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# End-of-Life Plastics Management: A Review

## Mechanical recycling, pyrolysis and hydrocracking methods

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End-of-life plastics present a significant challenge to achieving a sustainable economy. It is crucial to develop environmentally friendly technologies to process the waste streams beyond landfilling. This review provides a detailed overview of end-of-life plastics management, covering mechanical recycling, pyrolysis and hydrocracking methods. Mechanical recycling is the predominant technique employed on a large scale in recycling end-of-life plastics, and this review discusses the technoeconomic assessment and life cycle assessment (LCA) of mechanical recycling. This review also summarises key studies concentrating on chemical recycling techniques for handling end-of-life plastics. Among these, pyrolysis and hydrocracking are discussed in depth. Recent advancements and fundamentals of these two techniques are covered, highlighting their significance in tackling the plastic waste challenge. The prospects of scaling up pyrolysis and hydrocracking technologies are interpreted in terms of technical and economic feasibility. The discussion concludes with recommendations for future research to commercialise chemical recycling of end-of-life plastics.

## Introduction

Plastics are ubiquitous and play a significant role in our daily lives. Although plastics have facilitated the development of our society in many aspects, end-of-life plastics pose an imminent threat to our environment. There are seven major plastic species: (a) polyethylene terephthalate (PET); (b) high-density polyethylene (HDPE); (c) polyvinyl chloride (PVC); (d) low-density polyethylene (LDPE); (e) polypropylene (PP); (f) polystyrene (PS); and (g) other plastics not made from the above species. According to the statistics from the United States Environmental Protection Agency (US EPA) in **Figure 1** (1), LDPE, PP and HDPE constitute the major plastic components in municipal solid waste followed by PET, PS, PVC and other plastics.

The report from the World Economic Forum in **Figure 2** showed that around 40 million tonnes of plastic waste was generated in the USA in 2021. Only 5–6% of it was recycled, 15–16% was incinerated and the rest were landfilled based on the estimates (2). Furthermore, estimates indicated 75–199 million tonnes of plastic waste was littered in both land and oceans (2). Incineration and landfill of plastic waste have given rise to a multitude of environmental hazards including air pollution, groundwater contamination, soil quality degradation and proliferation of marine microplastics (3–8).

The activities taking place inside landfills drive the production of gas and possible environmental impacts on the soil. Gases including methane,

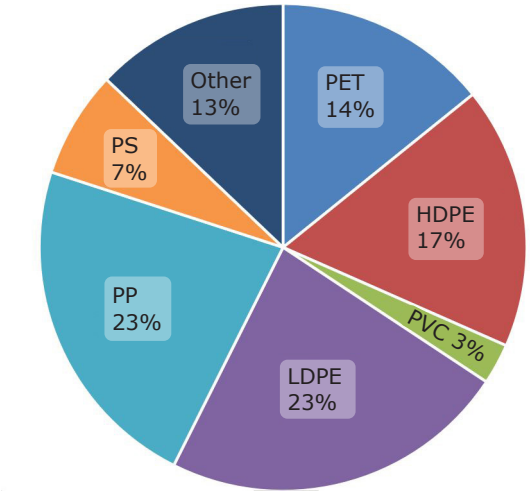


Fig. 1. Compositions of municipal solid waste plastics reported from EPA (1)

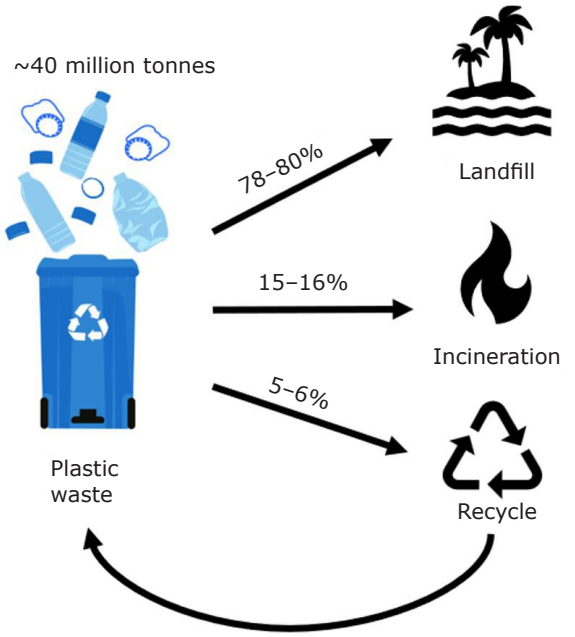


Fig. 2. Current plastic waste management situations (2)

