Chemical Recycling of Polymeric Materials from Waste

in the Circular Economy

Final Report

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Abstract

The purpose of the study was to investigate the current state of knowledge regarding the chemical recycling of polymeric materials (e.g., plastics, rubber) from waste. Considering the scale of plastic pollution and the potential role that chemical recycling could play in addressing some of the related issues, this study focused on chemical recycling of plastic waste. Six research topics were addressed: chemical recycling technologies, waste streams, recovered substances, materials and waste residues, chemical recycling and substances of very high concern, chemical recycling and policy developments and chemical recycling and tracking systems. The literature review covered 228 research and grey literature sources published since 2015 and consultation was carried out with 22 experts in chemical recycling. The authors found that there is lack of clarity and consistency in chemical recycling terminology. Chemical recycling is an umbrella term which covers different technologies with varying potential to contribute to the circularity of plastics. There is a fragmented knowledge about the fate of substances of concern in various chemical recycling processes, and a paucity of scientific papers discussing regulatory issues in chemical recycling. Digital technologies could contribute to improving the traceability of substances of concern in recycling. However, their implementation requires substantial inter-organisational and organisational efforts.

Table of Contents

Table of figures

Table of tables

Abbreviations

ABS – acrylonitrile-butadiene-styrene
BAMB – Buildings as Material Banks
BAT – best available technique
BAU – business as usual
BDO – butanediol
BFR – brominated flame retardants
BHET - bis(hydroxyethyl) terephthalate
BPA – bisphenol-A
Br – bromine
Br-ABS – brominated acrylonitrile-butadiene-styrene
Br-HIPS – brominated high impact polystyrene
BTX - benzene, toluene, xylene
C&D – construction and demolition
CFRP – carbon fibre reinforced plastics
CH – Switzerland
CH_4 – methane
Cl – chlorine
CLP – Classification, Labelling and Packaging
CO – carbon monoxide
CO_2 – carbon dioxide
DBL – digital building logbooks
DecaBDE – Decabromodiphenyl ether
DETA – diethylenetriamine
DLT – distributed ledger technology
DMA – dimethyl adipate
DMC – dimethyl carbonate
DMDEA – dimethyl-1,2-diaminoethane
DMP – digital material passport
DMT – dimethyl terephthalate
DOTP – dioctyl terephthalate
EC – European Commission
ECHA – European Chemicals Agency
EF – environmental footprint
EG – ethylene glycol
ELV – end-of-life vehicles
ELVD – End-of-Life Vehicles Directive
EPDs – Environmental Product Declarations
EPS – expanded polystyrene
EVA – ethylene-vinyl acetate
FGC – flue gas cleaning
FPUF – flexible polyurethane foam
FRP – fibre reinforced plastics
FRs – flame retardants
GADSL – Global Automotive Declarable Substance List
GDP – gross domestic product
GFRP – glass fibre reinforced plastics
GPPS – general-purpose polystyrene
H_2 – hydrogen gas
H_2S – hydrogen sulphide
HBCD – hexabromocyclododecane
HBr – hydrogen bromide
HCl – hydrogen chloride/hydrochloric acid
HDPE – high-density polyethylene
HHV – high heating values
HIPS – high impact polystyrene
IMDS – International Material Data System
LCA – life cycle assessment
LDPE – low-density polyethylene
LIBS – Laser-induced breakdown spectroscopy
MAE – microwave-assisted extraction
MAHs – monoaromatic hydrocarbons
MDA – methylenedaniline
MDC – methylene diphenyl carbamate
MPW – municipal plastic waste
MSW – municipal solid waste
n.d. – no date
N_2 – nitrogen gas
NH_3 – ammonia
NO – Norway
NO_x – nitrogen oxides
P2F – plastic to fuel
P2P – plastic to plastic
PA – polyamide
PAHs – polycyclic aromatic hydrocarbons
PBDD – polybrominated dibenzo-p-dioxins
PBDD/Fs – polybrominated dibenzo-p-dioxins and polybrominated dibenzofurans
PBDFs – polybrominated dibenzofurans
PBT – poly(butylene terephthalate)
PC – polycarbonate
PCBs – polychlorinated biphenyls
PCDDs – polychlorinated dibenzo-p-dioxins
PCDD/Fs - polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans
PCDFs – polychlorinated dibenzofurans
PE – polyethylene
PET – poly(ethylene terephthalate)
PLA – poly(lactic acid)
PLE – pressurised liquid extraction
PLLA – poly(L-lactic acid)
PMMA – poly(methyl methacrylate)
POPs – persistent organic pollutants
PP – polypropylene
PP-GF – glass fibre reinforced polypropylene
PPE – poly(phenylene ether)
PS – polystyrene

PPWD – Plastic Packaging Waste Directive
PU/PUR – polyurethane
PVC – poly(vinyl chloride)
PW – plastic waste
QR - Quick Response
REACH - Registration, Evaluation, Authorisation & restriction of Chemicals
RFID – Radio Frequency Identification
RoHS – Restriction of Hazardous Substances
SAN – styrene-acrylonitrile resin
SCIP – Substances of Concern in Products
SCR – selective catalytic reduction
SFE – supercritical fluid extraction
SoC – substances of concern
SVHCs – substances of very high concern
TBBPA – Tetrabromobisphenol A
TEA – techno-economic assessment
THF – tetrahydrofuran
TPA – terephthalic acid
TRL – technology readiness level
UHMWPE – Ultra-high-molecular-weight polyethylene
VOCs – volatile organic compounds
WEEE – waste electrical and electronic equipment
WFD – Waste Framework Directive
Wt – weight
XRT – X-Ray transmission

Glossary of Terms

Additive 'means a substance which is intentionally added to plastics to achieve a physical or chemical effect during the processing of the plastic or in the final material or article; it is intended to be present in the final material or article' (European Commission, 2011, p.8).

Article 'means an object which during production is given a special shape, surface or design which determines its function to a greater degree than does its chemical composition' (European Parliament, 2006a, (REACH) article 3(3)).

Best Available Techniques (BATs) 'means the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole: (a) 'techniques' includes both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned; (b) 'available techniques' means those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator; (c) 'best' means most effective in achieving a high general level of protection of the environment as a whole' (European Parliament, 2010, p.12).

Blockchain 'distributed ledger with confirmed blocks organized in an append-only, sequential chain using cryptographic links. Blockchains are designed to be tamper resistant and to create final, definitive and immutable ledger records' (International Organization for Standardization, 2020).

Chemical recycling 'conversion to monomer or production of new raw materials by changing the chemical structure of plastics waste through cracking, gasification or depolymerization, excluding energy recovery and incineration' (International Organization for Standardization, 2008).

