Chemical Recycling Briefing

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Chemical Plastics Recycling

Chemical plastics recycling can be used to describe any technology that utilises processes or chemical agents that directly affect the chemistry of the polymers within plastics[1]. It breaks down long hydrocarbon chains in plastics into shorter hydrocarbon fractions or into monomers using chemical, thermal, catalytic or purification processes. Purification is a slightly different method as it uses solvents for removing additives from the polymers. Some authors consider purification to be outside of the scope of chemical recycling, as traditionally, these technologies only covered pyrolysis, gasification and some forms of depolymerisation. However, purification has been included in this overview for completeness.

The output from all types of chemical recycling process is the creation of a new substance from waste plastic that can be used as a raw material for the re-manufacturing of plastics and other products. It complements the mechanical recycling process by enabling the further extraction of value from the polymers that have exhausted their economic potential for mechanical processing.

Mechanical recycling cannot effectively separate additives from polymers and cannot separate any non-intentionally added substances that have entered the plastic waste during use or reprocessing[3].

Both mechanical and chemical recycling can therefore be complementary processes, as when plastic waste is contaminated and or mixed, it cannot always be effectively processed by mechanical recycling methods, which is currently the only large-scale recycling technology available. Mechanical recycling is effective by tackling primarily homogeneous plastic waste such as plastic bottles. However, when it comes to recycling plastic waste that is hard to recycle, there is a risk that it could end up in incinerators in the UK or overseas with the resultant detrimental carbon emissions. Therefore, in this instance chemical recycling may become a highly effective solution for keeping the materials in circulation.

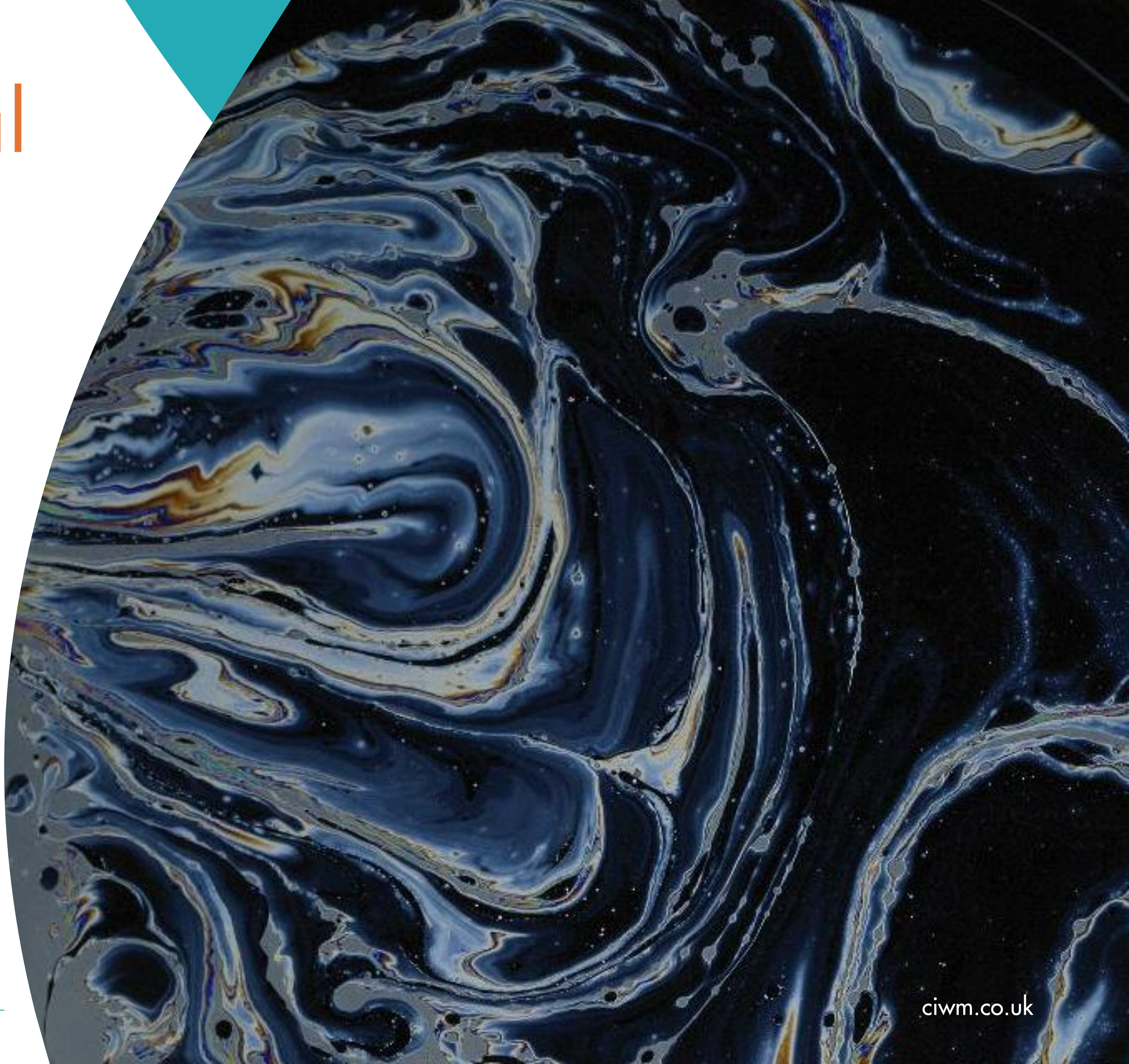
1,2. https://www.bpf.co.uk/plastipedia/chemical-recycling-101.aspx
3. https://chemtrust.org/wp-content/uploads/Chemical-Recycling-Eunomia.pdf