carbon dioxide and hydrogen sulfide are released by landfills, which harm the quality of the air. The production of hazardous wastewater known as landfill leachate, which is produced when waste is dumped in landfills, is one of the main problems with this practice (9). Leachate is produced in large part because of groundwater, precipitation and rainwater seeping into exposed landfills. Although the composition and amount vary depending on precipitation, rainfall, evapotranspiration, landfill age, waste type composition and degree of compaction, landfill leachates mainly consist of: (a) dissolved organic matter; (b) macro-inorganic components; (c) heavy metals; and (d) xenobiotic organic compounds (10, 11). Numerous methods have been studied based on biological and physicochemical approaches to handle leachate; however, individual biological or physicochemical methods are not enough to achieve satisfactory removal. In the laboratory scale, sequential steps of two or more treatments from both biological and physicochemical processes are needed to satisfy the chemical oxygen demand (COD) effluent standard (11). Interestingly, no single unit process is available to degrade leachate to a satisfactory level because current wastewater treatment systems cannot degrade the harmful chemicals present (10).

Marine plastic pollution constitutes a prominent issue within the larger problem of plastic waste management. In 2010, it is estimated around 7 million tonnes of plastic waste was dumped in the ocean (12). Several studies prove microplastics' existence in marine biota. Microplastic has been found in *Mytilus edulis* and *Mytilus galloprovincialis* varying from 3 to 5 fibres per 10 g of mussels in European countries (13). In addition, ingested microplastic was also found in the Pacific area around Japan in the hindguts of Lysianassoidea amphipod populations in ocean depths of 7–10 km. This study records the deepest finding of microplastics in the ocean and indirectly implies all levels of depth are already affected by the presence of microplastics (14).

Plastic pollution has caused various environmental hazards. Significant attention from all parties of interest, including policymakers, industries, research communities, academia and the general public in a country is needed in order to address these issues. Although the USA is the largest producer of plastic, as indicated by the 0.35 kg $day^{-1}$ plastics production per capita, only around 2% of plastic waste was mismanaged (12). On the other hand, India and Indonesia are reported to have the highest amount of mismanaged plastics: 4.28 million tonnes and 3.16 million tonnes respectively (12). The term 'mismanaged' in the context of plastic waste has several implications (12). Firstly, it refers to inadequately managed plastic waste that remains uncollected or improperly contained due to lack of proper waste management infrastructure. Secondly, mismanaged plastic waste also includes illegal dumping, which involves the intentional or unintentional disposal of waste in areas where it is prohibited or not designated for such purposes. Thirdly, mismanaged plastic waste also applies to exported plastic waste which ends

up in places without adequate waste management infrastructure. Lastly, littering is another implication of plastic waste mismanagement and littered plastic waste can be found in unpermitted areas or the environment (12). The involvement and collaboration of all stakeholders become imperative in addressing the issues of plastic waste management, which are directly associated with the prevailing plastic upcycling methods.

The four predominant plastic recycling methods include primary recycling, secondary recycling, tertiary recycling and quaternary recycling (15). Primary recycling refers to the closed-loop recycling and reuse of end-of-life plastics without any modification. This method is effective if the polymer components: (a) consist of minimal additives, colour and additional materials; and (b) are stable during reprocessing and subsequent reuse (16). As for secondary recycling, end-of-life plastic is physically modified into materials with subpar properties. Both primary and secondary recycling methods are considered as mechanical recycling approaches. Tertiary recycling is the chemical recycling of end-of-life plastics into chemical feedstock, while quaternary recycling involves energy recovery from valorisation of end-of-life plastic or pyrolysis as this process produces liquid oil as an energy source (17). Primary recycling is limited to the source of the stream so only in some limited cases is this method feasible. Secondary recycling is most likely to be inefficient due to bigger energy input compared to the product's obtained value (15). Plastic has a lower heating value compared to normal fuels used during incineration and emits harmful waste if not handled properly (18–20). Tertiary recycling and quaternary recycling, particularly pyrolysis and hydrocracking, have some potential as these processes produce higher value products that can be useful for society. These processes may be referred to as upcycling.