Chemolysis (also known as solvolysis, chemical depolymerisation) 'involves treating the classified polymeric wastes with solvents and reagents (or catalysts) to depolymerize the polymer to low molecular weight (LMW) chemicals and oligomers' (Zhou et al., 2016).

Circular economy 'means rejecting the linear take-make-waste economy and adopting a regenerative model: using processes that restore, renew or revitalise their own sources of energy and materials and wasting as little as possible' (European Commission, n.d.).

Closed-loop recycling is a system where 'material from a product is recycled in the same product system' (International Organization for Standardization, 2006a).

Depolymerisation 'reversion of a polymer to its monomer(s) or to a polymer of lower relative molecular mass' (International Organization for Standardization, 2013).

Emissions 'means the direct or indirect release of substances, vibrations, heat or noise from individual or diffuse sources in the installation into air, water or land' (European Parliament, 2010, p.12).

Gasification 'transformation of a solid and/or liquid material to a gaseous state' (International Organization for Standardization, 2013).

Lifecycle Assessment (LCA) 'Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle' (International Organization for Standardization, 2006a).

Manufacturer 'any natural or legal person established within the Community who manufactures a substance within the Community' (European Parliament, 2006a, (REACH) article 3(9)).

Material recovery 'means any recovery operation, other than energy recovery and the reprocessing into materials that are to be used as fuels or other means to generate energy. It includes, *inter alia*, preparing for re-use, recycling and backfilling' (European Parliament, 2008, p. 5).

Mixture 'is a mix or solution of two or more substances. Under the EU chemicals legislation, mixtures are not considered substances' (European Parliament, 2006a, (REACH) article 3(2)).

Open-loop recycling is a system where 'material from one product system is recycled in a different product system' (International Organization for Standardization, 2006a).

Persistent organic pollutants (POPs) are chemicals that persist in the environment, bioaccumulate through the food web, and pose a risk of causing adverse effects to human health and the environment. This group of priority pollutants consists of pesticides (such as DDT), industrial chemicals (such as polychlorinated biphenyls, PCBs) and unintentional by-products of industrial processes (such as dioxins and furans) (European Commission, n.d.a).

Plastics 'means a material consisting of a polymer as defined in point 5 of Article 3 of Regulation (EC) No 1907/2006, to which additives or other substances may have been added, and which can function as a main structural component of final products, with the exception of natural polymers that have not been chemically modified (European Parliament, 2019a).

Polymer 'is a substance consisting of molecules characterised by the sequence of one or more types of monomer unit. Such molecules must be distributed over a range of molecular weights. Differences in the molecular weight are primarily attributable to differences in the number of monomer units. In accordance with REACH (Article 3(5)), a polymer is defined as a substance meeting the following criteria: 50% of the weight of that substance consists of polymer molecules (see definition below); and, the amount of polymer molecules presenting the same molecular weight must be < 50% of the weight of the substance' (European Parliament, 2006a, (REACH) article 3(5)).

Producer of an article 'any natural or legal person who makes or assembles an article within the Community' (European Parliament, 2006, (REACH) article 3(4)).

Pyrolysis 'irreversible chemical decomposition caused solely by a rise in temperature' (International Organization for Standardization, 2013). 'The term generally refers to reaction in an inert environment' (IUPAC, 2021).

Recovery 'means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Annex II sets out a non-exhaustive list of recovery operations' (European Parliament, 2008, p.10).

Recycling 'means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations' (European Parliament, 2008, p.10).

Substance 'means a chemical element and its compounds in the natural state or obtained by any manufacturing process, including any additive necessary to preserve its stability and any impurity deriving from the process used, but excluding any solvent which may be separated without affecting the stability of the substance or changing its composition' (European Parliament, 2006a, (REACH) article 3(1)).

Substances of concern (SoC) are those identified under REACH as substances of very high concern, substances prohibited under the Stockholm Convention (POPs), specific substances restricted in articles listed in Annex XVII to REACH as well as specific substances regulated under specific sectorial/product legislation' (European Commission, 2018a).

Substances of Very High Concern (SVHC) substances that are carcinogenic, mutagenic, and toxic for reproduction (CMR); persistent, bioaccumulative and toxic (PBT); very persistent and very bioaccumulative (vPvB), have endocrine-disrupting properties (ED) or those for which there is scientific evidence for serious effects to human health or the environment that give rise to an equivalent level of concern to those substances that listed in the Article 57 ((a) to (e) list). The latter are identified on a case-by-case basis as outlined in the Article 59 (European Parliament, 2006a, (REACH)).

UVCB (Unknown or Variable Composition, complex reaction products or of Biological materials) is a substance with many different constituents, some of which may be unknown. The composition can be variable or difficult to predict (ECHA, 2017a).

Waste is any substance or object which the holder discards or intends or is required to discard (European Parliament, 2008).

Executive Summary

*The **purpose** of the study was to investigate the current state of knowledge regarding the chemical recycling of polymeric materials (e.g., plastics, rubber) from waste. The specific objectives of the study were the collection of information, through the review of literature, the consultation of experts and the development of case studies, and the preparation of a report on the following areas: sources, main materials, substances and processes of chemical recycling; current performance of chemical recycling technologies; opportunities and challenges; benefits in the context of the circular economy; readiness level of different technologies and regulatory oversight.*

*Chemical recycling is used for processing various types of waste, including biomass, concrete and plastic waste. Only a small part of all plastic waste ever produced has been recycled or incinerated, with the rest accumulating in landfills and becoming ubiquitous in the natural environment. The importance of reducing plastic pollution has been recognised in various EU strategic documents, where chemical recycling has been considered among various potential solutions to contribute to recycling of plastics. Considering the scale of plastic pollution and the potential role that chemical recycling could play in addressing some of the related issues, this study focuses on **chemical recycling of plastic waste**. The research questions were organised into six topics: chemical recycling technologies, waste streams, recovered substances, materials and waste residues, chemical recycling and substances of very high concern, chemical recycling and policy developments and chemical recycling and tracking systems.*

*It should be noted that the study focuses on the **European Union situation and developments in chemical recycling**, although relevant studies from other countries have been reviewed where appropriate.*

