Plastic to Oil: 
Saudi Arabia and Global Perspectives

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Key Points

The use of plastic is attractive for almost every industry, as its ability to change and adapt its shape adjusts to almost any industrial need. However, the attractive characteristics of plastic in several industries have come at a price: waste plastic disposal.

According to the “OECD Global Plastic Outlook” published in 2022, global plastic waste production increased by more than 2.25 times between 2000 and 2019 to 353.3 million tons (MMT). Unfortunately, only 9% of this waste is recycled (OECD 2022a).

The Kingdom of Saudi Arabia produces approximately 53 MMT of garbage annually (Hersey 2022), 95% of which ends up in landfills. The Kingdom’s recycling capacity between the start of 2020 and the first half of 2021 covered only 5% of its total waste, including plastic, metal, and paper (Hersey 2022).

The potential of oil production from plastic at a global level is slightly more than 1% of the total current global oil production (1.2 million barrels per day (MMb/d) based on 2019 results). However, that potential assumes that all waste plastic is used to produce oil liquids. A more accurate estimation is that only 200 thousand barrels per day (Kb/d) can currently be produced. However, by 2060, the plastic-to-oil potential could reach 4 MMb/d.

The oil production potential through plastic pyrolysis technology in the Kingdom of Saudi Arabia is only 12.33 Kb/d, with the possibility of reaching 124.31 Kb/d by 2060. This level is very low compared to the total oil production capacity of the country of approximately 12 MMb/d, which is planned to increase even further in the future.

It might be helpful to emphasize that plastics-to-oil technology will be operated as a plastic waste management solution and not as an oil production alternative.
Summary

Today, it is impossible to imagine life without plastics due to their flexible characteristics. However, the attractive characteristics of plastic in several industries are generating another global problem: waste plastic disposal. According to the “OECD Global Plastic Outlook” published in 2022, global plastic waste production increased by more than 2.25 times between 2000 and 2019 to 353.3 million tons (MMT). However, only 9% of that plastic waste is recycled.

The potential of technologies to convert plastic has been presented as one of the options for solving the waste plastic disposal problem. These technologies offer profitable solutions to waste plastic management, generating monetary motivation for recycling activities. However, the current amount of plastic recycled globally is still insignificant compared to the total amount of plastic waste produced, representing one of the most critical challenges to using plastic for energy generation.

In Saudi Arabia, approximately 53 MMT of garbage is produced annually (Hersey 2022), of which 95% ends up in landfills. The Kingdom’s recycling between the start of 2020 and the first half of 2021 was only 5% of its total waste, including plastic, metal, and paper (Darley 2021). However, the Saudi Arabian government, as part of its Vision 2030, is determined to change this situation in favor of a “circular economy” based on zero waste. By 2035, the Kingdom aims to treat more than 106 MMT of waste, with 42% recycling capacity and 19% dedicated to burning/energy generation (MWAN 2022).

Plastic-to-oil pyrolysis has emerged as an alternative technology for improving waste plastic management. Cataloged as technology readiness level (TRL) 9, plastic-to-oil technology consists of the thermal degradation of organic materials—in this case, plastic—in an inert atmosphere. In other words, plastic’s long-carbon chains are thermally broken into fuels. The resulting products can be changed from solid components, such as char, to gaseous fuels. The breakdown depends on temperature (Fulgencio-Medrano et al. 2022).

The volume of oil liquid yield depends on the type of plastic used, ranging from 30% to 95%. In other words, 10 tons of plastic can produce 3 to 9.5 tons of fuel. However, this technology faces several challenges that must be solved to increase its popularity. Some of these challenges are as follows:

- The quantity and quality of pyrolysis products depend on the ability to control operational conditions, resulting in an expensive process.
- The higher efficiency and selectivity of catalytic pyrolysis processes need more comprehensive adoption for fluidized bed reactors.
- Some of the side products of plastic pyrolysis are known toxic air pollutants with a potentially harmful effect on human health and the environment and thus must be treated.
- The combination of the high energy intensity of pyrolysis and the need for catalyst acquisition, maintenance, and replacement limits the commercial viability and environmental benefits.
- It is challenging to evaluate the production outlooks of these products in the face of the uncertain generation/availability of plastic waste as feedstock for the process.
- Currently, there is no consensus on the greenhouse gas emissions benefits of pyrolysis oil production, considering that a life-cycle assessment (LCA) is needed to account for the emissions impacts of the processing steps and the utilities applied to the operations.
As the world counts on enough conventional sources to produce oil, this technology competes with conventional oil production, which offers more attractive profits to investors.