## Current State of Mechanical Recycling

Mechanical recycling takes place in a material recovery facility (MRF) or a specialised plastic recovery facility (PRF) (21, 22). PET and HDPE are the main types of plastic that are typically recycled due to their feasibility in terms of producing quality recycled materials (15). Here the discussion is focusing mostly on PET as it is the most recycled plastic at MRF sites. The quality of recycled plastic is significantly influenced by the proportion of PET among all plastic types. Therefore, recycling PET back into its monomeric form, whether as polymer granules, pellets or flakes, is valuable for subsequent uses (23).

MRF facilities serve single-stream recycling and dual-stream recycling in the USA (24). Single-stream recycling processes all recyclable materials, like paper, plastic, glass and metal, which are collected and sorted later (25–27). Dual stream recycling, on the other hand, handles recyclable materials that are sorted into different groups either by consumers or during collection (25, 26). Single-stream MRFs have become more common recently due to the higher recovery rate and increasing rates of participation of communities collecting recyclable material in separate bins (24). Additionally, it is claimed that single stream MRFs could produce 50% more recycled products than dual-stream MRFs (25). Some strategies are now being conducted to increase the collection of recyclable materials, including expansion of the availability of recycling services and bins, simplifying the collections process to make it more convenient for individuals, promoting the significance of recycling in relation to the three pillars of sustainability, transferring responsibility to producers through extended producer responsibility (EPR) programmes and generally raising awareness and educating the public to encourage greater participation in recycling efforts (23). However, it should be noted that single-stream MRFs still encounter significant technical and economic challenges. These challenges encompass aspects such as waste collection and transportation, uncertainties regarding the composition of waste streams, tipping fees, sorting efficiencies, sorting costs, the presence of low-quality recyclable materials and the volatility of market prices for post-consumer recovered materials (24). Although there are several issues in collection, 67.5% of all bottles collected in the USA are recycled into useful products as indicated in the mass flow of PET released by the National Association for PET Container Resources (NAPCOR) shown in **Figure 3** (23).

The technical processes in the MRFs face various challenges that significantly impede their processing capacities and efficiencies. Some additives in plastics can impact the mechanical recycling of post-consumer plastics products since these additives have the potential to undermine the quality or lifespan of plastic packaging manufactured from recycled resins containing such additives (28). 25% of PET contains some form of additives, which

 

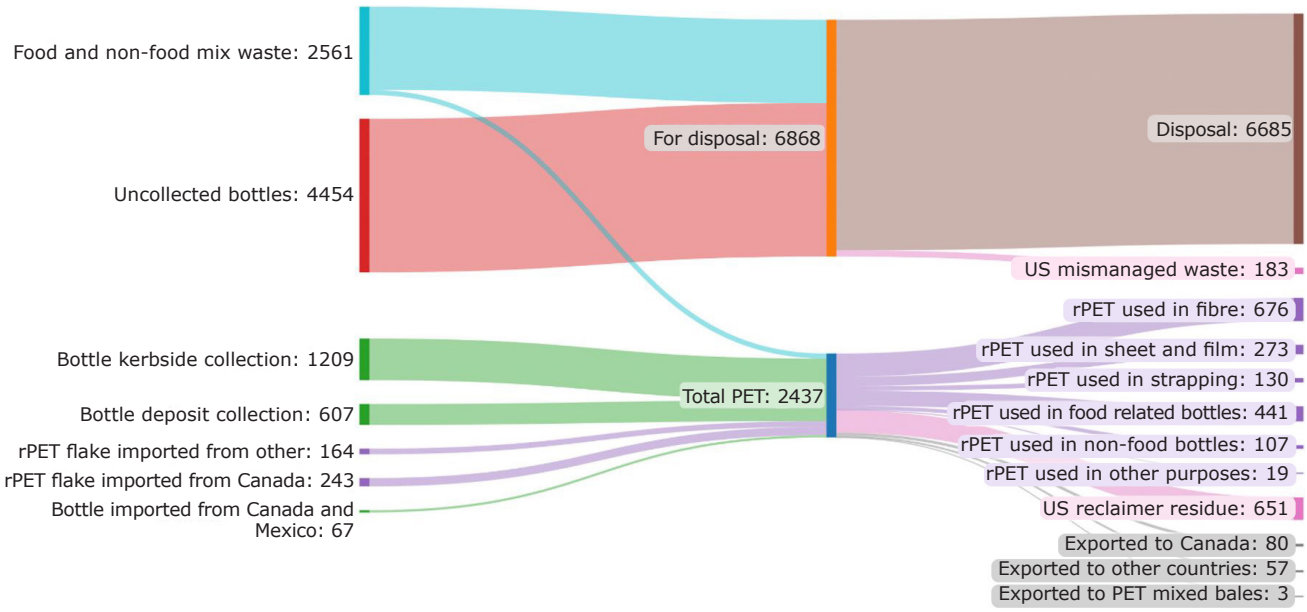


Fig. 3. Mass flow diagram of recycled PET in the USA in million-pound (lb) scale (23)

