Can pyrolysis oil unlock greater plastic circularity?

Combining pyrolysis and vapour-phase catalytic upgrading offers lower temperature and energy requirements, higher yields, and optimised product distribution and selectivity

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Much of our society is dependent on plastics, with the first synthetic plastics manufactured more than 150 years ago. Plastics made the development of computers, cell phones, and advances in modern medicine possible. Food production, transport, and power rely on plastic for efficiency and safety, while our possessions are cheaper, lighter, stronger and safer.

It is no wonder that plastic production is increasing exponentially. Between 1950 and 2018, consumption grew about 180 times, from two million tons to 368 million tons. The UN Environment Programme (UNEP) states that 430 million tons of plastic are produced each year; production is expected to double yet again by 2050. However, the reputation of plastics has suffered in recent decades due to environmental and public health concerns.

Looking at start-of-life, approximately 98% of single-use plastic produced today comes from fossil fuels. About 4% of global oil and gas production is being used as feedstock for plastics, while 3-4% is used to provide energy for the manufacture of plastics. A 2021 report found none of the 100 largest plastic producers procure more than 2% of their feedstock from recycling sources, presenting a window for opportunity.

Criticism of plastics has largely been directed towards end-of-life management. A third of plastics are single-use; if we look specifically at the plastic used in packaging, about 95% of its material value is lost after a short first-use cycle, representing an $80-120 billion missed opportunity. The amount of plastics that end up in landfill, incinerated, or leaked into the environment stands at 72%, and the rate of successful plastic recycling sits at a reported 9%. Emissions from plastic production and disposal are expected to double in the next 35 years.

A more circular economy is needed to improve the current state of these bespoke statistics. Chemical recycling has been touted as part of the solution, with one particular method, pyrolysis, gaining interest internationally and offering a route to de-fossilising raw material streams into refineries. Organic material, including biomass, waste, tyres, and especially plastics, is transformed into pyrolysis (pyrolytic) oil or gas, which can be repurposed and utilised as reusable crude oils.

Plastic recycling status

There is no single reason behind low recycling rates; they stem from multiple factors. One significant challenge is the make-up of many individual plastic products using materials such as flexible films, multilayer materials, and coloured plastics, which cannot be recycled with conventional mechanical recycling or are entirely non-recyclable. Despite this, industries and legislators face growing public pressure to increase the collection, recycling, and reuse of all plastics. However, varied international management of the problems also presents a barrier to this.

In European Organisation for Economic Co-operation and Development (OECD) countries, the annual plastic waste generated per person is 114 kg. In the US, annual plastic waste generation is 221 kg per person, while Australia generates 148 kg per person. In the UK, figure for 2021 was reported at 99 kg per person. The Asian continent is the largest plastic waste producer, and individual Asian countries can vary widely in plastic waste rates. Developing countries in South and Southeast Asia are major destinations for waste exports, particularly from the EU and US.

There is no dedicated international instrument in place for plastics recycling today. Some countries are taking action to reduce plastic consumption or increase recycling through campaigns and awareness-raising measures. Other countries have specific laws in place, obliging businesses to minimise waste, adopt recycling targets, and phase out single-use plastics. The EU aims to ban single-use plastics by 2030 and cut the amount of plastic packaging by 15% by 2040. Australia mandated that 100% of plastic be recycled or reused by 2040. However, the country's largest soft-plastics recycling scheme collapsed in 2022.

Collection of waste differs between developed economies, where recyclable waste is typically collected by waste management companies and sorted and cleaned with equipment, and developing countries, which often rely on human waste pickers. The US faces difficulty because its systems for collection and management of plastics waste are organised at state and regional levels, but they are highly variable. In many Asia Pacific countries, the main drivers of plastic pollution are inadequate waste collection and processing infrastructures.

The primary existing method of plastic recycling, an industry standard, is mechanical recycling. Established on an international scale and around for decades, mechanical recycling sees plastic waste processed into secondary raw materials or products without chemically disrupting polymer chains in the process. An energy-efficient process, mechanical recycling boasts a low-carbon footprint, minimal environmental impact, and helps reduce landfill disposal. In cases of mixed and/or contaminated plastic streams, these must be sorted and cleaned thoroughly to make a product of good quality – a process that ends up being both time-intensive and costly.