The type of fuel obtained depends on the kind of plastic, the primary use of that plastic, and the recycling options for plastics. For example, plastics used for water bottles (polyethylene) can be recycled to produce pillows and sleeping bags, and shopping bags can be used for recycling bins. Therefore, most high-quality plastics can be reused as plastic, reducing the amount of high-quality plastic available to produce oil liquids. However, even if all high-quality plastic waste were used for the conversion to fuels, the resulting product from pyrolysis still contains the contaminants present in the original plastic waste, making further treatment necessary before the fuel/oil can be used.

Considering these challenges and based on previous experiences, we chose a conservative conversion rate for plastic to oil of 70%. Based on this conversion factor, the potential oil produced from plastic at a global level is slightly more than 1% of the total global oil current production (1.2 million barrels per day (MMb/d) based on 2019 results). However, that potential assumes that all waste plastic is used in oil production. A more accurate estimation is that only 200 thousand barrels per day (Kb/d) can currently be produced. However, by 2060, the plastic-to-oil potential could reach 4 MMb/d.

For Saudi Arabia, the potential presents similar limitations. Today, oil production through plastic pyrolysis in the Kingdom is only 12.33 Kb/d, with the possibility of reaching 124.31 Kb/d by 2060. Very low compared to the total oil production capacity of the country of approximately 12 MMb/d, which is planned to increase even further in the future.

Plastic waste conversion to fuels is among the solutions to incentivize better plastic waste management by redirecting plastic disposal to extract the embodied energy in plastic materials. It might be helpful to emphasize that plastics-to-oil technology aims to run as one of the plastic waste management solutions and not as an oil production alternative.
Introduction

Today, it is impossible to imagine life without plastics. Based on synthetic organic polymers, plastic has the ability to change and adapt its shape, offering many opportunities for making bottles, clothing, packaging, medical supplies, electronic goods, construction material, toys, etc. However, the attractive characteristics of plastic in several industries have come at a price: waste plastic disposal. The packaging industry, for example, uses a product only once before disposal, resulting in a significant amount of plastic waste. Additionally, the slow decomposition of plastic waste generates toxic environments in human occupational and residential environments (Alabi et al. 2019). Thus, there is an urgent need to act properly to reduce the amount of plastic in human environments.

According to the “OECD Global Plastic Outlook” published in 2022, global plastic waste production increased by more than 2.25 times between 2000 and 2019 to 353.3 MMT. Unfortunately, only 9% of this waste is recycled. The bulk of plastic waste ends up in landfills, is incinerated, or leaks into the environment (OECD 2022a).

The Kingdom of Saudi Arabia produces approximately 53 MMT of garbage annually (Hersey 2022), of which 95% ends up in landfills. What is not buried often ends up on city streets as discarded plastic bags, food containers, bottles, cans, and other forms. The Kingdom’s recycling capacity between the start of 2020 and the first half of 2021 reached only 5% of its total waste, including plastic, metal, and paper (Hersey 2022).

Under all these considerations and as part of the initiative of KAPSARC to promote the circularity of plastics by reducing plastic waste in the environment, this report analyzes the potential of technologies to convert plastic to oil at the global level and in Saudi Arabia. After presenting the waste plastic situation and future perspectives worldwide and in Saudi Arabia, the report briefly discusses plastic-to-oil technology. It then summarizes the challenges this technology faces, highlighting energy intensity, capital cost intensity, and environmental impacts.

The potential oil production from plastic at a global level is slightly more than 1% of the total global oil current production (1.2 MMb/d based on 2019 results). However, that potential assumes that all waste plastic is used in the production of oil. A more reasonable estimation is that only 200 Kb/d can currently be produced. However, by 2060, the plastic-to-oil potential could reach 4 MMb/d.

For Saudi Arabia, the potential presents similar limitations. Today, oil production through plastic pyrolysis in the Kingdom is only 12.33 Kb/d, with the possibility of reaching 124.31 Kb/d by 2060. This level is very low compared to the total oil production capacity of the country of approximately 12 MMb/d, which is planned to increase even further in the future.

Finally, the report closes with a section of final findings and comments, highlighting that despite the limited potential of oil production through plastic pyrolysis compared to the total oil production globally and in Saudi Arabia, this technology has several other advantages in addition to merely generating oil. The most relevant point supporting this technology is the possibility of generating a profitable market for recycled plastic waste, a condition that would accelerate the recycling process in many places around the world. In addition, benefits to humans and other living beings are implicit in having less plastic waste in the environment.
Current Situation of Plastic Management in the World and Saudi Arabia

Today, it is impossible to imagine life without plastics. Based on synthetic organic polymers, plastic has a malleability that offers many opportunities for bottles, clothing, packaging, medical supplies, electronic goods, construction material, toys, etc. However, the attractive characteristics of plastic in several industries are generating another global problem: waste plastic disposal. Some industries, such as the packaging industry, use a product only once before disposal, resulting in a significant amount of plastic waste.

