REPACKAGING THE PLASTIC PROBLEM

Tech-driven opportunities
in plastic packaging recycling

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White Paper

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EXECUTIVE SUMMARY

When China and other Asian countries closed their doors to exported plastic waste starting in 2018, it sent a strong message to the global community: plastic is everyone's problem—not just Asia's. These policies drove home the fact that existing measures were not enough to deal with the large volumes of plastic waste produced annually. This realisation, aided by legislation in several countries, has led to the increasing global demand for recycling solutions that deal with plastic packaging products.

Plastic packaging waste is an umbrella term that encompasses different types of plastics—some easier to recycle than others. Mechanical methods, which physically break down plastic waste, struggle to deal with more complex and contaminated packaging materials. Increasingly, governments and industries have turned to chemical recycling solutions, which break plastics down to their constituents and convert them into usable feedstocks.

To date, stakeholders in the plastic value chain have established various partnerships to improve on these technologies and facilitate recycling closer to the source. Multinational companies have been especially active in developing chemical recycling methods, creating technologies to further enhance already sophisticated techniques.

While powerful, these chemical methods are not perfect. A glimpse at the plastic recycling innovation landscape reveals high interest and developments that enable further value extraction from chemical recycling and make the technology more cost-efficient and scalable.

This white paper presents an overview of the existing and emerging technologies used to recycle plastic waste as well as their place within the plastic packaging value chain. In doing so, we hope to identify the gaps and opportunities for businesses seeking to make waves in the plastic recycling industry.

Key highlights

01
The future of recycling is domestic

The import ban implemented by Asian countries on plastic waste may have catalysed the demand for solutions that recycle plastic locally.

02
Rising demand for recycled plastic content promotes collaboration across the plastic value chain

Petrochemical producers are working with recyclers, Fast-Moving Consumer Goods (FMCG) manufacturers and other members of the value chain to create new solutions in light of increased demand for recycled plastic content.

03
Opportunities to innovate abound

Methods that can accommodate more complex and diverse kinds of plastics compared to conventional mechanical recycling are already being developed by companies across the plastic packaging value chain.