can be classified into four main categories: (a) colourants; (b) physical modifiers; (c) fillers; and (d) functional additives (23). This becomes one of the factors that lower economic viability of a mechanical recycling facility. There are other factors including the low capacity and low availability of high quality recyclable materials, tipping fees, waste transportation and post-recovered material market prices. A study conducted in Seattle, Pennsylvania and Oregon analysed the net present value (NPV) for a single-stream MRF and concluded that the NPV is sensitive to waste composition. It ranges from US$3.75 million, US$30.54 million and US$43.99 million for Seattle, Oregon and Pennsylvania waste compositions, respectively (24). The emphasis of the wide range of NPV is more towards the fraction of aluminium, HDPE, plastic film and PET as those are easier to achieve post-recycled market quality (29).

LCA is also an important aspect to consider after addressing possible technical issues and economic viability. To begin with, the greenhouse gas (GHG) emission in mechanical recycling is approximately 4120 $CO_2$-eq per 1000 kg PET while that of chemical recycling is 3920 $CO_2$-eq per 1000 kg PET (30). The sensor-based sorting in mechanical recycling causes 6 kg $CO_2$-eq per 1000 kg plastic input, while incineration of sorted residues accounts for 60% of $CO_2$ emission (31). There are some factors that make a difference both in economical and LCA; for instance, a change of 30% diesel consumption can affect the global warming potential (GWP) from 7.20 kg to 8.29 kg $CO_2$-eq.

Interestingly, waste collection distance does not significantly affect the GWP value (24). Circularity, which is defined as the ratio of restorative flows to amount in system use, is also an essential aspect in LCA. In the context of mechanical and chemical recycling, the circularity ratio measures the proportion of restorative flows (recycled materials) compared to the total amount used within the system. With a circularity ratio of 0.34 in mechanical recycling and 0.9 in chemical recycling, the chemical recycling process achieves a higher level of material restoration and utilisation compared to mechanical recycling. This implies that chemical recycling has the potential to contribute more towards a circular economy by maximising the reuse of resources (30).

## Recent Research Progress in Chemical Upcycling of Plastics

Current plastic recycling practices include mechanical resizing and repurposing of plastic waste into materials with reduced structural properties. Plastic upcycling refers to the process of transforming plastic waste into valuable materials with higher quality and functionality. Tertiary or chemical recycling of plastic waste has been extensively investigated in the past several years (32–35). Researchers have claimed significant advancements in developing various technologies for converting end-of-life plastics into valuable monomeric or oligomeric feedstock. These technologies, such as pyrolysis, depolymerisation

 

and catalytic cracking, can convert plastic waste into fuels (36–42), aromatics (43–45), plastic building blocks (46–51) and other chemicals (52–54). These efforts aim to reduce plastic pollution, conserve resources and move towards a more sustainable and circular economy (32). As shown in **Figure 4**, waste plastics that cannot be mechanically recycled can be converted to fuels, lubricants, olefins, naphtha and aromatics. The market value estimates are obtained from converted data published by the US Department of Energy (55), US Energy Information Administration (56), US Bureau of Transportation Statistics (57), statista.com (58, 59) and other research articles (60, 61). While upcycling waste plastics into fuels can be a potentially lucrative endeavour, it is important to note that this approach may result in increased carbon emissions. Therefore, it should not be considered a sustainable strategy for achieving carbon-neutral or carbon-negative plastic waste management, unless the plastics are converted specifically into aviation fuels, given the absence of suitable alternatives (62, 63).

The upcycling of waste plastics into chemical feedstocks, such as olefins, naphtha, aromatics or lubricants, can indeed be considered a sustainable approach to plastic waste management. By converting the carbon contained in the plastics and incorporating it into the production-upcycling loop, the potential for carbon emissions is significantly reduced. This method allows for the reuse of plastic materials, effectively extending their lifespan and minimising environmental impact.