*To address the research questions, the authors reviewed **229 research and grey literature sources** and interviewed **22 experts in chemical recycling**. The review covered literature published since 2015 to collect and analyse the most recent information. This selection criterion did not apply to legislation and guidance on its implementation. The expert consultation was aimed at complementing and cross-checking the information found in the literature through expert judgement. The experts were selected through an internet poll publicised by the authors and the European Chemicals Agency and consulted using the semi-structured interviewing method. Thematic analysis was applied for the interpretation of the interview results. The research topics were addressed in the following thematic parts of the study: Chemical Recycling in the Context of the Circular Economy (Section 3), Waste Streams in Chemical Recycling (Section 4), Chemical Recycling Technologies (Section 5), Substances of Concern in Chemical Recycling (Section 6), Regulatory Issues in Chemical Recycling (Section 7), and Technical Issues in Chemical Recycling (Section 8).*

The study resulted in six conclusions and four recommendations:

***CONCLUSION 1. The lack of clarity in chemical recycling terminology leads to confusing conclusions on the potential role of chemical recycling in the circular economy.** In scholarly literature, the concept of 'recycling' has a broader meaning than in EU regulatory documents and includes fuel as a possible product of recycling. Production of fuel by means of chemical recycling received substantial attention in scholarly literature. However, civil organisations criticise the production of fuel through chemical recycling, pointing to the associated environmental impacts. In grey literature, there is a lack of clarity on what technologies should be considered as chemical recycling, with some reports classifying dissolution as a chemical recycling technology. However, dissolution does not imply chemical changes in the structure of the recovered polymers, which may be considered a definitive feature of chemical recycling technologies.*

RECOMMENDATION 1.1 *Harmonisation of chemical recycling terminology is necessary for a sound and consistent discussion about the potential of chemical recycling in the circular economy. Papers, reports and regulatory documents should always specify the chemical reprocessing technologies included in their scope. This would allow distinguishing the technologies that meet the definition of 'recycling' provided by the Waste Framework Directive from those that do not meet the definition.*

CONCLUSION 2. Chemical recycling technologies differ in their potential to contribute to the circularity of plastics*. Based on the qualitative evaluation of research papers on chemical recycling, the established technologies – pyrolysis, gasification and chemolysis – vary in their ability to ensure the circularity of plastics. Pyrolysis and gasification produce by-products and non-reusable residues that need to be disposed of. Both technologies mostly produce intermediates that require further processing to become either chemical products, fuels, or energy, and therefore do not result in circular closed-loop systems for plastics. Both technologies can treat heterogeneous streams of plastic waste, including mixed and contaminated post-consumer plastic waste, and could therefore complement mechanical recycling in dealing with waste streams that otherwise would be landfilled or incinerated. Chemolysis is reported to produce monomers of a virgin-grade quality. The literature search did not identify discussions on by-products or residues of chemolysis.*

RECOMMENDATION 2.1 *The potential of specific chemical recycling technologies to contribute to the circularity of plastics should be evaluated case-by-case to avoid mistaken generalisations of advantages/disadvantages of one technology to the whole field of chemical recycling.*

CONCLUSION 3. Analysis of research literature has shown fragmented knowledge about the fate of substances of concern in various chemical recycling processes*. Available studies mainly focused on various types of pyrolysis of e-waste and the fate of brominated flame retardants; however, no studies were identified for other established chemical recycling technologies. It is important to note that various pyrolysis technologies demonstrated different abilities to cope with substances of concern. The findings of the identified studies do not provide a solid ground for making conclusions about the fate of substances of concern in all established chemical recycling processes. Furthermore, it is not clear if the technologies analysed in the scholarly literature have been applied in industrial settings.*

RECOMMENDATION 3.1 *The behaviour and fate of substances of concern in gasification and chemolysis should be investigated. Moreover, in order to make sound conclusions, such investigation should be carried out in commercial or pilot chemical recycling plants applying gasification, chemolysis or any other chemical recycling technology.*

CONCLUSION 4. Regulatory issues in chemical recycling are not discussed in the scientific literature*. Several issues raised in mechanical recycling could be relevant to specific chemical recycling technologies as well. These issues include insufficient measures to promote recycling of plastic waste in the EU directives on packaging, construction materials and end-of-life vehicles, the absence of information about the presence of SoCs in plastic waste streams and regulatory uncertainties over the waste classification, end of waste criteria and related duties of the operators. However, the opportunities and challenges posed by the REACH Regulation and other chemicals, waste and product safety legislations remain specific to each chemical recycling technology. It should be noted that important steps have been taken to review the EU directives and overcome their weaknesses related to recycling.*

RECOMMENDATION 4.1 *The regulatory issues in chemical recycling should be studied on a case-by-case basis, separately for each type of chemical recycling technology.*

CONCLUSION 5. Digital technologies contribute to improving the traceability of substances of concern in recycling*. Some chemical recycling technologies are either sensitive to specific constituents* *of plastic waste or can process only some sorts of plastic waste. The literature analysis has shown that many databases with information about chemical substances contained in articles exist to assist recyclers in locating information about substances of concern. Screening and sorting technologies in recycling facilities help to identify substances of concern. The importance of sorting the incoming waste was recognised in the stakeholder interviews. However, the databases lack historical information about legacy substances of concern, and information is dispersed across various datasets with different access and search options. In addition, screening technologies vary in their ability to detect SoCs, with the most accurate and sophisticated technologies also being the most expensive.*

CONCLUSION 6. Blockchain technology offers a solution for monitoring substances of concern in plastic waste; however, its implementation requires substantial inter-organisational and organisational efforts*. The main advantages of blockchain are decentralised management, verifiability of information, ability to track any event or transaction at different lifecycle stages of plastic materials and goods from manufacturing to end-of-life. However, the benefits of blockchains for recyclers come at the cost of large-scale digital transformation of the whole supply chain. The success of such initiatives depends on commitment, investments and collaboration between multiple players and requires a substantial amount of time to make blockchain solutions functional. Different existing digital tools – databases, screening and sorting technologies, digital and printed tags can be combined for satisfying the practical needs of recyclers.*

1 Introduction

Chemical recycling is used for processing various types of waste, including biomass, concrete (Ho et al., 2020) and plastic waste (Briassoulis et al., 2019). Chemical recycling of plastic waste has been widely studied (e.g., Ragaert et al., 2017; Hong & Chen, 2017). While being a valuable material for many uses, plastic persists in the environment and causes environmental pollution on an unprecedented scale. An estimated 80% of all virgin plastics ever produced (6,500 million metric tonnes) has accumulated in landfills and the natural environment by 2018 (Geyer et al., 2017). Annual emissions of microplastics to surface waters from the EU, Norway, and Switzerland have been estimated in the range of 75,000 – 300,000 tonnes (European Commission, 2018c). The importance of reducing plastic pollution has been recognised in various EU strategic documents. In 2018, the European Commission published the European Strategy for Plastics in a Circular Economy (2018) that aims to protect the environment and reduce the pollution caused by plastics and transform the patterns of design, production, consumption, and recycling of plastics in Europe. Among other objectives, the strategy aims to invest in innovative recycling solutions. According to the Strategy, "innovative solutions for advanced sorting, chemical recycling and improved polymer design can have a powerful effect" (European Commission, 2018c).

