čolnik, M.; Knez, Ž.; Škerget, M. Sub- and Supercritical Water for Chemical Recycling of Polyethylene Terephthalate Waste. *Chem. Eng. Sci.* **2021**, *233*, 116389. https://doi.org/10.1016/j.ces.2020.116389

(65) Jin, K.; Vozka, P.; Kilaz, G.; Chen, W.-T.; Wang, N.-H. L. Conversion of Polyethylene Waste into Clean Fuels and Waxes via Hydrothermal Processing (HTP). *Fuel* **2020**, *273*, 117726. https://doi.org/10.1016/j.fuel.2020.117726

(66) Mathew, M.; Nahil, M. A.; Ross, A. B.; Williams, P. T. Supercritical Water Liquefaction of Mixed Waste Polystyrene, Polypropylene, and Polyethylene for Production of High Yield Oils. *Energy Fuels* **2024**, *38* (14), 12810–12823. https://doi.org/10.1021/acs.energyfuels.4c01819

(67) Zhao, P.; Yuan, Z.; Zhang, J.; Song, X.; Wang, C.; Guo, Q.; Ragauskas, A. J. Supercritical Water Co-Liquefaction of LLDPE and PP into Oil: Properties and Synergy. *Sustain. Energy Fuels* **2021**, *5* (2), 575–583. https://doi.org/10.1039/D0SE01486A

(68) Song, Z.; Xiu, F.-R.; Qi, Y. Degradation and Partial Oxidation of Waste Plastic Express Packaging Bags in Supercritical Water: Resources Transformation and Pollutants Removal. *J. Hazard. Mater.* **2022**, *423*, 127018. https://doi.org/10.1016/j.jhazmat.2021.127018

(69) Mathew, M.; Quarton, C.; Nahil, M. A.; Williams, P. T. Supercritical Water Liquefaction of Mixed Plastic Waste 'Contaminated' with PET (Polyethylene Terephthalate): Influence on Yields and Product Composition. *Fuel Process. Technol.* **2026**, *285*, 108428. https://doi.org/10.1016/j.fuproc.2026.108428

(70) Lu, T.; Jan, K.; Chen, W.-T. Hydrothermal Liquefaction of Pretreated Polyethylene-Based Ocean-Bound Plastic Waste in Supercritical Water. *J. Energy Inst.* **2022**, *105*, 282–292. https://doi.org/10.1016/j.joei.2022.10.003

(71) Sadat-Shojai, M.; Bakhshandeh, G.-R. Recycling of PVC Wastes. *Polym. Degrad. Stab.* **2011**, *96* (4), 404–415. https://doi.org/10.1016/j.polymdegradstab.2010.12.001

(72) Takeshita, Y.; Kato, K.; Takahashi, K.; Sato, Y.; Nishi, S. Basic Study on Treatment of Waste Polyvinyl Chloride Plastics by Hydrothermal Decomposition in Subcritical and Supercritical Regions. *J. Supercrit. Fluids* **2004**, *31* (2), 185–193. https://doi.org/10.1016/j.supflu.2003.10.006

(73) Tito, E.; Dos Passos, J. S.; Rombolà, A. G.; Torri, C.; Bensaid, S.; Pirone, R.; Biller, P. Sequential Hydrothermal Dechlorination and Liquefaction of PVC. *Energy Convers. Manag.* **2024**, *304*, 118228. https://doi.org/10.1016/j.enconman.2024.118228

(74) Fu, Z.; Zhang, Y. S.; Ji, G.; Li, A. Experimental Analysis on Products Distribution, Characterization and Mechanism of Waste Polypropylene (PP) and Polyethylene Terephthalate (PET) Degradation in Sub-/Supercritical Water. *Chemosphere* **2024**, *350*, 141045. https://doi.org/10.1016/j.chemosphere.2023.141045

(75) Darzi, R.; Dubowski, Y.; Posmanik, R. Hydrothermal Processing of Polyethylene-Terephthalate and Nylon-6 Mixture as a Plastic Waste Upcycling Treatment: A Comprehensive Multi-Phase Analysis. *Waste Manag.* **2022**, *143*, 223–231. https://doi.org/10.1016/j.wasman.2022.03.002

(76) Cocero, M. J. Supercritical Water Processes: Future Prospects. *J. Supercrit. Fluids* **2018**, *134*, 124–132. https://doi.org/10.1016/j.supflu.2017.11.018