Types of Chemical Recycling Technologies

There are a range of different chemical recycling technologies, e.g. pyrolysis, gasification, hydro-cracking, purification and depolymerisation[4].

These processes fall under the following three key technology categories: chemical depolymerisation; thermal depolymerisation, and; solvent purification which are explored below.

4. https://worldplasticscouncil.org/resource/chemical-recycling-plastics-circular-economy/#:~:text=Chemical%20recycling%2C%20also%20referred%20to%20as%20feedstock%20or,recycling%20decomposes%20them%20to%20their%20original%20building%20blocks



CHEMICAL DEPOLYMERISATION

Chemical depolymerisation is a process whereby a polymer chain is broken down via the use of chemicals. In this process, waste plastic feedstock is pre-treated to remove any solid contaminants before the depolymerisation process takes place[5]. The next step is that chemicals are used to break down the polymer into monomers. Once the depolymerisation has occurred, the monomers are recovered from the reaction mixture and purified[6]. In theory, the resulting outputs from the waste plastic should be of identical quality to the primary raw material. [7]

5. https://cefic.org/a-solution-provider-for-sustainability/chemical-recycling-making-plastics-circular/chemical-recycling-via-depolymerisation-to-monomer/#:~:text=The%20depolymerisation%20recycling%20process%20starts%20with%20an%20initial,and%20heat%20to%20break%20down%20polymers%20into%20monomers
6. Coates, G. W., & Getzler, Y. D. (2020). Chemical recycling to monomer for an ideal, circular polymer economy. Nature Reviews Materials, 5(7), 501-516
7. Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

Key Concerns

Some of the key concerns surrounding chemical depolymerisation centre around waste treatment, energy and contamination. The chemical depolymerisation process requires homogeneous waste streams as an input. Therefore, this requires extensive pretreatment and sorting technologies for non-homogenous waste streams which are the most common. In addition, some of the chemical reactions require catalysts to increase the speed of the chemical process, and the quantities of the chemical reagents used within this procedure are not fully understood. There is also a lack of clarity regarding overall energy input requirements associated with current technologies. It is thought that the process requires extremely high energy inputs which could be a limiting environmental and commercial factor. Contamination is also a concerning issue, there is generally a lack of understanding around the level of contamination that current technologies can manage and how contaminants are dealt with following purification. Finally, there is limited published information provided for hazardous inputs or byproducts that might be found within the system. Therefore, it's full application and limitations cannot be fully confirmed.[3]

Example Technologies

It is important to note that the chemical depolymerisation process is only possible for particular types of plastic, some examples include polyethene, terephthalate and polyurethane.

Glycolysis, hydrolysis, and methanolysis are all depolymerisation pathways that have demonstrated success at a pilot plant level or larger.[3]

Glycolysis is the most advanced in terms of demonstrating commercial viability on a larger scale. Other forms of depolymerisation including aminolysis and ammonolysis, have been tested at laboratory demonstration level, however there is currently no evidence of progress beyond this small scale.[8]

There are a wide range of technologies currently being explored to commercialise[9] the chemical depolymerisation process, however a lack of information regarding potential yields at plant level are a barrier to successful commercialisation.