According to the “OECD Global Plastic Outlook” published in 2022, global plastic waste production increased by more than 2.25 times between 2000 and 2019 to 353.3 MMT. However, only 9% of that plastic waste is recycled. The bulk of plastic waste ends up in landfills, is incinerated, or leaks into the environment in different ways, such as in streets, rivers, and seas (OECD 2022b).

While no official numbers are available, there is a consensus that the impact of the COVID-19 pandemic on the use of plastic has been significant. Experts estimate that an additional 3.5 MMT of plastic waste was created just from the use of masks in a single year (Drahl 2022), without counting the extra plastic used in the health or food delivery industry or other activities that started using plastic in preventive measures (Recycle Coach 2022). Based on this assumption, it is possible to estimate that 2020, 2021 and 2022 plastic waste volumes increased.

Several decades of plastic pollution due to indiscriminate disposal in the environment is one of the significant environmental burdens of modern times. Several studies have confirmed that in addition to damage to the aquatic environment, the breakdown of plastics also generates toxic substances in human occupational and residential environments (Alabi et al. 2019). As most plastic waste is deposited in landfills (Figure 1), the risk

Figure 1. Global plastic waste produced in 2019 by end-of-life fate (MMT).

Source: OECD (2022a).
to human communities is high unless we find new ways to use or reuse plastic.

The U.S. is the world's largest producer of plastic waste, with more than 72.84 MMT of plastic waste produced in 2019, or 20.62% of the total world production, followed by China with 18.52%. At the same time, the U.S. has the lowest recycling percentage, with only 4% of its plastic waste being recycled. Even OECD Europe, which has the highest plastic recycling index globally, recycles only 14% of its plastic waste. The Middle East and North Africa (MENA) stand at 5% (Figure 2).

To increase the reuse of plastic, waste managers are promoting policies and actions that will help improve recycling intensity. At the same time, extensive campaigns to reduce and remove the use of single-use plastics are being implemented. The EU, Canada, some U.S. cities, India, China, and many

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Figure 2. Global plastic waste produced in 2019 by end-of-life fate (percentage).

Source: OECD (2022a).
other regions have banned or are currently banning single-use plastics (Masterson 2020; PIB 2022).

In any case, the current amount of plastic recycled globally is still insignificant compared to the total amount of plastic waste produced, marking one of the most critical challenges to using plastic for energy generation.

As shown above, plastic waste management has become a global problem. Despite initiatives worldwide to reduce the amount of plastic waste released into the environment, the amount of recycled plastic remains small. There are several ways to incentivize people to recycle more, but one method has been shown to be the most effective, especially in developing regions. The concept of the plastic bank, or plastic for money, is one of the most attractive methods for increasing plastic recycling (Karz 2019). The plastic bank, or plastic for money, consists of offering people financial compensation for recycling. However, this initiative relies on donors and/or other ways to sustain money flows for plastic to help maintain the idea in the long term. Among other proposed solutions, plastic to energy, specifically plastic to oil, is one of the solutions offered by new technologies, especially if oil prices can cover production costs.
Plastic consumption is linked to almost every human activity. Communities with growing economies and increasing populations have corresponding faster growth in plastic waste generation, as is the case in the five Gulf Cooperation Council countries—Bahrain, Saudi Arabia, the UAE, Qatar, and Kuwait. These countries rank in the top 10 in terms of solid waste generation per capita (Radwan 2022).

Saudi Arabia produces approximately 53 MMT of garbage annually (Hersey 2022), of which 95% ends up in landfills. What is not buried often ends up on city streets in the form of discarded plastic bags, food containers, bottles, etc. The Kingdom’s recycling between the start of 2020 and the first half of 2021 was only 5% of its total waste, including plastic, metal, and paper (Darley 2021).

Nearly half of the total waste comes from three major cities: 21% from Riyadh, 14% from Jeddah, and 8% from Dammam.

However, the Saudi Arabian government, as part of its Vision 2030, is determined to change this situation in favor of a “circular economy” based on zero waste. A key agent in this transition is the Saudi Investment Recycling Company (SIRC), established by royal decree in 2017 as a wholly owned subsidiary of the Public Investment Fund.

The SIRC will play a key role in achieving the goal of treating more than 106 MMT of waste by 2035, according to Saudi Arabia’s National Center for Waste Management, with 42% recycling capacity and 19% dedicated to burning/energy generation (MWAN 2022).