The **purpose** of this study is to investigate the current state of knowledge regarding the chemical recycling of polymeric materials (e.g., plastics, rubber) from waste. The specific objectives of the study are the collection of information, through the review of literature, the consultation of experts and the development of case studies, and the preparation of a report on the following areas: sources, main materials, substances and processes of chemical recycling; current performance of chemical recycling technologies; opportunities and challenges; benefits on the context of the circular economy; readiness level of different technologies and regulatory oversight.

The research questions addressed in this study were organised into six topics:

- **Chemical recycling technologies**: types, performances, advantages and disadvantages.
- **Waste streams**: past, present and future of waste sources, types and quantities.
- **Recovered substances, materials and waste residues, side streams and by-products**: identification, safety aspects and markets.
- **Chemical recycling and substances of very high concern**: sources, identities, treatment, fate and emissions.
- **Chemical recycling and policy developments**: UVCB substances classification and mixture rule, authorisation requirements for mixtures containing SVHC constituents.
- **Chemical recycling and tracking systems**: mandatory communication requirements, sector by sector or waste stream-by-waste stream approach, blockchain technologies.

To address the research questions, the authors carried out a **literature review** and **expert consultation**. The literature review focused on research publications and available grey literature, mainly targeting research reports by various reputable organisations, strategic and legal documents, websites, popular magazines, or internet media.[1] The expert consultations were aimed at complementing and cross-checking the information found in the literature with expert judgement. The experts were identified by using convenience and purposive sampling and an "identification by intervention" approach (i.e. publications for academia, position papers and blog posts for industry associations, trade unions, NGOs and think tanks, policy documents for national authorities). They were then selected through an internet poll asking for their availability in participating in the consultation and their expertise on the six defined topics. The poll was also publicised by the European

[1] The latter sources were only used for finding relevant examples of applications of chemical recycling in the industry.

Chemicals Agency. The experts were consulted by using the semi-structured interviewing method. Thematic analysis was applied for the interpretation of the interview results.

The study focuses on the **European Union situation and developments in chemical recycling**, although relevant studies from other countries have been reviewed where appropriate.

The review covered **229 research and grey literature sources**, including 113 papers in scientific journals, eight books, 21 websites and 87 publications of other types (reports by governmental agencies, consultancies and non-profit organisations, strategic and legislative documents). The review was limited to literature published since 2015 to collect the most recent information. This selection criterion did not apply to legislation and guidance on its implementation.

The study is organised in thematic parts:

- Section 2 details the methodology followed for the literature search and the expert consultation.
- Section 3 *Chemical Recycling in the Context of the Circular Economy* provides a definition of chemical recycling and discusses how it relates to the main objectives of the EU circular economy strategies.
- Section 4 *Waste Streams in Chemical Recycling* provides an overview of polymeric waste streams and trends in plastic production and management that could affect the future volumes of plastic waste or issues related to its management.
- Section 5 *Chemical Recycling Technologies* reviews commercially available, close to the commercial stage and developing chemical recycling technologies, and discusses advantages and disadvantages of various technologies.
- Section 6 *Substances of Concern in Chemical Recycling* discusses the definition of substances of concern, reviews main substances of concern in plastic waste streams, analyses behaviour and fate, emissions of SoCs, including emission control and best available technologies.
- Section 7 *Regulatory Issues in Chemical Recycling* discussed waste management and chemicals legislation relevant for recyclers, main legal obligations in chemical recycling, uncertainties and challenges faced by recyclers in complying with legal requirements.
- Section 8 *Technical Issues in Chemical Recycling* provides an overview of available technical solutions, including established and emerging technologies that contribute to monitoring substances of concern and closing information gaps in the process of chemical recycling.
- Section 9 presents the analysis of the findings of the expert consultation.
- Section 10 presents the conclusions and recommendations of the study.

2 Methodology

2.1 Literature search strategy

The **collection of the relevant literature** was carried out by:

- automated keyword extraction by using Python scripts; the keywords were used for searching relevant literature;
- refining and complementing of search results by reviewing the titles and abstracts of the papers and by following a snowballing approach;
- gathering links to relevant publications by means of expert consultation (see section 2.2);

These methods were applied to both **scientific publications** and the **deliverables of projects** funded through the 7th Framework Programme, LIFE and Horizon 2020. Additional searches were conducted to find relevant **examples of chemical recycling applications**.

Due to the abundance of publications (e.g., a Google Scholar search for the phrase "chemical recycling" produces over 16,400 results), the search timeframe is limited to **2015-2021 publications**. However, this selection principle was not applied to legislation and guidance documents (e.g., ECHA, European Commission guidance on the implementation of legal acts).

The procedure of data collection is summarised in Figure 2-1.

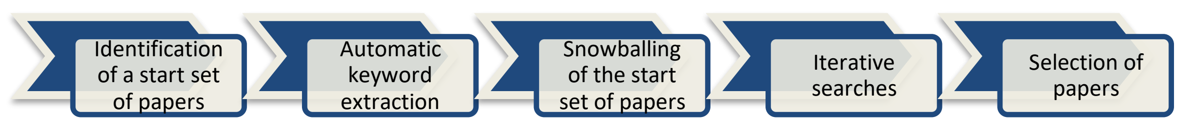

Figure 2-1: Data collection procedure

As shown in Figure 2-1, the first task was the **identification of a start set of papers**. The identification of the start set of papers to be reviewed for each subtopic was based on keywords selected by the project team on the basis of the research questions specified in the Terms of Reference. Further selection was informed by the review of the 2020 Eunomia report "Chemical Recycling: State of Play", the most cited papers and reports within the Eunomia report and by the consultation with the scientific advisor.

Two information discovery platforms, Lens and Dimensions, were used to identify scholarly, policy and patent literature. These platforms provide access to the world's largest publicly available databases with internal transparency metrics. **Dimensions** is an inter-linked research information system provided by Digital Science (https://www.dimensions.ai) with more than 120 million records. We have chosen this system because of the huge amount of data it provides, including the number of citations and social networks presence per publication and other relevant metrics. It also offers an API to perform queries using a specific DSL (Domain Specific Language). **Lens** (lens.org) has over 197 million

Scholar records sourced from Microsoft Academic (the major source), Pubmed, and Crossref, and it is used as a consistency gateway.

The searches resulted in 46 papers to be used as a start set. The number of papers by the various research topics is summarised in Table 2-1.