However, mechanical recycling is feedstock specific, only accepting polyethylene terephthalate (PET), high-density polyethylene (HDPE), polypropylene (PP), or low-density polyethylene (LDPE) in most cases. Its impact is also limited on a global scale, as it cannot be utilised for hard-to-recycle plastics, which is where chemical recycling comes in.

Chemical recycling

Also known as advanced recycling, chemical recycling is the process of converting polymeric waste by altering its chemical structure and returning it to substances that can be used as raw materials. While introduced to industry decades ago, interest in these recycling technologies and the possibilities they present has been renewed in recent years.

Complementing existing plastic recycling methods, chemical recycling can better deal with mixed plastic waste streams, like films and laminates, that would otherwise result in incineration or landfill. Examples of these methods include gasification, depolymerisation, hydrocracking, and pyrolysis.

Pyrolysis has the potential to convert used plastic waste streams unsuitable for mechanical recycling into high-quality feedstock for even the most sensitive petrochemical industry applications

A transformative chemical recycling technology, pyrolysis has the potential to convert used plastic waste streams unsuitable for mechanical recycling into high-quality feedstock for even the most sensitive petrochemical industry applications.

The process sees plastics collected at the end of their product life cycle and heated to high temperatures (300-900ºC) in an inert atmosphere without oxygen. Thermal degradation causes these plastic materials to break down into smaller molecules, in turn, transforming plastic waste into pyrolysis (pyrolytic) oil or gas, which can be repurposed and utilised in the form of reusable crude oils.

Suitable for multiple applications, pyrolysis oil can reduce dependence on fossil fuels, presenting a lower carbon solution for hard-to-abate sectors and diversifying energy materials. In petroleum refineries, it can be used as a more sustainable and high-quality feedstock alternative to fossil naphtha, including ethylene and propylene production, which are core monomer building blocks of most plastics.

Pyrolysis oil can also be used as a fuel to power vehicles and machinery (once refined and blended with conventional fuels), which is particularly beneficial for industries that still rely heavily on crude oil and natural gas, such as shipping, construction, and manufacturing. It can even replace diesel with regard to engine performance and energy output in certain instances. Primary drivers of increasing pyrolysis capacity are oil and gas corporates, which are expected to utilise most pyrolysis oil as a fuel replacement.

Global interest in pyrolysis as a means of managing plastic waste can be seen in the development of significant commercial pyrolysis technologies for the processing of plastic waste. In the US, the American Chemistry Council advocates for state and federal policies that support these technologies for recycling and has emerged as a prominent research area in Europe.

Large chemical companies are starting to invest in pyrolysis oil production. Initial commercial plants vary between 10 and 50 kta; as of 2023, at least nine 10 kta capacity pyrolysis or hydrothermal chemical recycling units were scheduled to come online in Europe. Of those, however, only two are known to have achieved production by the end of the same year.

Since 2021, the global input capacity for pyrolysis plants has increased by more than 60%. Even so, the true potential of pyrolysis is still predominantly untapped. Approximately five million tons of plastic waste is currently mechanically recycled in Europe, compared to the 50,000 tons of plastic waste that is chemically recycled. There is clearly a significant opportunity to increase these rates, provided certain challenges can be overcome.

Meeting specifications

Pyrolysis oil contamination is one such hurdle, affecting purity and composition. Mixed waste plastics are often a complex combination of polymers. The final composition of such products can differ due to regional and country-specific factors. Plastics such as PET and polyvinyl chloride (PVC) can yield oxygenated and chlorinated compounds. These chlorides and their complexity pose an additional issue.

Tending to exist in roughly equal concentrations throughout the boiling point range of pyrolytic oil, they attach to hydrocarbons of varying chain lengths and have differing levels of steric hindrance. This can cause corrosion issues in steam cracking furnaces in petrochemical plants and result in plant and equipment breakdown.

Steam crackers feature very tight specifications that need to be satisfied if the oil is added as a feedstock. As such, these impurities need to be removed in an economical and sustainable way. Currently, the amount of plastic pyrolysis oil that can be fed into a steam cracker is less than 10%. Therefore, it is not possible to use the oil in steam crackers on any commercially significant scale.

Additionally, the products formed from pyrolysis are heavily dependent on both the composition of the feedstock and the process conditions. Impacts include type of reactor, heat transfer, residence time, heating rate, and temperature. When looking specifically at commercial catalytic pyrolysis, a major challenge is improving selectivity, promoting deoxygenation reactions, and reducing catalyst degradation through coke formation.