8. Miao, Y., von Jouanne, A., & Yokochi, A. (2021). Current technologies in depolymerization process and the road ahead. Polymers, 13(3), 449
9. QMRE unveils the UK's first plastic waste-2-oil system https://www.qmre.ltd/qmre-introduces-first-vixla-plastic-waste-to-oil-system-to-uk/

THERMAL DEPOLYMERISATION

Thermal depolymerisation is the process whereby a polymer is broken down into smaller molecules using extreme heat.[9] Plastic inputs initially go through a number of pre-treatment steps including cleaning, drying and shredding before being placed in a reactor and subjected to high temperatures causing depolymerisation. The resulting hydrocarbon fragments then go through subsequent distillation and purification steps in order to recover these products.[10]

There are two main approaches to thermal depolymerisation; pyrolysis, also known as thermal cracking, utilises high temperatures in the absence of oxygen, while gasification employs low volumes of oxygen to aid the degradation process.[8] The volume of oxygen utilised and the associated reaction conditions are crucial for controlling degradation and for avoiding incineration of the plastic.[11]

Gasification typically occurs at high temperatures (700 - 1500°C), converting plastics into a gaseous mixture of carbon dioxide, carbon monoxide, hydrogen, methane, water and other light hydrocarbons, collectively known as synthesis gas (syngas).[12] While some of these feedstocks can in principle be utilised to reproduce plastic, this would require significant subsequent processing stages to convert the raw syngas products into new materials. It is perhaps for this reason that there is little demonstrated evidence of this depolymerisation technology as a mechanism to remanufacture plastics.[3]

9. Pielichowski, K., Njuguna, J., & Majka, T. M. (2022). Thermal degradation of polymeric materials. Elsevier
10. Ragaert, K., Delva, L., and Van Geem, K. (2017) Mechanical and chemical recycling of solid plastic waste, Waste Management, Vol.69, pp.24–58
11. Zhang, F., Zhao, Y., Wang, D., Yan, M., Zhang, J., Zhang, P., ... & Chen, C. (2021). Current technologies for plastic waste treatment: A review. Journal of Cleaner Production, 282, 124523
12. Makwana, J., Dhass, A. D., Ramana, P. V., Sapariya, D., & Patel, D. (2023). An analysis of waste/biomass gasification producing hydrogen-rich syngas: a review. *International Journal of Thermofluids*, 100492

Key Concerns

Some of the key concerns surrounding thermal depolymerisation centre around its stability, waste sources, and lack of environmental data. As with other chemical recycling processes, there is often a requirement for a more homogeneous waste source in order to provide a higher output. As previously discussed, homogeneous waste streams can be difficult to find in the volumes required for a process to be commercially viable. In addition, the nature of the depolymerisation process in this context can lead to a mixture of resulting products. Therefore, it can often require the implementation of costly purification systems to isolate the usable products from the mixture.

There is currently limited or no understanding regarding the ability to recycle byproducts and reagents which are formed as part of the process. Furthermore, there is a lack of available data from the majority of technology providers, therefore limited understanding of long- term toxicity concerns which may present themselves owing to employing this technology.[3]

Example Technologies

Thermal depolymerisation has received significant attention in recent times, however, so far it has been unable to achieve commercial viability in the long term at an industrial scale. This is primarily due to the trade-offs between energy inputs and the quality of the outputs generated by the system.[3] It can be noted that there are pilot and commercial scale plants in operation producing chemical feedstocks. The outputs from these plants result in products for plastics manufacturing (e.g. monomers) or for other chemicals, however, it is often in tandem with the production of fuels in order to make the process economically viable in the current market. The long-term economic viability of thermal depolymerisation, will ultimately be dependent on whether the demand for these recycled feedstocks can balance the energy and purification costs required to produce them.[13] In view of this, the technology in its current format is more likely to be used to produce simpler chemical feedstocks such as ethanol for fuel.