Table 2-1: Start set of papers according to research topics

Research topics	Number of papers
Chemical recycling technologies (topic 1)	11
Waste streams (topic 2)	10
Recovered substances, materials and waste residues (topic 3)	5
Chemical recycling and substances of very high concern (topic 4)	8
Chemical recycling and policy developments (topic 5)	7
Chemical recycling and tracking systems (topic 6)	5

For the purposes of keywords' extraction, the textual content of these papers was pre-processed with tokenization, lowercasing and minimal cleaning using python built-in functions and common tools and packages (e.g. Pandas, NLTK corpus). Three methodologies to extract keywords were applied:

1. ***TF-IDF:*** Text Frequency Inverse Document Frequency analysis, at a high level, finds the words that have the highest ratio of occurrences in the document analysed and give them scores.

2. ***TextRank algorithm (with Gensim):*** Gensim is a Python NLP library created to automatically extract semantic topics from documents. It is an open-source vector space modelling and topic modelling toolkit using NumPy, SciPy. The Gensim coding implementation is based on the popular TextRank algorithm. It also allows lemmatization of the words.

3. ***RAKE Algorithm:*** RAKE Algorithm refactors Python's search algorithm to capture the co-occurrences (two words appearing in proximity). The project team built a co-occurrence matrix that showed the number of times a 'term x' appeared near a 'term y'. This matrix provides combinations of key terms that could be useful for searches.

The project team "fed" the selected papers to the algorithms that produced lists with words and occurrence values. The first 30-40 rows were considered. In addition, "comparison csv lists" were produced, analysing the intersection of words for each of the methods used and identifying the keywords that were present in all the papers on each subtopic. The keywords occurring the most in each paper and across papers are presented in Annex 1. The project team further enhanced the resulting keywords and used them to carry out iterative searches using Dimensions.ai.

Following keywords extraction, **snowballing of the start paper set** was performed. "Snowballing" is the use of the reference list of the reviewed papers, citations and authors to identify additional papers. The approach also benefits from looking at where the papers were actually referenced and cited. The use of references and citations is referred to as backward and forward snowballing. Both techniques were applied on the start set of seminal and highly cited papers in the areas investigated. Through backward snowballing, the project team looked at the reference list of the start set of papers for each subtopic and excluded those papers that did not fulfil the basic criteria, such as language, publication year and type of publication. For the purposes of snowballing, a text scraping programme in python was created. It used open-source libraries such as NumPy, PANDAS, or PyPDF2 that can extract all the citations within the papers included in the start set, and count how often those have been used. This data mining strategy allowed to assign relevance scores to citations based on the number of organic appearances throughout the different sections of the documents.

Using the extracted keywords, **iterative searches** were performed. **Search results were screened for inclusion** in the data sources of this research. The publications were included with an outlook to the scientific metrics of the publication (e.g., impact factor for scientific journals) and a number of citations and altmetrics. The fact that the newest literature sources may have fewer citations than older ones was considered. **Due to the substantial volume of research on many topics of this study, where appropriate priority was given to literature reviews and bibliometric studies**. The recommendations by ECHA and scientific advisor were also considered. Papers suggested by the participants of the expert consultation were screened and included where appropriate. Several search iterations were performed based on the discussions with ECHA and the assessment of the quality of the literature review presented in the interim report.

As a result of searches and screening, the review considered **229 publications**: 113 papers in scientific journals, eight books, 21 websites and 87 other sources (e.g., policy and legal documents, reports and studies published by non-profit organisations and governmental agencies).

2.2 Expert survey

The project team carried out **semi-structured interviews** with a number of experts to collect new information and complement information collected through the literature review. Semi-structured interviews are an effective technique of data collection, considering:

- The broad spectrum of research questions we need to address;
- Varying levels of depth of each subtopic;
- Diverse level of expertise of the interviewees across the topics.

The main advantages of semi-structured interviews are the ability to achieve the maximum level of detail on each topic and the opportunity to get comparable results from different interviews by using the same questionnaire template.

Convenience and purposive sampling were combined to reach the pool of relevant experts. RPA's, RPA Europe's and ECHA's networks were used to identify the experts. Experts who possess expertise in any of the six research topics (or a combination of those) and representing different organisations active in the study field (e.g., academic researchers, companies, industry associations, governmental agencies, non-profit organisations) were selected.

On 13 April 2021, the team launched a two-week poll to survey the interests and availability of chemical recycling experts in participating in the consultation for this study. Invitations were sent to 24 industry associations, 42 companies, two national authorities and six non-governmental organisations for a total of 74 stakeholders. The invitation to poll was posted on the RPA and RPA Europe websites and LinkedIn profiles. The poll was advertised on ECHA Weekly News on 21 April. One hundred and twelve answers were received from businesses, industry associations, non-governmental organisations, national and regional authorities, academia etc. The summary of the poll results is provided in Annex 2.

The concept of data saturation, which is employed as guidance for non-probabilistic sampling, was used to reach an adequate **sample size** for addressing all six research topics. Data saturation refers to the data collection stage when no new themes emerge in the interviews. The widely cited experiment with data saturation by Guest et al. (2006) suggests that six interviews are enough to reveal the main sub-themes within one research topic, while 12 interviews allow reaching the full data saturation. Depending on the availability of experts, the sample was constructed within this range.

An online survey was open for one month in July 2021. The survey questionnaire aimed to complement information gathered through the expert interviews and focused on regulatory challenges, in particular with chemical legislation, of chemical recycling facility operators. Nineteen (19) responses were provided, mainly by large companies with chemical recycling technologies already operating at industrial scale. Survey questionnaire and results are presented in Annex 5.

Thematic analysis, a widespread qualitative method applied for the interpretation of textual research data, was used for the **interpretation of data f**rom both interviews and the survey. It allows mapping of the main topics in the text without quantifying them.

3 Chemical Recycling in the Context of the Circular Economy

3.1 Defining chemical recycling

The Waste Framework Directive (WFD, European Parliament, 2008) defines recycling as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations". Importantly, WFD defines waste hierarchy to guide the prioritisation of specific initiatives and methods in waste prevention and management policy and legislation (see Figure 3-1).

Figure 3-1: Waste hierarchy - *Source: European Commission, n. d.b*

As shown in Figure 3-1, prevention of waste is the most preferred method, followed by preparing for re-use, recycling, recovery and ending up with the least preferred method – disposal, used only when other alternatives are not possible (European Parliament, 2008).