**Figure 3.** Saudi total waste volume is 53 MMT per year.

Note: Others include WEEE, lubricants, used cooking oil, batteries, ELV & trees. **Source:** (Darley 2021).
A report recently published by Expert Market Research (EMR), a U.S.-based consulting firm, estimates that Saudi Arabia recycled 1.6 MMT of plastic in 2021 and has the potential to reach 2.7 MMT by 2027, increasing at a compound annual growth rate (CAGR) of 5.9% between 2022 and 2027 (EMR 2022). The EMR report is more optimistic than the estimations presented by ChemAnalyst, a subsidiary of Techsci Research, in its report “Saudi Arabia Plastic Recycling Market Analysis” published in August 2021 (ChemAnalyst 2021). In this report, ChemAnalyst considers that Saudi Arabia will be capable of recycling 2.67 MMT of plastic by 2030, increasing at a CAGR of 5.79% between 2020 and 2030.

Despite current limitations on plastic recycling activities in Saudi Arabia, the Kingdom’s potential to use plastic for energy is significant. The forecasts presented in the previous paragraph could easily be exceeded if there is concerted support for the existing waste management program.
Plastic-to-Oil Technology

The world is continually seeking technologies that could help reduce the amount of plastic waste. Ideas such as the use of nanocellulose to accelerate the biodegradation of polymers or genetic techniques to increase the production of bioproducts that could replace plastic have emerged. However, those technologies are all in a natal stage of development, and the amount of accumulated plastic is already critical (Mohanti 2021). However, one already existing technology offers, to a point, a solution to plastic waste in the environment, that is, the process of transforming plastic to oil.

Plastic-to-oil pyrolysis, cataloged as TRL 9, consists of the thermal degradation of organic materials—in this case, plastic—in an inert atmosphere. In other words, the long-carbon chains of plastic are thermally broken into fuels. The resulting products can be changed from solid components, such as char, to gaseous fuels. The breakdown depends on temperature (Fulgencio-Medrano et al. 2022).

The main target of the conversion is to obtain final fuel products, such as gasoline and diesel. The chemical complex can be completed with a catalytic reactor and a fractionating tower (Figure 4). Currently, several petrochemical providers are offering these technologies. Many oil companies are also showing interest in this technology, including SABIC, which is among the world’s largest petrochemical manufacturers worldwide and has confirmed the production of certified circular polymers using feedstock from mixed plastic waste (SABIC 2019).

The oil yield ranges from 30% to 95% depending, among other factors, on the type of plastic used to produce fuel. In other words, 10 tons of plastic can produce 3 to 9.5 tons of fuel. A Chinese-based company, Doing Holdings Co., has confirmed on its website that its technology can recover 9.5 tons of fuel from 10 tons of plastic if the base is polythene plastic or 90% from polypropylene (DOING Holdings 2020). As good as this sounds, it is not easy to believe that this conversion rate is possible outside the laboratory, as the experiences of other producers have shown (OMV Group 2018; SABIC 2019).

In Austria, the OMV Group, which is in charge of the national petrochemical complex, confirmed in 2018 that its new ReOil unit could process up to 100 kilograms of plastic per hour and obtain 100 liters of valuable crude oil (OMV Group 2018), a conversion rate of approximately 80%–85%.

In addition, a purifier unit is needed to eliminate all the contaminants that were initially part of the plastic waste raw material. The purifier unit is usually installed before the catalytic reactor. Experimental investigations of pyrolysis products have revealed a range of physical and chemical properties similar to fuel gas, gasoline, diesel, and heavy oil (Sharuddin et al. 2018). Table 1 compares some of these characteristics with those of traditionally produced gasoline and diesel from petroleum refineries.

However, the pyrolysis process has an intense heat requirement, delivered under a delicate reaction system at an operating temperature of approximately 500°C (Sharuddin et al. 2018).
Figure 4. Plastic-to-fuels process—pyrolysis by direct heating.


Table 1. Fuel properties of plastic pyrolysis oil.