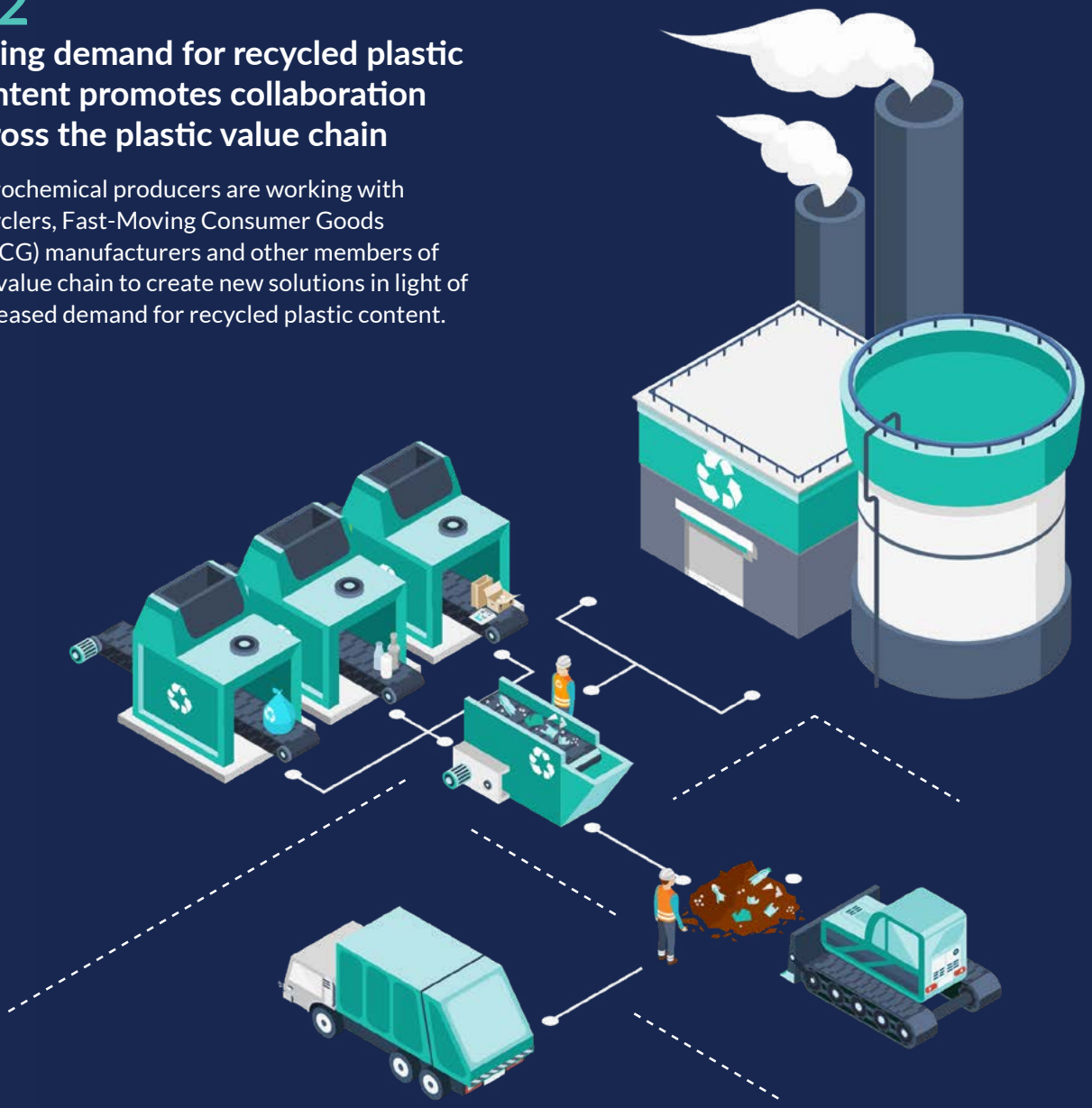


Figure 1 *A simplified waste management process.*

THE CHALLENGE OF PLASTIC RECYCLING: VOLUME, VARIETY AND VARYING REGULATIONS

When plastic was first developed in 1869, it was quickly recognised for its near-limitless potential[1]. As a synthetic polymer that could be crafted into virtually any shape, plastic was an opportunity to break free from the constraints of natural products like wood, metals, or animal horns. Nearly two centuries later, plastics have become indispensable to the global economy, with diverse industries relying on plastics to create strong, lightweight and inexpensive consumer products.

However, plastics create as many environmental problems as they solve. Since the 1950s, over 8.3 billion metric tonnes of plastic have been created. Because of their disposability, most plastic products inevitably end up as trash, where a whopping 91 percent are not recycled[2]. This amount of plastic waste has overwhelmed waste management systems and caused serious environmental harm.

Not all plastics are alike

Plastic recycling is further complicated by the fact that there are different types of plastics used in packaging, each with a unique set of characteristics. Commonly recycled varieties include polyethylene terephthalate (PET), used in beverage bottles, and high-density polyethylene (HDPE) used in cleaning

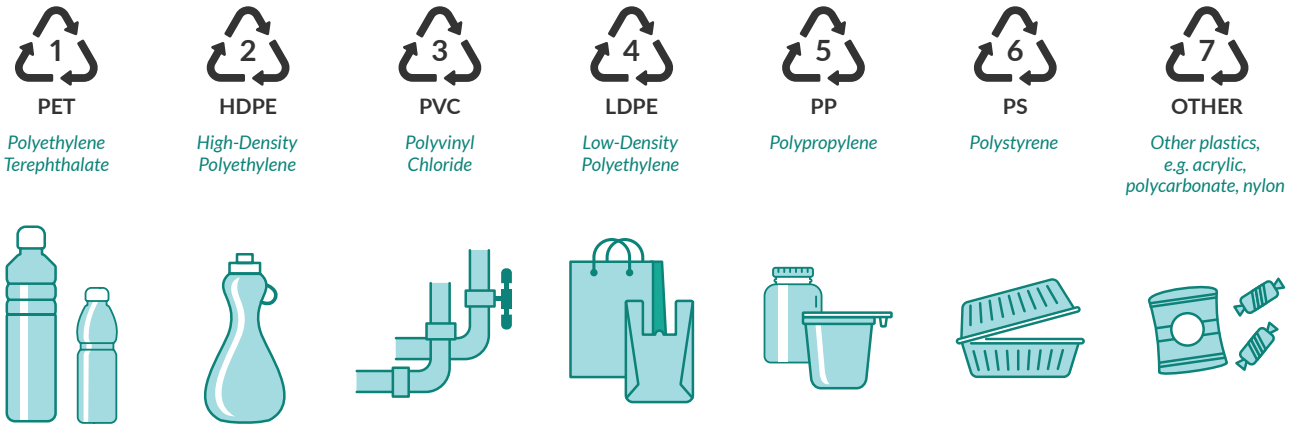


Figure 2 *Seven types of plastic materials in the market.*

[1] A brief history of plastic's conquest of the world. (2011) *Scientific American.* Retrieved on March 2021 from https://www.scientificamerican.com/article/a-brief-history-of-plastic-world-conquest/
[2] A whopping 91 percent of plastic isn't recycled. (2018) *National Geographic.* Retrieved on March 2021 from https://www.nationalgeographic.org/article/whopping-91-percent-plastic-isnt-recycled/

agent containers. These accounted for 55 percent and 33 percent, respectively, of all the plastics recycled globally in 2017[3].

Interestingly, despite their considerable market share at about 18 and 19 percent respectively, low density polyethylene (LDPE) and polypropylene (PP) are some of the hardest plastics to recycle. The former due to different melting points of its components and contamination issues, and the latter due to its resistance to heat, acids, bases and solvents commonly used in plastic recycling.

Breaking free from plastic waste

Historically, developed nations exported plastic waste to developing countries in Asia to be recycled. However more often than not, the materials cannot be recycled and can either end up in illegal processing facilities, or are discarded irresponsibly without treatment, creating risks to the environment and human health.

Consider China, which had imported most of the world's recyclable plastics for nearly three decades[5]. In 2018, it introduced Operation National Sword, a waste import ban decreasing the foreign inflow of plastic waste[6].

This measure displaced the movement of plastic waste into neighbouring countries like Malaysia and Vietnam—spurring their governments to impose import bans as well. Singapore has also restricted the export of contaminated, mixed, or non-recyclable plastic waste since October 2020, in line with the country's obligation to the Basel Convention Plastic Waste Amendments.

Globally, one of the greatest contributors to plastic waste are single-use plastics. Accordingly, countries including the US[7], Thailand[8] and Indonesia[9] have implemented bans and fees to restrict their use, with the European Union and China set to follow suit.

Given all these restrictions, there are multiple opportunities for businesses to develop innovative plastic recycling solutions that enable recycling at the source. Such solutions may address the scourge of plastic waste.