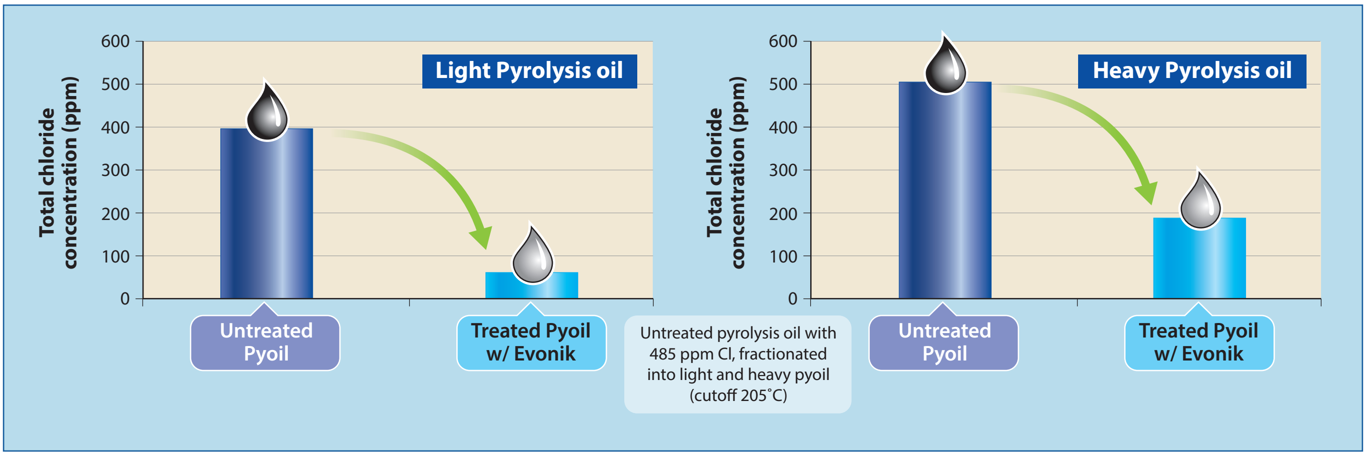

Figure 1 Treating light and heavy pyrolysis oil with Evonik's specialised adsorbent resulted in significant reduction of chlorides

Catalyst solution

Recent technological advancements, notably new and improved catalysts, have increased pyrolysis efficiency and output quality. Catalysts play a key role in both the quality and quantity of recycled plastic waste processing. Part of this movement includes catalytic pyrolysis, a process that combines pyrolysis and vapour-phase catalytic upgrading, offering lower temperature and energy requirements, higher yields, and optimised product distribution and selectivity.

For PVC, pyrolysis produces toxic, corrosive organochlorine compounds and hydrogen chloride (HCl). However, the right catalysts can be used to dechlorinate and condense these gases. To minimise HCl emissions, adsorbents or additives introduced in close contact with the plastic vapour in the reactor can assist with dichlorination through adsorption, a technique also known as in situ upgrading.

Evonik's chloride and fluoride adsorbents and hydroprocessing catalysts allow for the separation of impurities and the reduction of contamination during production. Researchers are taking industrially proven processes and adsorbents used elsewhere in the industry and applying and adapting them to plastic waste recycling processes to introduce new brands of products for purification.

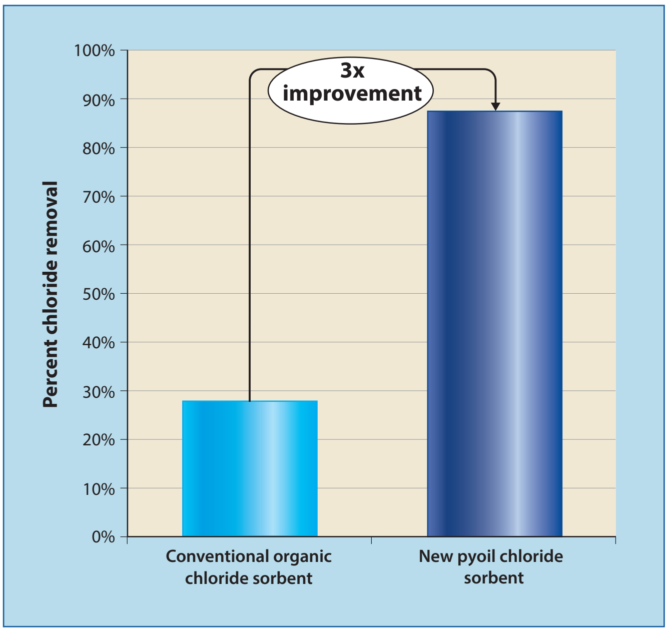

Figure 2 Evonik's specialised adsorbent demonstrates significant improvements over existing sorbents

Hydroprocessing catalysts are an important tool for contributing to refineries' sustainability goals because they can be regenerated and reused. As well as catching unwanted elements and removing contaminants, hydroprocessing also reduces olefins and aromatics, decreasing heater fouling in steam crackers, increasing yields, and helping make pyrolysis oil suitable for steam cracking.