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>Type of plastic (experimental typical value)</th>
<th>Commercial standard value (ASTM 1979)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PET</td>
<td>HDPE</td>
</tr>
<tr>
<td>Calorific value (MJ/kg)</td>
<td>28.2</td>
<td>40.5</td>
</tr>
<tr>
<td>API gravity @ 60°F</td>
<td>n.a.</td>
<td>27.48</td>
</tr>
<tr>
<td>Viscosity (mm²/s)</td>
<td>n.a.</td>
<td>5.08a</td>
</tr>
<tr>
<td>Density @ 15°C (g/cm³)</td>
<td>0.90</td>
<td>0.89</td>
</tr>
<tr>
<td>Ash (wt%)</td>
<td>n.a.</td>
<td>0.00</td>
</tr>
<tr>
<td>Octane number MON (min)</td>
<td>n.a.</td>
<td>85.3</td>
</tr>
<tr>
<td>Octane number RON (min)</td>
<td>n.a.</td>
<td>95.3</td>
</tr>
<tr>
<td>Pour point (°C)</td>
<td>n.a.</td>
<td>-5</td>
</tr>
<tr>
<td>Flash point (°C)</td>
<td>n.a.</td>
<td>48</td>
</tr>
<tr>
<td>Aniline point (°C)</td>
<td>n.a.</td>
<td>45</td>
</tr>
<tr>
<td>Diesel index</td>
<td>n.a.</td>
<td>31.05</td>
</tr>
</tbody>
</table>

Source: Sharuddin et al. (2018).

n.a., not available in the literature.

a Viscosity at 40°C.
b Viscosity at 30°C.
c Viscosity at 25°C.
d Viscosity at 50°C.
Technical Challenges of the Plastic-to-Oil Value Chain

The quantity and quality of pyrolysis products are dependent on maintaining controlled operational conditions, including temperature, pressure, residence time, catalyst selection, reactor design, and reaction system, resulting in expensive processes.

Pyrolysis can be performed in various kinds of reactors, such as batch, semibatch, fixed-bed, fluidized bed, or conical bed reactors. However, the higher efficiency and selectivity of catalytic pyrolysis processes (as opposed to pure thermal processes) have necessitated wider adoption and preference for fluidized bed reactors (Sharuddin, Abnisa et al. 2018).

The analysis of oil products resulting from pyrolysis from different plastic waste types indicates that they are mixtures of various compositions of aromatic and aliphatic hydrocarbons with a heating value around the range for conventional diesel (Miandad, Rehan et al. 2019), implying that pyrolysis oil can serve as a substitute for conventional diesel. The reaction products, comprising the main products of the process (pyrolysis oil), along with other side products and impurities must undergo refining (fractional distillation) to separate the desired products from the others. Some of the side products of plastic pyrolysis are known toxic air pollutants with potential harmful effects on human health and the environment. They therefore must be treated to regulated standards before effluent release.

The combination of the high energy intensity of pyrolysis and the need for catalyst acquisition, maintenance, and replacement limits the commercial viability and environmental benefits of this pathway to fuel production. Additionally, significant capital investment is needed to acquire the reactor and fractionators for a pyrolysis plant.

Furthermore, considering the variability of pyrolysis oil yields for different plastic waste types and combinations thereof, it can be challenging to evaluate the production outlooks for these products in the face of the uncertain generation/availability of plastic waste as feedstock for the process.

Currently, there is no consensus on the greenhouse gas emissions benefits of pyrolysis oil production, considering that an LCA is needed to account for the emissions impacts of the processing steps and the utilities applied to the operations. An LCA of waste plastic pyrolysis will ascertain the actual environmental impacts of the process through detailed material and energy flow accounting based on supply chain activities such as input material extraction and processing and product production, distribution, use and end-of-life applications (Miandad, Rehan et al. 2019).

Consequently, if the energy sources used in the process are not GHG-free, pyrolysis might prevent the leakage of plastic wastes into the environment while exacerbating the release of global warming gases into the atmosphere (Inman 2012). From the relative economic and environmental performance perspectives, it must be demonstrated that the plastic waste-to-pyrolysis oil (diesel) production pathway can outperform other established larger-scale commercial production pathways, such as conventional diesel, biodiesel, and renewable diesel pathways.

Additionally, similar to every emerging technology, converting plastic to oil is significantly more expensive than producing oil from conventional sources. As the world counts on enough conventional sources to produce oil, this technology competes with conventional oil production, which offers much more attractive profits to investors.
Supply Chain Challenges of the Plastic-to-Oil Value Chain

The discussion in the previous sections reflects the challenges still faced by the process of converting plastic into oil. In addition to the chemical process, this technology relies on other factors, such as the purity of the recycled plastic, impurities in the waste plastic, volume, and economics. In general, plastic waste is a mixture of different polymers, such as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET), with traces of polyamide (PA), polyurethane (PUR), poly(methyl methacrylate) (PMMA) and others and further containing numerous additives and auxiliary materials (Kusenberg et al. 2021). Most of these plastics can be reused in their original form or remanufactured for different functions.

Depending on the type of plastic, Table 2 provides an idea of the primary uses and recycling options for plastics. For example, plastics used for water bottles (polyethylene) can be reused to produce pillows and sleeping bags, and shopping bags can be used for recycling bins.