Effective upcycling strategies are tailored to targeted plastic species. Prevailing plastic upcycling strategies include pyrolysis, hydrocracking, solvolysis and photocatalysis (34, 54, 64). Thermal upcycling approaches such as pyrolysis and hydrocracking are highly promising and have the potential for large-scale implementation and distribution due to their scalability and economic potential (32, 65–67). Researchers have been devoting their efforts to improve the yield and selectivity of target products from plastic upcycling practices (32, 68). For polyolefins such as LDPE, HDPE, PP and PS, thermal upcycling approaches including pyrolysis, depolymerisation and catalytic cracking can be employed to produce original building monomers or other valuable feedstock including aromatics, hydrocarbon fuels and other petrochemical products (32, 68, 69). **Table I** summarises recent research efforts in the chemical recycling of plastics.

Chemical recycling processes have predominantly focused on the conversion of plastic waste into hydrocarbons, which are subsequently utilised as fuels or monomers for further applications. Although hydrogen has been explored in certain cases, liquid hydrocarbons and light gas products remain prevalent. Some efforts have been directed towards producing valuable carbon-based materials such as anodes, cathodes and adsorbents (70–73). Microwave-assisted technology has been pivotal in enhancing the performance of plastic-to-carbon material recycling processes. However, scaling up these processes faces challenges related to reproducibility. The issue lies in the penetration problem at larger scales where higher power inputs are needed to ensure uniform effects throughout the system. As reported by Kim *et al*.,, the application of microwave-assisted sulfonation

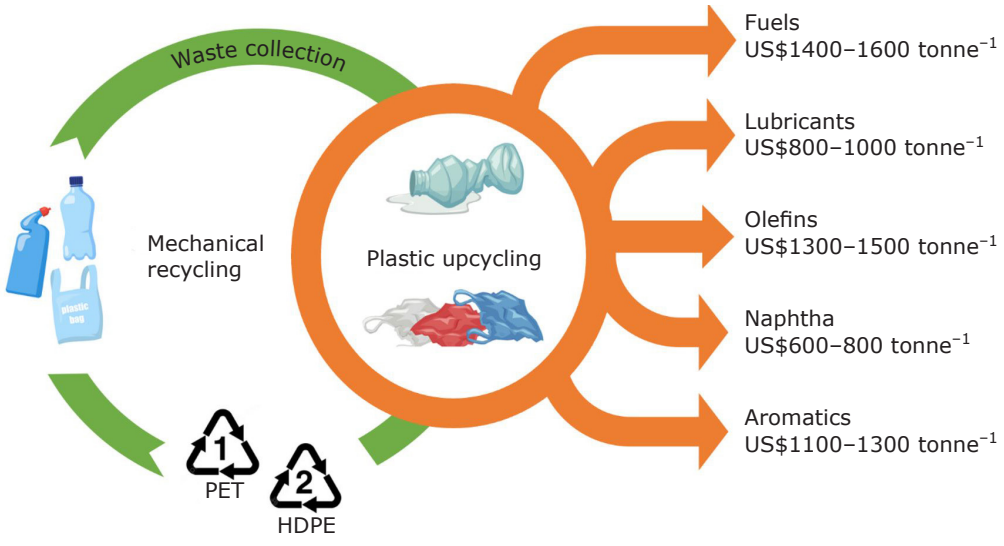


Fig. 4. Current sustainable plastic waste management recycling and upcycling routes

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**Table I Summary of Recent Investigations into Chemical Recycling of Plastics**