[3] CSIRO (2017). The recycled plastics market: global analysis and trends.
[4] Polyprolylene plastic can finally be recycled. (2019) Bloomberg. Retrieved on March 2021 from https://www.bloomberg.com/news/features/2019-09-25/polypropylene-plastic-can-finally-be-recycled
[5] How China's plastic waste ban forced a global recycling reckoning. (2019) National Geographic. Retrieved on March 2021 from https://www.nationalgeographic.com/magazine/article/china-plastic-waste-ban-impacting-countries-worldwide
[6] Single-use plastic: China to ban bags and other items. (2020) BBC. Retrieved on March 2021 from https://www.bbc.com/news/world-asia-china-51171491
[7] State plastic bag legislation. (2021) National Conference of State Legislatures. Retrieved on March 2021 from https://www.ncsl.org/research/environment-and-natural-resources/plastic-bag-legislation.aspx
[8] Thailand's capital bans single-use plastic bags from markets and malls. (2020) The Straits Times. Retrieved on March 2021 from https://www.channelnewsasia.com/news/asia/major-thai-stores-to-stop-giving-plastic-bags-2020-11938314
[9] Indonesia's capital bans single-use plastic bags from markets and malls. (2020) The Straits Times. Retrieved on March 2021 https://www.straitstimes.com/asia/se-asia/indonesias-capital-bans-single-use-plastic-bags-from-markets-and-malls

UNDERSTANDING THE PLASTIC VALUE CHAIN

Packaging materials make up around 60 percent of all plastic waste, with post-consumer packaging waste being particularly difficult-to-recycle due to contamination and other issues. To understand where opportunities in plastic recycling come into the picture, it is worth looking at the life cycle of such post-consumer packaging materials.

A plastic packaging product starts out at petrochemical plants or polymer producers, where raw materials like crude oil are refined using high temperatures and chemically transformed into resins called virgin plastics. They emerge from this process as cylindrical pellets, flakes or powders. These pellets are then combined with other raw materials by plastic processors, which include converters and compounders to modify physical properties for specific uses. Compounds produced from this process are re-melted and crafted into industrial and consumer packaging and products. Whatever form plastics come in, most will eventually be discarded after use.

At this point, collection and recycling begins. Collectors take what is recyclable and process them into pellets that can be reused by processing plants.

Collaborations Across the Plastic Value Chain

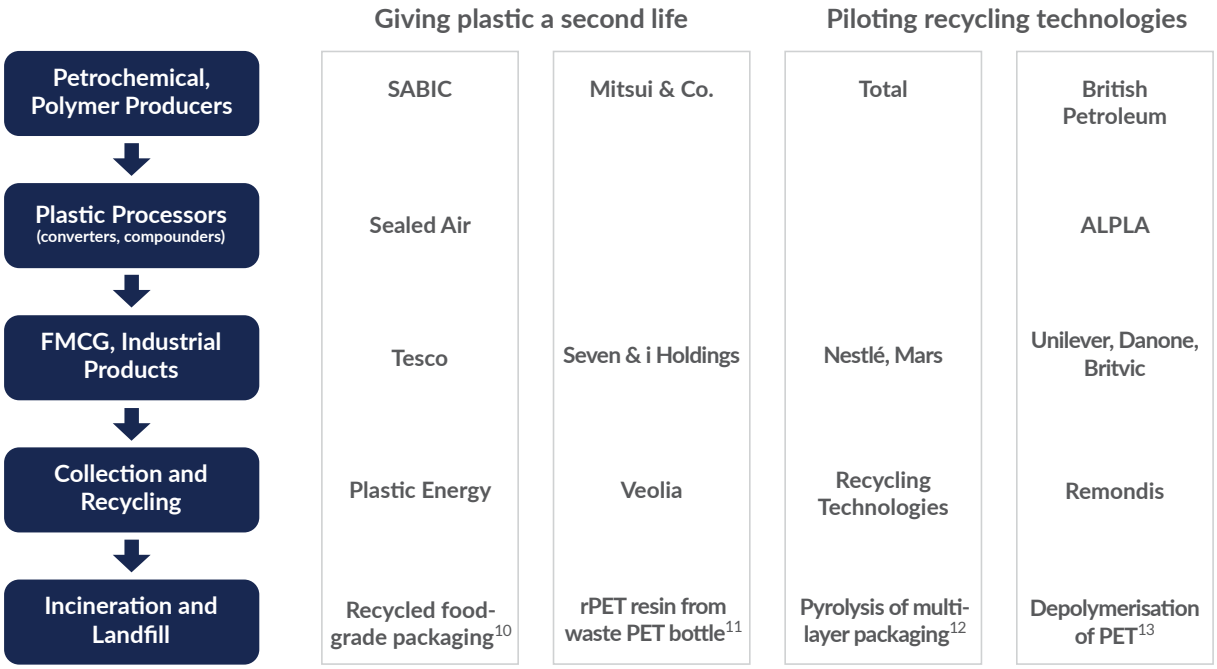


Figure 3 *Players across the plastic value chain are now collaborating to develop novel recycling technologies.*

[10] Tesco introduces the first recycled food grade soft plastic packaging from materials returned by customers (2020). Plastic Energy. Retrieved on March 2021 from https://plasticenergy.com/tesco-introduces-the-first-recycled-food-grade-soft-plastic-packaging-from-materials-returned-by-customers/

[11] 7-Eleven and Mitsui join to recycle 'low-quality' plastic bottles. (2020) Nikkei Asia. Retrieved on March 2021 from https://asia.nikkei.com/Spotlight/Environment/7-Eleven-and-Mitsui-join-to-recycle-low-quality-plastic-bottles

[12] Chemical recycling. (2021) Recycling Technologies. Retrieved on March 2021 from https://recyclingtechnologies.co.uk/technology/

[13] BP's new technology to enable circularity for unrecyclable PET plastic waste. (2019) BP. Retrieved on March 2021 from https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-new-technology-to-enable-circularity-for-unrecyclable-pet-plastic-waste.html

In the context of Singapore, materials deemed unfit for recycling go to waste-to-energy plants, where they are incinerated to produce electricity. Ashes produced by these incinerators are finally disposed in landfills. From cradle to grave, greenhouse gas emissions of plastics are set to reach 1.34 gigatonnes (Gt) each year by 2030—with accumulative emissions exceeding 56 Gt by 2050[14].