### Table 2. Recyclable plastic materials.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Type of plastic</th>
<th>Common uses</th>
<th>Recycled in</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Polyethylene Terephthalate</td>
<td>Soft drink &amp; Water bottles, Salad domes, Biscuit trays, Salad dressing containers</td>
<td>Pillow &amp; Sleeping bag filling, Clothing, Soft drink bottles, Carpeting, Building insulation</td>
</tr>
<tr>
<td>2</td>
<td>High-density Polyethylene</td>
<td>Shopping bags, Freezer bags, Milk bottles, Ice cream containers, Juice bottles, Shampoo, Chemical &amp; Detergent bottles, Buckets, Rigid agricultural pipe, Crates</td>
<td>Recycling bins, Compost bins, Buckets, Detergent containers, Posts, Fencing, Pipes, Plastic timber</td>
</tr>
<tr>
<td>3</td>
<td>Unplasticized Polyvinyl Chloride PVC-U</td>
<td>Cosmetic containers, Electrical conduits, Plumbing pipes &amp; Fittings, Blister packs, Wall cladding, Roof sheeting, Bottles</td>
<td>Flooring, Film &amp; Sheets, Cables, Speed bumps, Packaging, Binders, Mud flaps &amp; Mats, Gumboots &amp; Shoes</td>
</tr>
<tr>
<td>3</td>
<td>Plasticized Polyvinyl Chloride PVC-P</td>
<td>Garden hoses, Shoe soles, Cable sheathing, Blood bags &amp; Tubing</td>
<td>Flooring, Film &amp; Sheets, Cables, Speed bumps, Packaging, Binders, Mud flaps &amp; Mats, Gumboots &amp; Shoes</td>
</tr>
<tr>
<td>4</td>
<td>Low-Density Polyethylene</td>
<td>Cling wrap, Garbage bags, Squeeze bottles, Irrigation tubing, Mulch film, Refuse bags</td>
<td>Bin liners, Pallet sheets</td>
</tr>
<tr>
<td>5</td>
<td>Polypropylene</td>
<td>Bottles &amp; Ice cream tubs, Potato chip bags, Straws, Microwave dishes, Kettles, Garden furniture, Lunch boxes, Packaging tape</td>
<td>Pegs, Bins, Pipes, Pallet sheets, Oil funnels, Car battery cases, Trays</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>CD cases, Plastic cutlery, Imitation glassware, Low-Cost brittle toys, Video cases</td>
<td>Coat hangers, Coasters, White ware components, Stationery trays &amp; Accessories, Picture frames, Seed trays, Building products</td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>--------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Expanded Polystyrene</td>
<td>Foamed polystyrene cups, Takeaway clamshells, Foamed meat trays, Protective packaging, Building &amp; Food insulation</td>
<td>Coat hangers, Coasters, White ware components, Stationery trays &amp; Accessories, Picture frames, Seed trays, Building products</td>
<td></td>
</tr>
<tr>
<td>Letters below indicate ISO code for plastic types: e.g., SAN, ABS, PC, Nylon</td>
<td>Automotive &amp; Appliance components, Computers, Electronics, Cooler bottles, Packaging</td>
<td>Automotive components, Plastic timber</td>
<td></td>
</tr>
</tbody>
</table>

Source: AAA Polymer (2022).

Therefore, most high-quality plastics can be reused as plastics, reducing the availability of high-quality plastics for conversion to oil. However, even if all high-quality plastics were used for conversion to fuels, the resulting product from pyrolysis still contains the contaminants present in the original plastic waste, making further treatment necessary before the fuel/oil can be used. Many different chemical treatment options for plastic waste pyrolysis products are under development.

In summary, challenges occur in the following three main categories (Baranski 2021):

1. **A source of pollution.** As mentioned before, the pyrolysis process to convert plastic waste to oil results in synthetic fuel containing contaminants that can produce corrosion. The pollution content was demonstrated by Kalargaris, Tian, and Gu (2017) during a diesel machine test with synthetic oil from plastic. The authors tested a diesel engine using a blend of 75% plastic product oil (PPO) and 25% diesel (Kalargaris, Tian, and Gu 2017) and found that plastic product oil produced higher exhaust emissions than diesel. In addition, fuel oils extracted using higher temperatures in the pyrolysis process had higher emissions than those produced using low temperatures. A solution to this challenge is the introduction of a purifier unit.

2. **Technical breach.** As mentioned before, technologies that convert plastic to oil are relatively new. Methods and processes are still under development, and there is a need for further study in many fields before this technology becomes commercially profitable on a large scale. The cases presented herein are pilot projects with good results under controlled (laboratory) circumstances. Few cases have shown profitable scale results. However, it will take some time for these cases to be replicated in other regions.