13. Hann, S., & Connock, T. (2020). Chemical recycling: State of play. *Report for CHEM Trust, Eunomia*

ENZYMATIC DEPOLYMERISATION

A further type of depolymerisation is enzymatic depolymerisation. This technology allows for mixed, low quality and contaminated plastics to be recycled without them becoming degraded. In particular, Polyethylene Terephthalate (PET) is the main target material for this type of depolymerisation, as generally, degradation of this type of plastic would occur through mechanical processes and in thermal depolymerisation. Biological processes (enzymatic), work by placing plastic waste in a bioreactor with specific enzymes, for example, PETase and MHETase.[14] These enzymes bind to the PET polymers and monomers to break down the long PET polymer chains. Once monomers and constituents are separated out, they can be used and re-polymerized to create high quality plastics and other petrochemical products.[15]

14. https://emag.directindustry.com/2024/08/26/enzymatic-recycling-powers-the-circular-plastic-economy/
15. https://www.cleantech.com/enzymatic-depolymerization-and-recycling-using-enzymes-to-convert-linear-waste-streams-into-circular-supply-chains/

Some of the key benefits of this process is that it requires much less energy than other forms of depolymerisation and can also extend the life of plastics, potentially producing virgin quality recycled plastic outputs and materials. However, in some cases heat may be required as a pre- treatment step to prepare mixed plastic waste for this reaction. In some cases, this can increase emissions associated with the process and therefore have a negative impact on the environment. Although PET is the most common source of plastic for this type of reaction, companies and research groups are looking at other materials for commercialising this technology i.e. Polyethylene furanoate (PEF), Polyethylene (PE) and Polyurethane (PU) amongst other polymers.[16]

16. Jeswani, H., Krüger, C., Russ, M., Horlacher, M., Antony, F., Hann, S., & Azapagic, A. (2021). Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. *Science of the Total Environment*, *769*, 144483

SOLVENT PURIFICATION

The basis of solvent purification[17] is to use the principle of solubility to selectively separate plastic polymer from any other materials (contaminants) containing plastic waste.[18] Contaminants consist of a range of additives such as flame retardant and non-intentionally added substances (NIAS).[3] These substances are compounds both absorbed and produced within the plastic material during use. This can include side products from the manufacturing process as well as the degradation of products both from partial breakdown of the polymer and the additives contained within the plastic over its lifetime.[19]

During the solvent purification process, plastic is shredded and dissolved in a solvent that the polymer has a high solubility in, but one that the contaminants have a low solubility in. When the plastic material is placed in the solvent, the contaminants will remain solid so that these can be separated off from the liquid fraction to purify the polymer.[20]

Once the purification process is complete, the polymer is extracted from the solution and goes through a process of filtration, washing and drying. This technology is particularly effective because it is dependent on solubility. In respect to this, it can theoretically be applied to any type of polymer provided that a suitable solvent can be found. However, when implementing this technology on a commercial scale, its success is predominantly dependent on the homogeneity of the waste stream, the associated solvent and the energy inputs inquired required to ensure effective purification. Effective purification relies on understanding the exact composition of waste, including both the plastic component and contaminants within the waste input. However, there is a significant lack of clarity regarding the impurities that are commonly occurring. If all types of polymer contained within plastic waste are known, as well as the full range of contaminants, the process could be used to purify multi material waste streams, provided that sufficient solvent selection was achieved.[3] Theoretically this could avoid the costs associated with segregated collection and advanced sorting infrastructure required to separate specific polymer types.

17. Please note that some authors consider purification to fall under a separate category outside of the scope of chemical recycling. It has been included here for completeness in line with BPF guidance https://www.bpf.co.uk/plastipedia/chemical-recycling-101.aspx
18. Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions
19. Hahladakis, J. N., Velis, C. A., Weber, R., Iacovidou, E., & Purnell, P. (2018). An overview of chemical additives present in plastics: Migration, release, fate and environmental impact during their use, disposal and recycling. Journal of hazardous materials, 344, 179-199
20. Zhao, Y. B., Lv, X. D., & Ni, H. G. (2018). Solvent-based separation and recycling of waste plastics: A review. Chemosphere, 209, 707-720

Key Concerns

Screening materials in chemical recycling is a common pretreatment step to separate external contaminants.[21, 22] Mechanical treatments such as drying and crushing are also utilised to further prepare the plastics for purification. However, following purification, the risk of residual impurities remains an issue due to the reduction in the material properties compared with the virgin polymer.[23] A further concern is that remnant contaminants may be harmful to the environment, and further research is needed on this. If contaminants are found to be hazardous, further purification stages may be required which can be a barrier to commercial success.