In the research literature, chemical recycling is positioned as **tertiary recycling** within a four-tier recycling system. Primary and secondary levels involve physical processes and are referred to as mechanical recycling, and quaternary recycling produces energy from plastic waste. Tertiary recycling covers both the recovery of plastics and the production of fuels and other substances (Briassoulis et al., 2019; Lee & Liew, 2020; Sethi, 2016; Solis & Silveira, 2020). It means that in the research literature, the concept of recycling is broader than in the WFD (European Parliament, 2008). In the WFD, materials used for energy recovery, as fuels or for backfilling purposes are excluded from the definition of recycling. Recovery other than recycling is mainly associated with energy recovery and waste being used as fuel. The term backfilling falls under 'other recovery'. 'Other recovery' is any operation meeting the definition for 'recovery' under the WFD, but failing to comply with the specific requirements for recycling (or for preparation for re-use) (European Parliament, 2008; Eurostat, n.d.).

In fact, it also covers recovery operations as defined under the WFD because recovery considers the production of fuel. However, it is a less desired waste management method than recycling in accordance with the waste hierarchy (European Parliament, 2008).

Chemical recycling is an umbrella term that covers different methods of decomposition of plastic waste into its constituents (e.g., monomers, oligomers) and other substances, such as liquid, gaseous or solid hydrocarbons (Sethi, 2016; Davidson et al., 2021; Lee & Liew, 2020). Decomposition of polymers to monomers or oligomers is referred to as depolymerisation (Davidson et al., 2021; Vollmer et al., 2020). The International Standardisation Organisation provided a similar definition of chemical recycling in 2008: "conversion to monomer or production of new raw materials by changing the chemical structure of plastics waste through cracking, gasification or depolymerization, excluding energy recovery and incineration" (International Organization for Standardization, 2008).

In research publications, the use of the term 'chemical recycling' varies. It results in **different approaches to the outcomes of chemical recycling and varying classifications of technologies**. In many publications, two terms – 'chemical recycling' and 'feedstock recycling' are used. Some scholars treat them synonymously, while others use them differently (Davidson et al., 2021). Sometimes, 'feedstock recycling' is defined as a method for breaking the plastic waste down to feedstock (i.e., raw material) that is used for making new polymers (Vollmer et al., 2020). So, as precisely noted by Davidson et al. (2021), feedstock recycling is used synonymously to depolymerisation by some authors. However, the latest literature reviews on chemical recycling treat it more broadly than depolymerisation and consider chemical recycling technologies that produce liquids, gases, and other outputs (e.g., Ragaert et al., 2017; Solis & Silveira, 2020; Datta & Kupczynska, 2016). Similarly, a broader definition is adopted by the industry. For instance, the European Chemical Industry Council, Cefic (2020), defines chemical recycling as "a process where the chemical structure of the polymer is changed and converted into chemical building blocks including monomers that are then used again as a raw material in chemical processes".

Differently from other recycling methods, chemical recycling introduces **changes to the chemical structure of a polymer** (Sethi, 2016; Vollmer et al., 2020). For instance, primary and secondary recycling results only in physical changes of polymers through such treatment as crushing, remoulding or melting (Lee & Liew, 2020). Changes in chemical structure is an important criterion for distinguishing chemical recycling technologies from other approaches. For instance, the comparison of grey literature (Crippa et al., 2019; Hann & Connock, 2020; Patel et al., 2020; Cefic, 2020) with research publications reviewing chemical recycling (Ragaert et al., 2017; Solis & Silveira, 2020; Datta & Kupczynska, 2016) has shown different approaches in presenting chemical recycling technologies. Crippa et al. (2019), Hann and Connock (2020), Patel et al. (2020) include solvent-based purification (also known as dissolution) in their overviews of chemical recycling technologies. Cefic (2020) presents dissolution as a different technology and does not relate it to chemical recycling. The available literature reviews do not address dissolution as a chemical recycling technology at all (e.g., see Ragaert et al., 2017; Solis & Silveira, 2020; Datta & Kupczynska, 2016). The only exception is Vollmer et al. (2020), but they conclude that solvent-based purification is not a chemical recycling method because the chemical structure of polymers remains unchanged and they addressed this technology in the review for a different reason. Furthermore, CreaCycle GmbH specifies that its dissolution method CreaSolv is not a chemical recycling method due to the reason mentioned above, although it is often referred to as a chemical recycling technology (CreaCycle, n. d.).

Researchers use diverse criteria for **classifying chemical recycling** methods. Mainly, the research literature distinguishes thermal and chemical ways to decompose polymers based on the type of agents used for this purpose. Pyrolysis and gasification are well-known instances of chemical recycling technologies that use thermal energy for reprocessing of polymers. Chemical decomposition of polymers is a group of technologies, referred to as chemolysis (also chemical depolymerisation), that use chemical agents for breaking down polymers into monomers and oligomers (Ragaert et al., 2017).

Outputs of chemical recycling are used for the production of plastics or fuels. So, in terms of the European Parliament's (2008) definition of 'recycling', chemical recycling technologies can only in part be classified as recycling. Similarly, the reports by various non-profit organisations highlight that waste-to-fuel schemes in chemical recycling cannot be treated as recycling activities (Schlegel, 2020;

Patel et al., 2020). Differently, Ragaert et al. (2017) considers all outputs of chemical recycling and treats it as a supplementary route for mechanical recycling initiatives that is “preferable to energy recovery or landfilling”.

In summary, the research and grey literature ground their definitions of chemical recycling on a different understanding of the concept of recycling in general. It leads to different evaluations of the chemical recycling technologies and their potential. This study will use the wider approach to chemical recycling as outlined in the research literature and discussed above. However, the concept of recycling adopted by the WFD (European Parliament, 2008) will serve as guidance for evaluating the current state-of-the-art and developments in the chemical recycling field.

3.2 The role of chemical recycling in the circular economy

Chemical recycling technologies have attracted the interest of decision-makers, industries and scientists for several reasons. The first reason is the global increase in waste generation and various waste streams, often including hazardous materials, and the environmental pollution caused by this growth combined with ineffective management practices. The second reason (which is closely related to the first one) is the linear economy of consumption that leads to exhaustion of natural resources, climate change, and pollution, which could dramatically affect the future of human societies. For tackling this challenge, the development of a circular economy that would inspire reduced consumption of natural resources, safe and continuous use of materials and products, less waste and other benefits are seen as the solution.

These concerns and solutions are highlighted in the main strategic documents of the European Union that focus on the environmental and circular economy policies. A comprehensive understanding of the interlinkages between resources, industrial activities, environment, health, and well-being is reflected in the European Green Deal that represents a new and ambitious direction for European environmental policies. This includes both the level of environmental protection proposed, drawing on the “net zero” concept in GHG emissions reduction and the breadth of the connections made to wider societal and economic areas. The Green Deal connects the circular economy to the potential solutions for environmental issues.