Collaborations across the value chain

In light of the growing demand for recycled plastics, players across the value chain are pledging to use more recycled material and develop new recycling technologies. Nestlé, for instance, has pledged to use 35 percent recycled PET in its bottles by 2025[15] while Coca-Cola has committed to using 50 percent recycled PET in their plastic packaging by 2030[16].

Players in the plastics industry have also established consortia to develop innovative recycling technologies. In Project Fuscia, Recycling Technologies joined oil and gas giant Total, environmental NGO Citeo and global brands Nestlé and Mars to investigate the technicality and commercial feasibility of recycling complex plastic waste[17].

At the heart of this project is Recycling Technologies' RT7000, which chemically breaks down hard-to-recycle plastics into a feedstock that can be further refined to produce virgin-quality plastic, fuels or waxes[12].

Recently, British retailer Tesco joined a multi-stakeholder effort to tackle the post-consumer flexible plastics problem[18]. Specifically, the group applied Plastic Energy's pyrolysis technology on discarded flexible plastics from Tesco customers.

Chemical manufacturing company SABIC used the resulting feedstocks to create food-grade plastic pellets as safe and effective as virgin plastic. From these pellets, packaging producer Sealed Air designed special packaging containing at least 30 percent recycled material to package Bradburys Cheese's products[10].

Governments can also influence demand for recycled plastic content. South Korea, for instance, now allows chemically recycled plastic resins made from PET and polyethylene naphthalate (PEN) for use in direct food contact applications[19].

Other measures have also been set into motion in Singapore. For instance, by 2022, consumers will be partly refunded for returning beverage containers for recycling through the government's Deposit Refund Scheme[20]. Meanwhile, projects like Newoil and the National Environment Agency (NEA)-Shell joint study aim to study the feasibility of chemically recycling plastic waste in Singapore[21].

[14] (Micro)plastic crisis: Un-ignorable contribution to global greenhouse gas emissions and climate change. (2020) Shen et al., Journal of Cleaner Production. Retrieved on April 2021 from https://doi.org/10.1016/j.jclepro.2020.120138

[15] Nestlé accelerates action to tackle plastic waste. (2019) Nestlé. Retrieved on March 2021 from https://www.nestle.com/media/pressreleases/allpressreleases/nestle-action-tackle-plastic-waste

[16] Coca-Cola lends support to European PET recycling project. (2018) Packaging Gateway. Retrieved on March 2021 from https://www.packaging-gateway.com/news/coca-cola-lends-support-european-pet-recycling-project/

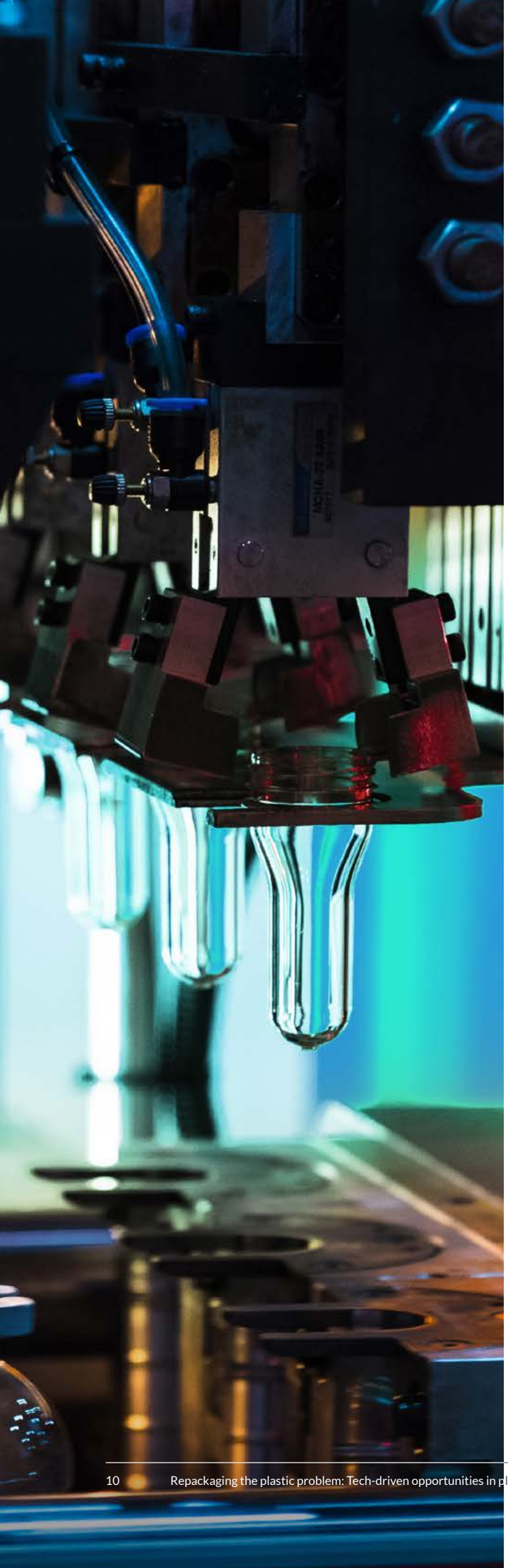
[17] New consortium to develop chemical plastic recycling in France. (2019) Packaging Gateway. Retrieved on March 2021 from https://www.packaging-gateway.com/news/consortium-chemical-plastic-recycling-france/