| Plastics | Catalyst | Reagent | Temperature | Pressure | Duration | Reaction System | Product | Application | Yield | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| PE (MW[a]: 3520) | 1.5%Pt/γ-$Al_2O_3$ | $H_2$, $CHCl_3$ | 280°C | – | 24 h | Batch, unstirred autoclave reactor | Low-MW hydrocarbon and wax | Chemical feedstock | 80% | (43) |
| PE (MW: 8000–158,000; 31,000) | Pt/$SrTiO_3$ | $H_2$ | 300°C | 170 psi | 96 h | Batch and spouted bed reactor | Liquid hydrocarbons | Fuels | 97% | (75) |
| LDPE and HDPE | $H_2SO_4$ (98%) | – | Solvothermal: 110°C, carbonation: 900°C | 1 atm | 12 h | Batch solvothermal: sulfonation, sized bed: carbonation | Amorphous carbon chips | Li-ion battery anodes | 63 ± 5% for LDPE and 54 ± 3% for HDPE | (71) |
| PP | CuCl | Co(acac), ferrocene | 800°C | 1 atm | – | Batch solvothermal | Magnetic carbon material | Dye absorption | 25% | (72) |
| HDPE | $HNO_3$ | – | 180°C | 1 atm | 4 h | Microwave-assisted hydrothermal | Polylactic plasticiser | PLA[b] composite | | (76) |
| LDPE | 0.1 M $HNO_3$ | – | 180°C | 1 atm | 3 h | Microwave-assisted oxidation process | Dicarboxylic acid | copolymer for polyesters and polyamides | 37% | (77) |
| LDPE | Sulfuric acid, Ar (two steps) | – | 900°C | – | 2 h | Microwave promoted sulfonation, then Ar under high temperature | PSC[c] | PSC (Li-S battery cathode electrodes) | – | (70) |
| PP | Ferrocene and sulfur | – | 700°C | 1 atm | 1.5 h | Autoclave | CNS[d] | Energy storage, solvents recovery, gas adsorption, catalyst support | 62.80% | (73) |
| PE, PP, PVC | Orthorhombic $Nb_2O_5$ | $AgNO_3$ Solution | 25°C | 1 atm | – | Photocatalytic system | 1st step: $CO_2$; 2nd step: $CH_3COOH$ | C2 fuels | – | (78) |
| PE, LDPE | 5 wt% Ru/C | $H_2$ | 200°C | 20 bar | 16 h | Batch, stirred reactor | Light alkane gases (C1−C6) | Chemical feedstock | 45% | (40) |

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**Table I—*Continued***

| Plastics | Catalyst | Reagent | Temperature | Pressure | Duration | Reaction System | Product | Application | Yield | Ref. |
|---|---|---|---|---|---|---|---|---|---|---|
| HDPE | Ni commercial catalyst (G90LDP catalyst from Süd Chemie) | – | 700°C | – | – | Conical spouted bed reactor followed by a fluidised bed reactor | $H_2$ | $H_2$ Production | 92.50% | (79) |
| PP | $Ru/TiO_2$ | $H_2$ | 250°C | 30 bar | 16 h | Batch, stirred reactor | Liquid hydrocarbons | Lubricants | 65.60% | (80) |
| LDPE | Ru-WZr | $H_2$ | 250°C | 50 bar | 2 h | Batch, stirred reactor | Liquid hydrocarbons | Fuels | 70% | (81) |
| LDPE (MW: 1700, 4000) | $Ru/CeO_2$ | $H_2$ | 240°C | 6 MPa | 1 h | Batch, stirred reactor | Liquid hydrocarbons | Fuels | 83% | (82) |
| PE, PP | $Pt/WO_3/ZrO_2$ | $H_2$ | 25°C | 30 bar | 2 h | Batch, stirred reactor | Liquid hydrocarbons | Fuels | 85% | (83) |
| HDPE | 5%Ru/C | Hexane, $H_2$ | 220°C | 30 bar | 1 h | Batch, stirred reactor | Liquid hydrocarbons | Fuels | 74.9% | (38) |
| Virgin and modelled real plastics conditions | $MoS_x$-HBeta | $H_2$ | 250°C | 2 MPa | 6 h | Batch | Liquid alkanes | Fuels | 96% | (84) |
| HDPE, LDPE, LLDPE | Ni complexes | [m]CPBA e | 80–90°C | 1 atm | 3 h | Teflon-lined batch, $N_2$ atmosphere | Hydroxylated polyethylenes | Polymerisation initiator | | (85) |
| PE, PP | Ru/FAU[f] | $H_2$ | 200°C | 30 bar | 16 h | Batch solvent-free hydrogenolysis | Liquid alkanes | Fuel, chemical feedstock | 67% | (86) |
| PP | Ru/C | $H_2$ | 250°C | 40 bar | 16 h | Batch solvent-free hydrogenolysis | Liquid alkanes | Fuel, chemical feedstock | 68% | (87) |
| PE | $Pt/F\text{-}Al_2O_3$ | | 280°C | 1 atm | 8 h | Batch, stirred autoclave, Ar atmosphere | Alkylaromatics | Solvents, surfactants | | (74) |
| PE | MTO[g]/Cl-$Al_2O_3$ | Ethene | 70°C | 1 atm | 5 h | CSTR[h] | Propene | Monomer for PP synthesis | 94% | (88) |