3. **Sustainability.** Like every energy source, this technology relies on the sustained supply of raw material, in this case waste plastic. As we highlighted in the section “Current situation of plastic management in the world and Saudi Arabia,” we have yet to attain a sustained, well-organized recycling system. Even in the most advanced economies, recycling is still
far from optimal. Under those considerations and given that pyrolysis products depend on the quantity and quality of the raw product, investors and project developers cannot confirm a permanent supply of good-quality plastic waste for pyrolysis plants, reducing the investment attractiveness of this kind of project. Additionally, energy recovery through plastic pyrolysis could undermine other solid waste management practices and other waste-to-energy processes, such as waste incineration or waste-to-energy incineration. Including pyrolysis in an integrated solid waste management strategy would require careful planning and implementation of appropriate policies and regulations.

Another external challenge that the industry faces is the lack of established technology suppliers. As the technology is relatively new, there are very few suppliers of proper pyrolysis systems that convert plastic to oil. However, many companies offer technology solutions and high recovery performance. Systems that are not well designed have the potential to generate significant air and soil pollution, resulting in problems for the hosting community. The technology supplier must count on all available accreditations to avoid possible risks to the community. A community is at risk of dangerous fumes or leakage of toxic lixiviates, among other dangers, if inappropriate pyrolysis technology is installed (DOING Holdings 2019).
Worldwide Potential

As mentioned earlier, several successful pilot programs have already applied the pyrolysis technique for converting plastic to oil. Most of them are in regions with advanced recycling options. Examples such as the OMV Group (OMV Group 2018) in Austria and Quantafuel (Ministry of Foreign Affairs of Denmark 2020) in Norway have confirmed that the pyrolysis process for converting plastic-to-oil products is possible under the proper conditions. The process is completed with purification and catalyst units that eliminate most contaminants from the synthetic fuel.

The OMV Group corroborated in 2018 that its ReOil unit could process up to 100 kilograms of plastic per hour and obtain 100 liters of valuable crude oil, a conversion rate of approximately 80%–85%. Quantafuel also asseverated in 2020 that it could produce 15 million liters of low-carbon diesel and other synthetic oil products annually from 19,000 tons of plastic waste, or close to a 79% conversion rate. Quantafuel also claimed that after the purification and catalyst process, the production of its synthetic products emitted 90% less CO2 than the production of traditional fuels. At the same time, the pure synthetic fuel emitted less NOx, SOx, and particles through the exhaust gases than ordinary fuel.

Based on those experiences, it is safe to say that a conservative conversion rate for plastic to oil is 70%. The results of the OECD global plastic outlook (OECD 2022a) indicate that the total plastic waste production by 2060 could reach more than 1 billion tons per year (Figure 5). Of that plastic, 50% will go to the landfill and only 17% will be recycled, corresponding to 176 MMT of plastic annually. Another 179 MMT will be incinerated in 2060, far beyond the 67 MMT incinerated in 2019.

To check the total global potential of plastic-to-oil technologies, we assume that all recycled and incinerated plastic waste is transformed into synthetic products with a 70% conversion rate. Under that assumption, by 2060, the total potential of synthetic oil products from plastic could reach 4.28 MMboe/d. Assuming that all plastic waste can be converted into oil is unrealistic. However, just for comparative purposes, assuming that all plastic waste is used for oil liquid production, the potential is 4.58 MMboe/d in 2022 and could reach as high as 12.23 MMboe/d by 2060 under the current technology (Figure 6).

A more reasonable assumption is that half of the projected recycled plastic waste will be redirected to oil production. Then, the amount of oil produced from plastic could reach only 1 MMboe/d. The results of the analysis under different assumptions are summarized in Figure 6. The potential of oil from plastics by 2060 would be between 1 and 4 MMboe/d. Technological developments may increase this potential. However, assessing how far the technology can go in the long term is complex, and it is impossible to assess how far those developments will go or fast they will be.
Figure 5. Plastic waste production outlook (MMT).

Source: OECD (2022a).
Figure 6. The global potential for converting plastic to oil based on end-of-life fate (MMboe/d).

Source: KAPSARC based on OECD (2022a).
The Potential of Saudi Arabia

In the previous sections, we highlighted the findings published by EMR and ChemAnalyst, which estimated that the amount of recycled plastic for Saudi Arabia will reach 2.7 MMT by 2027 (EMR 2022) and 2.67 MMT by 2030 (ChemAnalyst 2021), respectively. Both cases are significantly more optimistic than the values presented in the OECD Global Plastics Outlook (2022), which estimated that the MENA region will recycle only 1.55 MMT by 2030 (OECD 2022a).