[18] How SABIC is driving progress, one piece of recycled plastic at a time. (2020). The Straits Times. Retrieved on March 2021 from https://www.straitstimes.com/business/how-sabic-is-driving-progress-one-piece-of-recycled-plastic-at-a-time

[19] South Korea amending food packaging standards. (2020) Food Packaging Forum. Retrieved on March 2021 from https://www.foodpackagingforum.org/news/south-korea-amending-food-packaging-standards

[20] Parliament: S'pore looks to create Newoil by transforming waste plastic into alternative fuel. (2020) The Straits Times. Retrieved on March 2021 from https://www.straitstimes.com/politics/parliament-singapore-looks-to-transform-waste-plastic-into-oil

[21] NEA, Shell to explore feasibility of chemically recycling Singapore's plastic waste. (2020) Business Times. Retrieved on March 2021 from https://www.businesstimes.com.sg/energy-commodities/nea-shell-to-explore-feasibility-of-chemically-recycling-singapores-plastic-waste



CURRENT STATE OF THE ART

Whether used bottles are fed into giant shredders or reduced to their smallest components through chemical reactions, plastics must invariably be broken down before they can be reused.

Mechanical recycling is often used to recycle homogeneous plastic waste. As its name suggests, in this method, waste products are ground or shredded into tiny pieces and then washed, melted and turned into pellets, which are turned over to plastic processing companies for use in new products.

In contrast, chemical recycling is preferred for more difficult-to-recycle plastic waste. Chemical recycling refers to processes where sorted or mixed plastics are broken down into their basic building blocks by chemical solvents or treatment with heat. As a result, pyrolysis oil, monomers or other chemical products are formed.

Chemical recycling can be further subcategorised into solvent-based recycling, depolymerisation and pyrolysis. Solvent-based recycling works by dissolving the target polymer in one or more solvents to remove impurities, after which the plastic is processed into a polymer that can be transformed into a new plastic product.

Depolymerisation, on the other hand, occurs when the plastic polymers are reduced to their monomers, which can then be used anew. Lastly, pyrolysis involves the breaking down of plastics using high temperature into pyrolysis oil which can be further refined into feedstock for petrochemical plants.

Key considerations: Price and profitability

Despite the diversity of recycling technologies, there are key considerations that must be taken into account for each method.

Mechanical recycling, for instance, needs relatively lower capital expenditure (CAPEX) and relies on tried-and-tested techniques. Yet, the process also requires streams of different plastic types to be well-sorted to ensure higher product purity[22]. Although initiatives like Singapore's Deposit Refund Scheme will be introduced to boost the collection rate of waste plastic, there remains a need to raise consumer awareness on the importance of plastic recycling in Southeast Asia.

Meanwhile, chemical recycling techniques like depolymerisation avoid the CAPEX needed for steam crackers and aromatic plants. Its use at commercial scale however, is restricted to PET and polyamide recycling. Despite the upfront CAPEX required by pyrolysis, the technique can handle mixed plastic streams that cannot be mechanically recycled.

A crucial limitation of pyrolysis is volume dependency, as it requires large and consistent amounts of waste to ensure profitability. Another limitation associated with the technique is the level of contamination of processed waste, as the presence of impurities like PVC may require additional pre-processing or post-processing steps.