To counter environmental concerns, the technologies approaching commercial scale have designed the process to allow solvent recovery. In addition, on a laboratory scale, there have been examples of environmentally benign solvents that can dissolve specific polymers, but due to limited detail on the solvents used, overall toxicity is difficult to confirm.[24]

Example Technologies

Solvent purification is a chemical recycling technique that is yet to reach commercial scale. However, there are some examples of companies that are working towards, or have already reached the pilot plant stage. There have been some examples concentrating on chemically recycling polystyrene foam and PET/cotton blend fabrics.[25] The key purification technologies are currently aiming at Poly Propylene (PP), Low Density Polyethylene (LDPE) and Polyetylene (PE) film/ flexibles, focusing on a bleaching/purification process.

21. Li, H., Aguirre-Villegas, H. A., Allen, R. D., Bai, X., Benson, C. H., Beckham, G. T., ... & Huber, G. W. (2022). Expanding plastics recycling technologies: chemical aspects, technology status and challenges. Green Chemistry, 24(23), 8899-9002
22. Contaminants may consist of items sch as glue and tape

23. Schyns, Z. O., & Shaver, M. P. (2021). Mechanical recycling of packaging plastics: A review. *Macromolecular rapid communications*, 42(3), 2000415
24. Aboagye, E. A., Chea, J. D., & Yenkie, K. M. (2021). Systems level roadmap for solvent recovery and reuse in industries. Iscience, 24(10)
25. Choudhury, K., Tsianou, M., & Alexandridis, P. (2024). Recycling of Blended Fabrics for a Circular Economy of Textiles: Separation of Cotton, Polyester, and Elastane Fibers. *Sustainability* (2071-1050), 16(14)

Key Benefits of Chemical Recycling

One of the most important benefits of chemical recycling is that it serves as an alternative to landfill and incineration, it is particularly useful for hard to recycle plastic products such as films, multilayered and laminated plastics.[26]

Another potential key benefit is that it facilitates the supply of potentially high-quality raw materials back into the plastic supply chain. Most mechanical processing of plastic waste can produce secondary raw materials or products without significantly altering the material chemical structure, whereas chemical recycling breaks down plastics into valuable secondary raw materials.

These recycled raw materials can then be used to produce new chemicals and plastics with the same quality as those made from virgin materials without reliance on primary fossil resources.

In addition, the process could give a new value to plastic waste that is otherwise unused. For example, around 30 million tonnes of plastic waste is collected every year in Europe and around 85% of this is still incinerated or sent to landfill. As this is a significant waste of valuable resource, and in the context of incineration, adds damaging CO_2 emissions to the atmosphere, chemical recycling could help with regenerating contaminated and or mixed plastic waste that cannot be recycled through mechanical means.

In addition, and as an added benefit, there is potential for chemical recycling to address and separate legacy chemicals and substances of high concern, [27] substances that have serious and irreversible effects on human health (SVHCs) that can be present in end-of-life plastics after multiple years of use.[28]

26. https://www.bpf.co.uk/plastipedia/chemical-recycling-101.aspx#:~:text=Chemical%20recycling%20serves%20as%20an%20alternative%20to%20landfill,virgin-quality%20raw%20materials%20to%20the%20plastics%20supply%20chain
27. Wagner, S. and Schlummer, M., 2020. Legacy additives in a circular economy of plastics: Current dilemma, policy analysis, and emerging countermeasures. Resources, Conservation and Recycling, 158, p.104800
28. https://cefic.org/a-solution-provider-for-sustainability/chemical-recycling-making-plastics-circular/top-questions-about-chemical-recycling/

Conclusion

To conclude, chemical recycling has some significant benefits that can act as a complementary method to enhance recycling outputs overall, when used in conjunction with mechanical recycling and reuse initiatives.

However, this method of recycling, in the technology areas covered currently lacks evidence of success, commercial viability, and an understanding of environmental concerns which could be present from all process types.

It is, however, important to consider chemical recycling as a potential solution, particularly with HMRC's recent approval of chemical recycling as an acceptable method for producing recycled plastics under plastic packaging tax.

Further research and evidence are required in order to make this a commercial, viable process and work towards a circular system whereby more plastic can be recycled and utilised repeatedly.

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