An ambitious Circular Economy Package was designed to help EU businesses and consumers make the transition to a stronger and more circular economy, where resources are used more sustainably. In January 2018, the Commission published the Communication on the Implementation of the Circular Economy Package (European Commission, 2018a), which acknowledged that whilst the action of the Circular Economy Package helped to ‘close the loop’ of product lifecycles, recycling and re-use can be hampered by the presence of certain chemicals. These substances of concern can be hazardous to humans or the environment, have technical barriers preventing recycling, or, if the product to be recycled has a long lifetime, may now contain chemicals that are prohibited for use.

In March 2020, the European Commission launched The **Circular Economic Action Plan (CEAP)** (European Commission, 2020) to help accelerate the transformational change required by the European Green Deal. The plan offers several interrelated initiatives to establish a coherent and robust product policy framework that will help sustainable products, services and business models to become the norm and transform the current consumption patterns so that no waste is produced in the first place. The CEAP defined key value chains to be addressed as a matter of priority, with further measures to reduce waste and ensure the EU has a well-functioning internal market for high quality secondary raw materials.

The CEAP builds on the current interface between waste legislation, REACH, chemicals and products, an issue discussed at length in the Commission’s 2018 Staff Working Document (European Commission, 2018b) supplementing the Communication on the implementation of the Circular

Economy Package. Cefic's 'Molecule Managers' 2050 vision report (Cefic, 2019) also recognised the centrality of the circular economy to Europe's policy goals and noted that it expected to see European legislation recognise chemical recycling as a valuable waste management option. Chemical recycling is seen as a potential solution in fulfilling the goals of the circular and climate neutral economy in Europe:

- First of all, it is seen as an additional waste management option that may contribute to reducing waste entering the natural environment and substitute ineffective waste management practices that increase environmental pollution (e.g., landfilling or incineration). Landfilling and incineration are still widely used, especially for non-biodegradable plastic waste. Substantial plastic waste streams and mismanaged waste has caused unprecedented terrestrial and aquatic pollution (Geyer et al., 2017). Chemical recycling could be complementary to the conventional mechanical recycling of plastics (Crippa et al., 2019).
- Secondly, chemical recycling could be considered an additional tool to increase the circularity of plastic waste by recycling mixed and contaminated plastic waste streams that constitute the main part of municipal plastic waste (Crippa et al., 2019; Ragaert et al., 2017).
- Third, some chemical recycling technologies are seen as promising in eliminating legacy substances[2] (Wagner & Schlummer, 2020).

Despite these considerations, the potential of chemical recycling in delivering benefits for the circular economy is still a controversial topic due to several reasons.

Chemical recycling started receiving attention in the 1990s when **various projects were launched. However, many of these projects subsequently failed** due to insufficient plastic waste feedstock of appropriate quality grade, commercial and other operational issues. Even now, the technological and market readiness level of chemical technologies varies, and many of them have limited commercial application or are far from the industrial application level (Vollmer et al., 2020; Crippa et al., 2019).

The contribution of chemical recycling to the circularity of materials varies. The scholarly literature reviews about the advances of chemical recycling highlight that the products of some applied technologies, such as pyrolysis or gasification, result in the production of fuels or energy, while others, such as chemical depolymerisation, could lead to the production of value-added plastic materials (Ragaert et al., 2017; Solis & Silveira, 2020; Vollmer et al., 2020).

Opinions about chemical recycling prospects are strongly polarised among stakeholders. In 2020, several reports published by the environmental civil organisations strongly opposed chemical recycling: "All talks and no recycling: an investigation of the U.S. "chemical recycling" industry" (Patel et al., 2020) and "Chemical Recycling: Status, Sustainability, and Environmental Impacts" (Rollinson & Oladejo, 2020) by Global Alliance for Incinerator Alternatives (GAIA), "Deception by numbers" (Schlegel, 2020) by Greenpeace. Differently, a positive view on the prospects of chemical recycling has been taken in the *Quantis* report "Chemical Recycling: Greenhouse gas emission reduction potential of an emerging waste management route" (2020) commissioned by the European Chemical Industry Council (Cefic).

Projections and evaluations of the environmental, economic and technological performance **of chemical recycling and their viability under close-to-real-life conditions are currently missing**. These gaps result in the limited capacity of the available information to inform strategic decisions (Hann & Connock, 2020; Davidson et al., 2021).

[2] Substances that were formerly used as plastic additives but that, in the meantime, have been recognised as substances of very high concern and/or persistent organic pollutants and were therefore banned or restricted.

These circumstances make the analysis of the prospects of chemical recycling an engaging but yet challenging task.

3.3 Chemical recycling in the context of the EU plastic waste recycling policies and targets

In the Circular Economy Action Plan (CEAP, European Commission, 2020), plastics have been defined as a key value chain to be addressed. The proposed measures for plastics in the CEAP cover waste reduction and uptake of recycled waste, focusing on the most significant streams of plastic waste – packaging, construction materials, and end-of-life vehicles. Objectives and targets relevant to the recycling of plastic waste are provided in several EU policy documents: the Waste Framework Directive (WFD) 2008/98/EC, Packaging and Packaging Waste Directive 94/62/EC (PPWD) and End-of-Life Vehicle Directive 2000/53/EC (ELVD). The objectives, measures and targets provided in the above-mentioned policy documents refer to recycling in general and may also influence the incentives of chemical recycling.

The WFD is an overarching document concerning waste management in the EU. It provides a definition of **recycling, sets overall objectives in the prevention, reduction and recycling of waste**. The **WFD aims** "to protect the environment and human health by preventing or reducing the generation of waste, the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use, which are crucial for the transition to a circular economy and for guaranteeing the Union's long-term competitiveness". It developed targets for preparation for re-use and recycling of municipal solid waste and construction and demolition waste (the latter have been currently under review) that might contain plastics (European Parliament, 2018). According to the WFD, preparing for re-use and recycling of municipal waste shall be increased to a minimum of 55%, 60% and 65% by weight by 2025, 2030 and 2035, respectively. Under the WFD, the attainment of the targets must be measured using the weight of the packaging prepared for re-use and/or recycled.

In the domain of **plastic packaging**, **PPWD** contributes to the main goals of the European Green Deal and CEAP, as well as the European Strategy for Plastics. The **PPWD aims** "to harmonize national measures concerning the management of packaging and packaging waste in order, on the one hand, to prevent any impact thereof on the environment of all Member States as well as of third countries or to reduce such impact, thus providing a high level of environmental protection, and, on the other hand, to ensure the functioning of the internal market and to avoid obstacles to trade and distortion and restriction of competition within the Community" (Article 1, European Parliament, 2018a). The PPWD established a target of 50% of plastic packaging waste to be recycled by 2025 and 55% - by 2030 by weight. It uses the same method to calculate the attainment of the target as the WFD.