Plastic Recycling Technology Overview

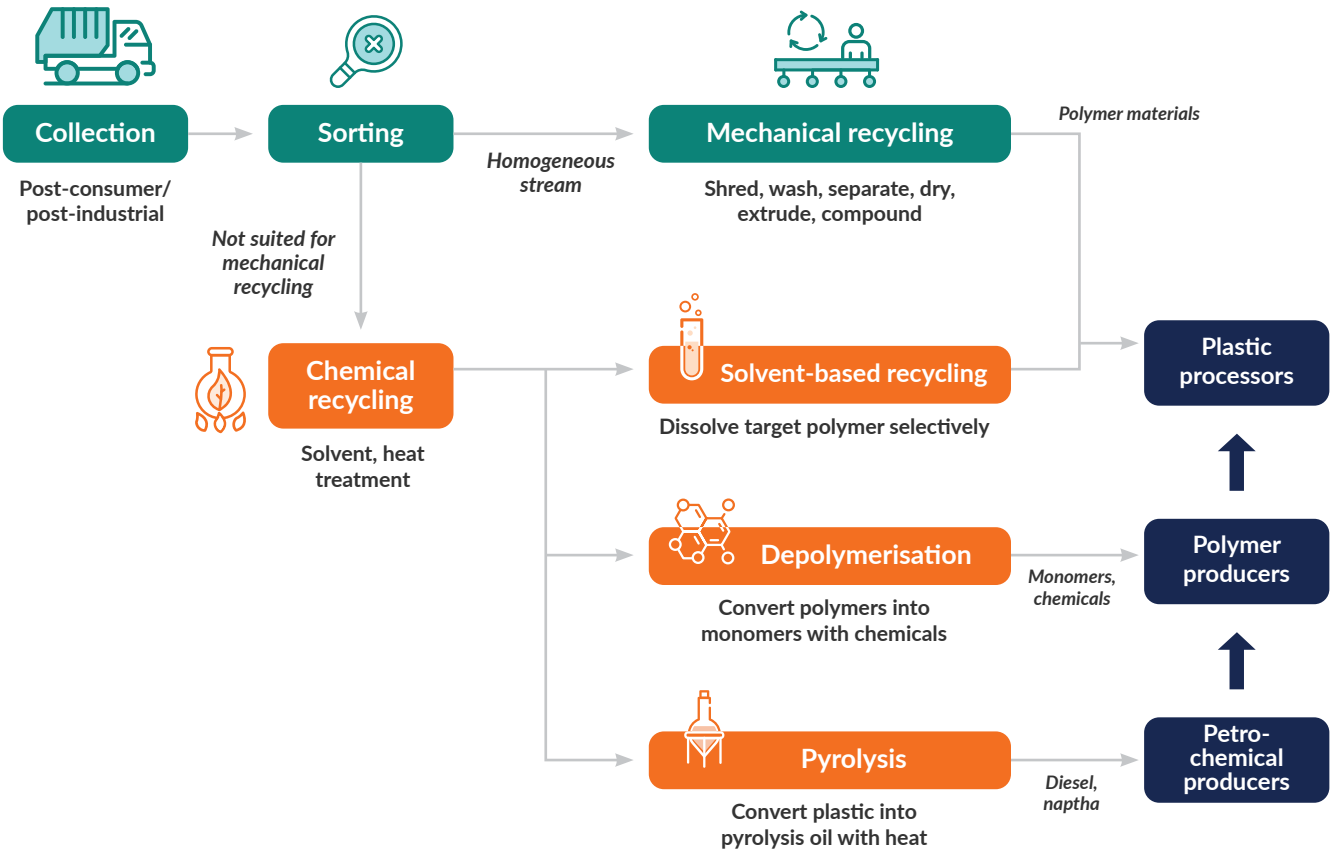


Figure 4 *The various technologies involved in plastic recycling.*

[22] Finding successful strategies for the circular economy. (2019) Lux Research. Retrieved on March 2021 from https://members.luxresearchinc.com/research/report/34512

EMERGING TECHNOLOGIES

With its potential to produce virgin-quality resins and process diverse kinds of plastics, chemical recycling has received much attention, especially from multinational companies looking to move towards more sustainable practices.

Diving deep into emerging chemical recycling technologies

Figure 5 highlights these emerging chemical recycling technologies along with considerations for their use. In multi-layer separation, plastic laminates are separated using solvents after sorting, shredding and micro-needle perforation treatments. Newer separation methods use safer water-based solvents than the potentially corrosive solvents used previously. However, this method may require the use of an adhesive that is compatible with the organic solvent.

Similarly, enzyme-based depolymerisation or biodegradation uses enzymes to break the bonds holding plastics like PET together, reducing them into monomers. This method foregoes the use of toxic catalysts and requires only mild temperatures of up to 70°C, but may need a longer residence time of up to 14 days in turn.

Meanwhile, microwave-assisted pyrolysis uses novel catalysts like silicon carbide to absorb microwaves and attain the temperatures reached by normal pyrolysis far quicker, saving time and energy.

Finally, techniques like pyrolysis oil refining reveal how opportunities in developing post-recycling treatments abound. Here, pyrolysis products are converted into higher-value fuels like diesel and gasoline. Materials that cause unwanted solid deposits are first stripped from the oil, which is then treated to avoid engine-damaging impurities. The latest techniques yield up to 95 percent of fuel, while requiring only ambient pressure and temperatures of less than 100°C.

Despite the exciting progress in the plastic recycling space, some of these technologies still require further development. The successful scale-up and commercialisation of these technologies still depends on certain factors, including the total cost of operating the plants, as well as the availability of suitable waste input, amongst others.

Emerging Technologies in Chemical Recycling

Multi-layer separation

TRL 4-6

- Separation of multi-layer film with proprietary solvents
- May require a compatible adhesive used on the film
- Complemented by sorting and shredding
- Technology owners: FYCH Technologies, Saperatec, Plastigram Industries

Enzyme-based PET depolymerisation

TRL 4-6

- Use of enzyme, e.g. esterase, lipase to catalyse glycolysis reaction
- Replace metal/alkali catalyst, improves degradation yield (75-90%)
- May require a long residence time (~14 days), mild temp (37-70°C)
- Technology owners: Carbios, Evoxx, Novoloop, Taraph Technologies, Austrian Centre of Industrial Biotechnology (ACIB)

Microwave-assisted pyrolysis

TRL 8-9

- Catalyst absorbs microwave energy for pyrolysis
- Reduced processing time and energy consumption
- Able to handle mixed plastic or single-polymer input
- Technology owners: Pyrowave, Nanyang Technological University (NTU), Plastic Energy, Recycling Technologies

Pyrolysis oil refining

TRL 4-6

- Purification with organic solvent mix and catalytic upgrading
- Reduce solids, gum formation, and up to 95% yield of diesel and gasoline
- Mild reaction conditions at ambient pressure and <100°C)
- Technology owners: Oxford Sustainable Fuels, SABIC, Borealis

Figure 5 *With its potential to process even plastics deemed too difficult-to-recycle, innovations in chemical recycling such as multi-layer separation, enzyme-based PET depolymerisation and microwave-assisted pyrolysis have emerged in recent years. Improvements in post-recycling technologies are also being developed.*

KEY TAKEAWAYS

The future of recycling is domestic

China's 2018 waste import ban compounded by Southeast Asian countries following suit, may have catalysed the demand for local plastic recycling solutions, instead of relying on those that recycle at the place of export. This has also led to more legislations around the world that promote domestic recycling, as well as an increased investment by companies in innovative recycling technologies.