[a]MW = molecular weight; [b]PLA = polylactic acid; [c]PSC = porous sulfonated carbon; [d]CNS = carbon nanosheets; [e] [m]CPBA = *meta*-chloroperoxybenzoic acid; [f]FAU = faujasite; [g]MTO = methyltrioxorhenium; [h]CSTR = continuous stirred tank reactor

processes has been essential in fabricating high-surface-area sulfonated carbon scaffold from LDPE (70). In the context of electronics, having uniform performance is critical. Consequently, when such processes are scaled up, ensuring products with consistent surface areas becomes a critical consideration. Discrepancies in surface areas of carbon products can significantly impact the performance of lithium-sulfur batteries and substantial challenges will arise in enhancing the battery performance. This aspect emphasises the significance of microwave-assisted technology in the high-precision electronics industry, particularly for manufacturing with sustainable materials.

Current research trends in chemical recycling of plastics into fuels mainly involve batch hydrogenation systems that utilise noble metals as catalysts. In addition, some researchers have sought to propose mechanisms that combine more than one pathway for the upcycling process. Despite their potential, batch hydrogenation method is time-consuming and prone to inaccuracies if not meticulously managed. Sun *et al*. recently introduced a protocol for quantifying polyethylene depolymerisation in batch reactors to address these concerns (74). This raises questions about the results of other groups. Differences in their product recovery and analysis procedures could potentially skew their reported catalyst performance or the proposed new routes. In addition, challenges associated with scaling up this system extend beyond time constraints and safety considerations due to high pressures. Complex operational procedures are further complicated by the need for product recovery processes, involving the release of headspace gases and separation of light gases and hydrogen for economical recycling purposes. Moreover, while these processes operate at lower temperatures compared to conventional pyrolysis, industrial implementation requires the system to undergo cooling and reheating phases during product recovery, demanding additional energy input.

## Pyrolysis

Pyrolysis has been commonly used as an effective chemical upcycling strategy to convert end-of-life plastics into gas, liquid and solid products through thermal decomposition in the absence of oxygen (34, 89–91). Direct pyrolysis enables the decomposition of plastics into lower molecular weight hydrocarbons, encompassing gaseous and liquid hydrocarbons, wax, char and hydrogen chloride especially when pyrolysing PVC (90, 92, 93). Nevertheless, products derived from direct pyrolysis of plastics often exhibit a wide distribution (94), especially as the feedstock for plastic pyrolysis always contains different polymers (94), making it challenging to control the selectivity and yield of desired products solely through adjustments in feeding gas flow rates, reaction temperatures and other operating parameters (94). Moreover, the broad distribution of products generated during pyrolysis necessitates additional costs for the installation and operation of separation units to effectively obtain end products with desired purities (34). Product species and contaminants strongly depend on the feedstock plastic waste composition. Various separation methods have been developed in past decades, such as manual separation, flotation separation (95), triboelectrostatic separation (96) and selective dissolution (97). The pre-separated plastics lead to different product yields under direct pyrolysis.

In contrast, catalytic pyrolysis involves the introduction of acidic catalysts like zeolites to fine-tune the selectivity of target products and enhance reaction kinetics (34, 46, 98). Depending on the types of catalysts used and reaction conditions, catalytic pyrolysis of plastics can yield a diverse range of products, including gaseous hydrocarbons, liquid fuels, aromatics, solid chars and a variety of other hydrocarbon compounds (41, 46, 50, 90, 98). Gaseous hydrocarbon products primarily consist of short-chain olefins, while liquid fuel products include hydrocarbons within gasoline-range, diesel-range and kerosene-range (18, 34, 37–39, 54, 67, 99, 100). Direct pyrolysis and catalytic pyrolysis are operated under inert gas atmospheres at high temperature conditions >400°C, and pyrolysis processes offer the capability to convert virtually all types of plastic waste into valuable pyrolysis products. However, it is important to note that halogenated polyolefins, such as PVC and PTFE (92, 98), require a preliminary pretreatment step to eliminate halogen atoms. Both direct pyrolysis and catalytic pyrolysis can be accommodated in various thermal reactors including fixed-bed reactors, fluidised-bed reactors and plug-flow reactors. The exceptional adaptability of pyrolysis and catalytic pyrolysis systems has positioned these strategies at the forefront of scaling up applications. While pyrolysis systems exhibit substantial economic potential and practical feasibility for upscaling, several challenges remain to be addressed, including high-energy input requirements, catalyst coking and deactivation, as well as product separation.