(77) Li, Y.; Duan, Y.; Wang, S.; Zhang, F.; Li, J.; Dai, Z.; Li, Z.; Zhang, Y.; Wang, Y. Supercritical Water Oxidation for the Treatment and Utilization of Organic Wastes: Factor Effects, Reaction Enhancement, and Novel Process. *Environ. Res.* **2024**, *251*, 118571. https://doi.org/10.1016/j.envres.2024.118571

(78) Vaiano, V.; De Marco, I. Removal of Azo Dyes from Wastewater through Heterogeneous Photocatalysis and Supercritical Water Oxidation. *Separations* **2023**, *10* (4), 230. https://doi.org/10.3390/separations10040230

(79) Webb, H.; Rosansky, S.; Al-Dirani, S. M.; Dasu, K.; Scheitlin, C. G.; Davis, J.; Chiques, L. PFAS Destruction Using Supercritical Water Oxidation (SCWO) at Peterson Space Force Base. *J. Hazard. Mater. Lett.* **2025**, *6*, 100156. https://doi.org/10.1016/j.hazl.2025.100156

(80) Lee, S.; Lee, H.; Lee, J.; Cho, H. Sustainable Chemical Recycling of Waste Plastics into Olefins through Low-Pressure Hydrothermal Liquefaction and Microwave Pyrolysis: Techno-Economic Analysis and Life Cycle Assessment. *Energy Convers. Manag.* **2024**, *317*, 118861. https://doi.org/10.1016/j.enconman.2024.118861

(81) Umdagas, L.; Orozco, R.; Kings, I.; Thom, W.; Al-Duri, B. Advances in Chemical Recycling of Polyolefins by Hydrothermal Liquefaction in Supercritical Water: A Comprehensive Review. *J. Supercrit. Fluids* **2026**, *227*, 106761. https://doi.org/10.1016/j.supflu.2025.106761

(82) Mallick, R.; Chien, S.-C.; Ranganathan, P.; Shiju, N. R. Integrated Experimental, Kinetic, and CFD Analysis of Hydrothermal Liquefaction of LDPE-Rich Plastics Waste. *Chem. Eng. J.* **2026**, *543*, 177615. https://doi.org/10.1016/j.cej.2026.177615

(83) Harisankar, S.; Pragadeshwar Babu, M. V.; Srinivasan, S.; Vinu, R. Hydrothermal Liquefaction of Diverse Plastics Using Water and Seawater. *Chem. Eng. J.* **2024**, *501*, 157365. https://doi.org/10.1016/j.cej.2024.157365

(84) *AMF*. https://www.iea-amf.org/content/fuel_information/diesel_gasoline (accessed 2026-09-15)

(85) Un, C.; Gentilcore, C.; Ault, K.; Gieng, H.; Vozka, P.; Wang, N.-H. L. Low-Pressure Hydrothermal Processing of Disposable Face Masks into Oils. *Processes* **2023**, *11* (10), 2819. https://doi.org/10.3390/pr11102819

(86) Gentilcore, C.; Un, C.; Martinez-Maldonado, J.; Vozka, P.; Wang, N.-H. L. Continuous Low-Pressure Hydrothermal Processing Methods for Polystyrene Conversion to Oils. *RSC Sustain.* **2025**, *3* (9), 3925–3946. https://doi.org/10.1039/D4SU00796D

(87) Onwudili, J. A.; Williams, P. T. Catalytic and Non-Catalytic Low-Pressure Hydrothermal Liquefaction of Pinewood Sawdust, Polyolefin Plastics and Their Mixtures. *J. Clean. Prod.* **2023**, *430*, 139733. https://doi.org/10.1016/j.jclepro.2023.139733

(88) Amsterdam, U. van. *Cooking plastics into oil - HIMS*. Van 't Hoff Institute for Molecular Sciences - University of Amsterdam. https://hims.uva.nl/content/news/2026/05/cooking-plastics-into-oil.html (accessed 2026-09-15)

(89) Saha, N.; Banivaheb, S.; Toufiq Reza, M. Towards Solvothermal Upcycling of Mixed Plastic Wastes: Depolymerization Pathways of Waste Plastics in Sub- and Supercritical Toluene. *Energy Convers. Manag. X* **2022**, *13*, 100158. https://doi.org/10.1016/j.ecmx.2021.100158