Rising demand for recycled plastic content promotes collaboration across the plastic value chain

The increased demand for recycled plastic has encouraged stakeholders from across the value chain to collaborate on technologies that improve different aspects of the recycling process. These include pilots that use cutting-edge techniques to convert waste plastic into food-grade packaging.

Opportunities to innovate abound

For businesses, there are multiple opportunities for innovation across the plastic packaging value chain. Among the developing technologies, chemical recycling methods have received the lion's share of attention for their ability to accommodate more complex and diverse kinds of plastic compared to mechanical recycling.

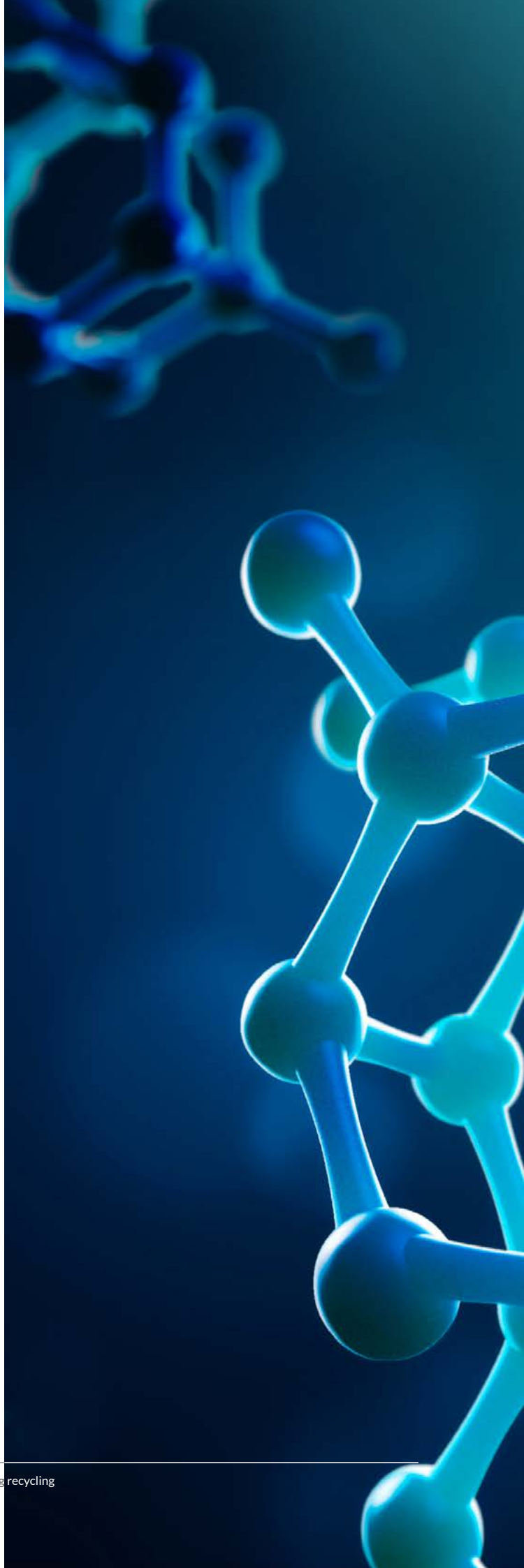
Moreover, chemical recycling alone can recover a plastic's raw materials, which can be subsequently processed into higher value products. Market leaders like SABIC, Borealis and Nestlé are capitalising upon these gaps and leading the way in developing novel chemical recycling technologies.

TECH OFFERS:
Discover collaboration opportunities

Now that we know more about plastic packaging recycling, it is time to discover technologies that can help your business make an immediate impact in the industry. These Tech Offers address various limitations across the value chain and can be the perfect fit for the right co-development partners.

Multi-layer separation

- Laminated plastics present a significant recycling problem due to the differences in melting points among its constituents, preventing them from being extruded into uniform shapes for processing.
- Traditional delamination methods rely on selective dissolution, where each layer is dissolved with costly organic solvents. These chemicals, however, present environmental and safety problems due to toxicity and flammability.
- The technology on offer utilises micro-needles which makes micro-perforations in crushed laminated plastic material, and then introduced into a reactor where water-based solvent remove ink and adhesive from the laminated material's interlaminar zone.
- This technology has been tested with different types of laminates at laboratory scale, including PE-PET, PP-ink-PP, PP-aluminium-PE.
- The provider is currently seeking technology licensing and research collaborations.
- View more details about multi-layer separation.



Recycling plastics into fuels and chemicals

- Plastic waste contributes to global warming when incinerated, persists indefinitely in landfills or pollutes the ocean when disposed irresponsibly.
- Given current recycling practices, sorting and cleaning is usually needed before plastic recycling itself can begin.
- While techniques that use sunlight to break down plastics like photoreforming exist, these use catalysts with toxic heavy metals like cadmium, which can be harmful to the environment.
- This technology uses a vanadium-based catalyst to break down plastics with a polyethylene backbone (like PE, PS and PP) into formic acid with the help of sunlight. Vanadium is less toxic, cheaper and far more abundant than cadmium.
- The technique can be used to turn plastics into more valuable chemical feedstocks and fuels. Recycled plastics are usually less versatile when used for the same product, due to their inferior quality compared to newly-produced plastics. This technology overcomes this limitation by converting plastics into simpler chemicals that can be feedstocks for more high-value products and processes.
- The provider is looking for collaborators for research and technology licensing.
- View more details on recycling plastics into fuels and chemicals.