As OECD estimations are far below those of the two specialized reports, we can assume that those numbers are underestimated, as MENA plastic recycling activities will improve significantly. In any case, according to our estimations, given the low recycling capacity of Saudi Arabia, the current capacity for synthetic fuel production from plastics in the Kingdom is approximately 20 Kboe/d, with the potential to reach almost 125 Kboe/d in 2060. By 2040, that potential could reach 67.5 Kb/d (Figure 7).

It is essential to consider that the potential assessment developed for this report is based on current technologies. Further technology development as well as economies of scale may improve the synthetic oil yields per kilogram of plastic, increasing the potential by up to an additional 43%.

Figure 7. The potential of Saudi Arabia for plastic-to-oil conversion based on end-of-life fate (Kboe/d)—results based on different sources.

Source: KAPSARC based on OECD (2022a), ChemAnalyst (2021), and EMR (2022).
Plastic producers have found useful applications in virtually every product we use daily, from automobile parts to telephones and computers. The reason is the ease of fashioning plastic materials into various desirable forms and shapes and their low cost relative to other materials used for similar applications. However, plastic waste has become a challenge of global proportions.

Plastic waste conversion to fuels is among the ways to incentivize better plastic waste management by redirecting plastic disposal to extract the embodied energy from plastic materials. Plastic-to-oil conversion faces challenges in achieving large-scale adoption. These technologies are currently not cost-competitive in comparison to conventional production methods for the same fuels. Their cost intensity stems from the high energy requirements of pyrolysis technology. The energy intensity calls for the use of catalysts that are mainly composed of expensive rare-earth materials. There is also a need for special reactor materials and designs to manage the specific requirements of the process.

Moreover, opponents of plastic-to-oil technologies have argued that they exchange plastic pollution for toxic air pollutants and higher GHG emissions. It has been argued that there is no net positive energy balance in the plastic-to-oil life cycle. Since the fuels produced from the process are ultimately combusted, the technology does not offer a closed-loop, circular economy for plastic waste management. In addition to the uncertainty of the plastic feedstock supply for fuel production, the total estimated potential fuel production from plastic wastes is limited to approximately 4.58 MMboe/d currently and 12.23 MMboe/d by 2060, assuming that all plastic waste produced is used in oil liquid production.

Furthermore, under the EU Waste Framework Directive, plastic-to-fuel processes are not considered recycling processes. Essentially, instead of producing fuels for dispersed mobile combustion systems, some have proposed plastic-to-energy conversion for electric power generation, which results in a stationary emission source that can be better managed with emerging carbon capture and storage technologies.

On the other hand, current producers of plastic-to-oil technology are working hard to solve the abovementioned issues/challenges. As they advance with their developments, there is an increasing possibility that plastic-to-oil technology will become a clean and profitable solution to the issue of plastic waste pollution worldwide. It might be helpful to emphasize that plastic-to-oil technology aims to operate as a plastic waste management solution and not as an oil production alternative.

Other avenues to effectively manage plastic waste entail improving public awareness of proper waste collection and separation, improvements in plastic material designs to optimize use and reuse, and developing better methods of waste diversion and sorting to increase recycling into new plastic products of similar or different functions.
Technology readiness levels (TRLs) are a method of estimating the maturity of technologies during the acquisition phase of a program, developed at NASA during the 1970s (Héder 2017). There are nine TRLs, with number one corresponding to the basic technology research level and nine being the system test, launch, and operations level. Plastic-to-oil conversion is at the last level, which means that it can be industrialized.
References


References


About the Authors

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Julio is an economist and civil engineer with over 20 years of experience in the energy field. His experience includes energy policy and data analysis for international organizations, governmental advisory services, and the construction of energy projects. Julio also has a passion for sustainable energy and project management, both supported by his postgraduate studies. Before joining KAPSARC, Julio worked as a senior energy consultant within different organizations. For over seven years, in his position as an energy policy analyst at OPEC, he was one of the major contributors to the OPEC World Oil Outlook (WOO). His experience in both the governmental and private sectors, in the field and office, enables him to understand the dynamics of the energy sector.

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About the Project

Plastics are a critical category in the chemicals value chain and have helped shape our modern economy. KAPSARC launched the Plastics in a Circular Economy project in 2021 to identify obstacles and opportunities to promote circularity and prevent the leakage of plastic into the environment. The KAPSARC team works with stakeholders from around the globe to focus on innovations and technologies to move from the linear approach to waste management to more sustainable options for plastics.