## Hydrocracking

Several research articles discuss the chemical upcycling of end-of-life plastics using hydrocracking, a well-established technology in petrochemical industries (84, 101, 102). Like pyrolysis, hydrocracking enables the conversion of large plastic molecules to lower molecular weight hydrocarbons by C–C bond cleavage at elevated temperature and in the presence of hydrogen (43, 83, 102). Hydrocracking is considered a promising method for plastic waste upcycling due to its ability to primarily generate saturated liquid fuels, in contrast to the unsaturated liquid hydrocarbons produced through pyrolysis and catalytic pyrolysis (43, 75, 83, 101–106). Furthermore, hydrocracking requires lower reaction temperatures than pyrolysis and catalytic pyrolysis, and coke formation can be significantly mitigated in hydrocracking. Hydrocracking also has advantages in removing halogen atoms in plastic waste such as fluorine, chlorine and bromine (51, 102, 107). Current plastic upcycling *via* hydrocracking is conducted in stirred or non-stirred batch reactors at moderate temperatures from 250°C to 450°C under 1–20 MPa hydrogen pressure (43, 75, 83, 102). Although plastic waste can be converted into saturated hydrocarbons in hydrocracking, the product distribution cannot be controlled without proper catalysts. Catalytic hydrocracking, on the other hand, can supplement such a disadvantage and facilitate the reaction kinetics (102, 103, 106). Bifunctional catalysts are required in catalytic hydrocracking with both hydrogenation-dehydrogenation and cracking functionalities. Bifunctional catalysts are usually acidic supports loaded with precious or non-precious metal particles (102, 106). Despite the mentioned advantages in hydrocracking and catalytic hydrocracking, hydrogen consumption, high pressure conditions and low energy efficiencies are the key obstacles in converting this technology into a green and sustainable plastic waste management approach (102).

## Conclusion and Future Recommendation

Disposal of municipal solid waste through landfilling is not considered an effective solution for plastic waste due to the production of leachate and emissions. The limitations of mechanical recycling and the relatively low energy value from incineration have motivated research on chemical plastic recycling or upcycling, aiming to create higher-value chemical products. This brief review explores the potential of pyrolysis and hydrocracking as two prominent chemical upcycling strategies and their pathways toward scaling up. Through the discussion of existing practices, it indicates that more comprehensive understanding of the compositions of various plastic waste streams is still needed for optimisation of the chemical processing conditions. It also suggests that chemical upcycling technologies can be integrated into today's waste management systems to leverage the advantages of distributed (*versus* centralised) processing and minimise transportation costs. By funnelling the hydrocarbons embedded in end-of-life plastics into value-added commodities or chemical feedstocks, it is plausible to make the processing of plastic wastes economic with reduced carbon footprint.

Given the findings from present chemical recycling or upcycling approaches, future research must emphasise creating methods that are not only efficient and scalable but also environmentally friendly. Collaboration between industry, academia and regulatory bodies will be crucial in establishing standardised protocols for plastic waste characterisation, ensuring consistent feedstock quality. As industries embrace the next wave of digital transformation, advanced technologies can play a pivotal role in enhancing the efficiency of the plastic recycling and upcycling processes. Real-time monitoring and predictive maintenance can offer crucial insights for optimising operations. By fostering policy incentives and strengthening public-private partnerships, we can drive significant investments in infrastructure and research. As we approach a new era of recycling innovation, collaborative and forward-thinking strategies are crucial to reimagining plastic waste as a valuable resource. Moreover, a shift towards sustainable and circular practices in the plastic industry can further complement these technological and collaborative advances. Community awareness and participation, alongside industry initiatives, can greatly amplify the impact, ensuring that recycling becomes an integral part of consumer behaviour. Over time, these combined efforts could not only reduce the environmental footprint of plastics but also position them within a sustainable economic model that benefits both industry and the planet.

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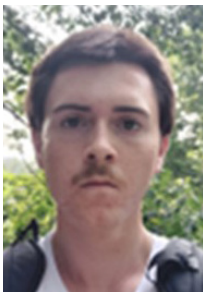

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