CONCLUSION

With billions of tonnes in plastic waste produced since the middle of the 20th century, both governments and companies are encouraging innovation in this space through legislation and tackling the plastic problem head on, respectively.

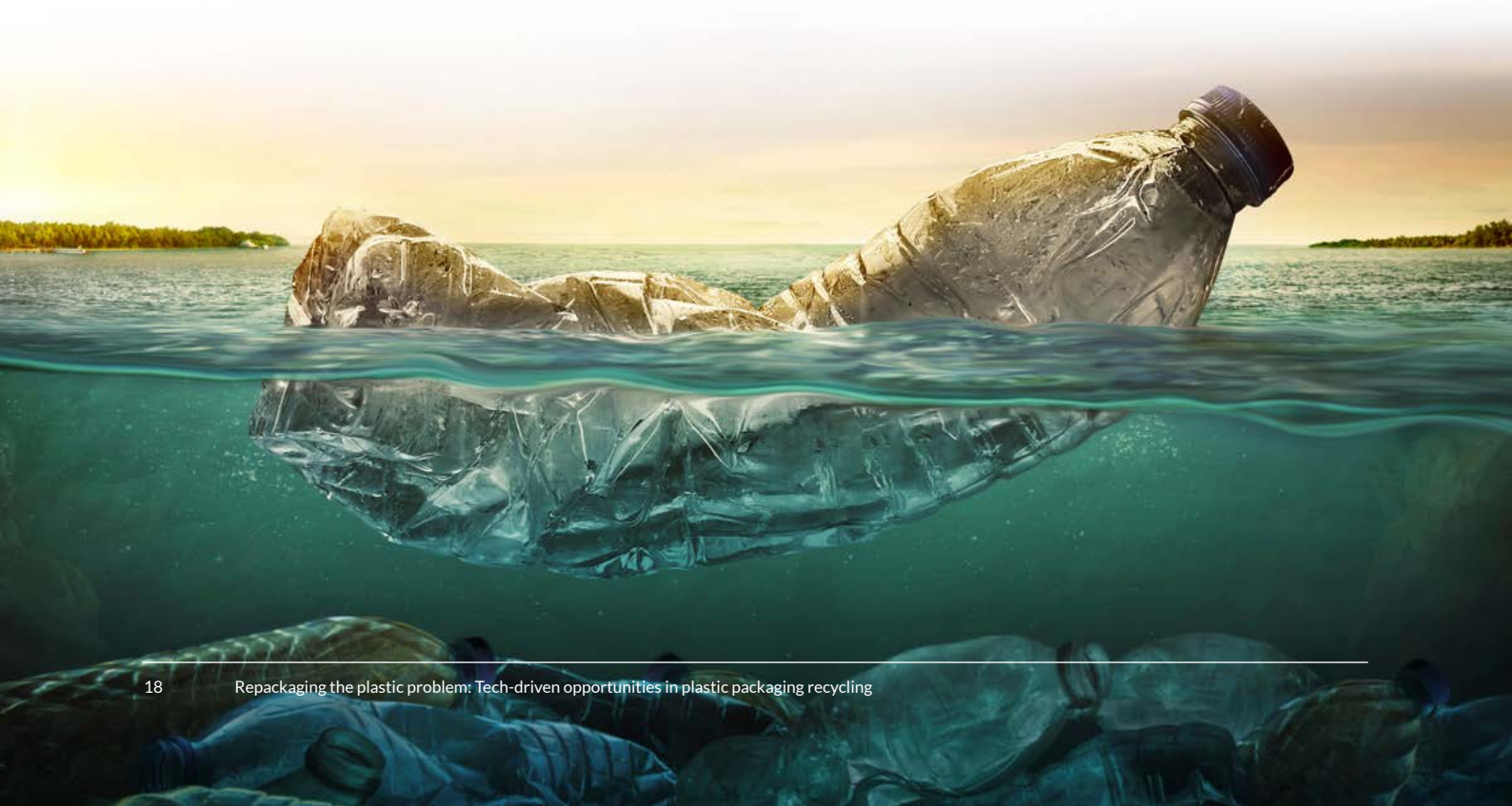
Among the various technologies, chemical recycling methods have received much attention. Whether it is through depolymerisation, pyrolysis or other techniques, chemical methods have the ability to reduce used plastics to their basic building blocks or produce higher-value products like petrochemical feedstock.

Despite their versatility, even chemical methods have limitations. The future therefore belongs to companies that can fill these gaps by generating solutions which are profitable not just for themselves, but also for the entire plastic value chain and society.

Likewise, the emergence of waste import bans by China and the like should be seen not as hindrances, but as opportunities for companies to drive innovation forward and create a more sustainable world. For those seeking to pioneer in this new age of recycling, IPI's doors are always open.

An overview of developing technologies shows that there is much left to do. With new ways to recycle bound to change our world and the environment for years to come, the question is: what role will *your* business play in this transformation?

If you would like more details and to learn about the opportunities outlined in this report, please contact **techscout@ipi-singapore.org.**



CONTRIBUTOR

Steven Lee
Innovation Manager
Manufacturing, Infocomm and
Built Environment, IPI

www.ipi-singapore.org

Designed by Wildtype Media Group