Case study

The recent development of a new specialised adsorbent for removing organic chlorides from plastic pyrolysis oil is shown in **Figure 1**, demonstrating significant chloride reduction across the treatment of both light and heavy pyrolysis oil.

In this case study, industrially produced pyrolysis oil was distilled into a naphtha (light) and residual (heavy) fraction with a cut-off point of 400°F (200°C). Chloride concentration decreased by 300 parts per million (ppm) across both oils, with removal efficiency higher for the naphtha fraction. These specialised adsorbents have also demonstrated three times higher chloride removal than conventional organic chloride sorbents (see **Figure 2**).

The brand's alkoxide catalysts and process technologies also enable the recycling of PET and coloured PET plastics, which are not suitable for mechanical recycling, at the end of their lifecycle.

Partnership and circular economy success

The management of plastic waste is clearly siloed, with mandates of usage and recycling differing between regions and countries. Businesses and industries are also having to adhere to stricter, although not uniform, emission rules, creating more confusion. Simultaneously, downstream brands and retailers are finding themselves increasingly subject to consumer pressure for more sustainable products; eco-friendly producers are growing more rapidly in the marketplace than other incumbents.

Part of the reason the management of this problem is so varied internationally is due to the high economic cost of plastic waste and the complexity that collecting, sorting, and cleaning said waste presents. According to McKinsey, $50 billion may be needed by 2030 to support the scale-up of plastic recycling investments. One-third will be dedicated to feedstock sourcing and preparation, while the remainder will go towards building out mechanical and advanced recycling capacity. To achieve 20-30% recycling content for plastic packaging globally, the estimated figure is $100 billion, spanning collection, sorting, and mechanical and advanced recycling technology.[1]

As such, more collaboration is vital from catalyst providers, refineries, plastic manufacturers, recycling facilities, and government and regulatory bodies. Such partnerships are important tools to de-risk the journey and could include buy-sell agreements for intermediates (including pyrolysis oil), new ventures to sort feedstock (plastics recovery facilities), and upstream investment by waste management companies. Additionally, government intervention and incentives can help reshape the industry, similar to what originally sustained the growth of fossil fuel feedstocks.

Positive momentum is already being seen. Upstream firms are investing in supplementary infrastructure for pyrolysis, a confirmation of their confidence. In February 2024, it was reported that 16 10 kta pyrolysis units were scheduled to come online in Europe in 2024 and 2025.

Conclusion

The urgency to find a solution for plastic waste increases alongside rising plastic consumption. The research supports shifting to a circular economy, suggesting that doing so could reduce the volume of plastics entering oceans by 80% by 2040, and greenhouse gas emissions by 25%. From an economic standpoint, a circular economy could save governments $70 billion by 2040, create 700,000 additional jobs, and represent a revenue opportunity of more than $1 trillion in Europe alone in 2050.

As an innovative and forward-looking solution, pyrolysis holds significant promise, and a greater adoption rate will benefit from economies of scale. It is estimated that by 2040, chemical recycling technologies will experience an average cost reduction of 37.5%, and by 2033, pyrolysis could reach positive net earnings. The costs for virgin plastics production are expected to increase substantially, by up to 71%. This estimate is driven in part by increased fossil fuel prices, making a method like pyrolysis a necessity.

By integrating knowledge across the entire value chain, the supply of pyrolysis oil feedstock and the demand for recycled materials can expand, diversifying and de-fossilising the pool of raw materials available to refineries. The important role that chemical recycling, particularly pyrolysis, plays in delivering a circular plastics economy cannot be denied.

Reference

1 McKinsey & Company, August 16, 2023, A unique moment in time: Scaling plastics circularity. www.mckinsey.com/industries/chemicals/our-insights/a-unique-moment-in-time-scaling-plastics-circularity

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