The PPWD laid out essential requirements, which set the most important criteria for packaging to comply with to be placed on the EU market. Among various features, these requirements indicate that packaging should be manufactured in a way that enables its reuse, recyclability and recoverability (see European Commission, Annex II).

A recent study prepared for the European Commission provided a critical evaluation of the effectiveness of the essential requirements (Eunomia et al., 2020). In general, the study concluded that the essential requirements do not reflect the current knowledge of the best end-of-life management options and do not provide effective definitions of concepts that would be well-connected with the objectives of the current strategic policy documents. For instance, the requirement for recyclability of packaging in PPWD implied that a certain percentage by weight must be recyclable if the packaging is intended for recycling. It lacked a definition of 'recyclability' that would link it to the current objectives of the European Strategy for Plastics, where packaging should be 'reusable or recyclable in a cost-effective manner'. Additionally, it lacked clear operationalisation and metrics to make its implementation effective. The stakeholder workshops conducted in the study resulted in three suggestions to overcome this weakness: to develop qualitative statements with increased enforcement, to employ design for recycling (DfR) criteria and to use quantitative metrics. Importantly, stakeholders who participated in the study highlighted that chemical recycling has the potential to increase the recyclability of plastic packaging waste if it is integrated into the waste management system in Europe. At the time of the study, chemical recycling was not sufficiently implemented on a commercial scale. The potential of chemical recycling to contribute to the circular economy objectives is in the recycling of waste that cannot be mechanically recycled (Eunomia et al., 2020).

The third-largest stream of plastic waste – **end-of-life vehicles –** is covered by the **ELVD** (European Parliament, 2020), which has currently been reviewed, including the targets. The ELVD aims at the "prevention of waste from vehicles and, in addition, at the reuse, recycling and other forms of recovery of end-of life vehicles and their components so as to reduce the disposal of waste, as well as at the improvement in the environmental performance of all of the economic operators involved in the life cycle of vehicles and especially the operators directly involved in the treatment of end-of life vehicles". Similar indicators based on weight as under the WFD and PPWD were laid out in the ELVD in 2015. The ELVD itself and its target have been under review by the European Commission (European Commission, n. d.c).

The review of the ELVD, performed by the European Commission, made the following conclusions that are relevant to recycling of plastic waste:

- The provisions aimed at the facilitation of dismantling of cars and uptake of the recycled materials are relevant but not sufficiently detailed, specific and measurable.
- The ELVD is not suitable to ensure a high recycling rate of lightweight materials (among them – plastics) that have been increasingly used in cars. It does not provide any targets for the recycling of these materials. Lightweight materials, such as carbon-fibre reinforced plastics, can make dismantling and recycling more costly and complicated.
- Targets of recycling in the ELVD are based on the overall weight of a vehicle, which does not encourage the recycling of lightweight materials, such as plastics. It results in avoiding the recycling of such materials and sending them to energy recovery or landfills (European Commission, 2021).

Similar conclusions have been reached by the study "Development and implementation of initiatives fostering investment and innovation in construction and demolition waste recycling infrastructure" prepared for the European Commission (Bilsen et al., 2018). The business model of processing a plastic fraction of construction and demolition waste for selling it as a secondary raw material for the plastics industry obtained low scores (2 of 5) in terms of economic profitability, sustainability, stability and compliance. The reasons for low scores included the following: a) low quantity of plastic in construction and demolition waste that would not substantially contribute to the overall goal of recycling construction and demolition waste; b) contamination of plastic waste with additives that pose risks to the sustainability of the secondary materials and its compliance with the regulatory requirements; c) competition with lower cost virgin materials.

In summary, the current implementation of strategic objectives in plastic waste management set ambitious targets for recycling and lays out important initiatives to increase the recycling of plastic waste. However, the practical implementation of the recycling policies has been complicated by the vague definitions of important concepts (e.g. recyclability), the lack of targets oriented at specific materials, and measures for attainment of targets that discourage the recycling of plastics. Important steps to boost the recycling of plastics have been taken as a part of the review and revision of the policy documents on packaging and end-of-life vehicles waste.

4 Waste Streams in Chemical Recycling

This chapter **aims** to determine the main streams, composition, quantities and sources of waste that could be chemically recycled and trends that will affect waste generation and management in future.

4.1 Main streams of plastic waste for chemical recycling

Plastic waste originates mainly from industry activities or consumer products. **Post-industrial plastic waste** is solid plastic waste that is generated during the manufacturing process, which never makes it to the consumer, and includes reject products, cuttings, trimmings, runners from injection moulding, residues from granulation (Ragaert et al. 2017; Schwabl et al., 2021). Post-industrial waste is usually clean and uncontaminated by organic matter or pollutants such as paper, wood or other plastics, and it is often mono-material or of known composition (polymers and their amounts in case of multi-material plastics) (Ragaert et al., 2018). Post-industrial waste usually remains in the company or is handled business-to-business; therefore, quantities of post-industrial plastic waste are not publicly available. **Post-consumer plastic waste** generated at the end-of-life of the product typically consists of mixed plastics of unknown composition. It is likely contaminated with organic fractions such as food waste or other non-polymers (metal or paper). Post-consumer waste is handled by municipalities and is usually well tracked throughout Europe (Ragaert et al., 2017; Schwabl et al., 2021).

The extent to which post-industrial and post-consumer solid plastic waste can be mechanically recycled depends on several important properties of waste. These features are summarised in Table 4-1.

Table 4-1: Composition of plastic waste streams

Properties	Composition	Source
Mono	One polymer	Ragaert et al., 2017
Mixed	Blend of polyethylene (PE), polypropylene (PP), poly(ethylene terephthalate) (PET), polystyrene (PS), poly(vinyl chloride) (PVC), variety of minor components, or unknown polymers	Möllnitz et al., 2021; Shehu, 2017; Eriksen et al., 2019; Ragaert et al., 2020; Fekhar et al., 2019
Multi-layer	Often PP/polyamide (PA), PP/PET, PET/PE/aluminium foil, waste electrical and electronic equipment (WEEE) plastics	Vollmer et al., 2020
Contaminated	Organic and inorganic impurities, other polymers, other non-polymers (wood or paper), non-ferrous metals (e.g., aluminium), chemicals, PVC	Vollmer et al., 2020; Ragaert et al., 2020; Ragaert et al., 2017; Schwabl et al., 2021; Ragaert, et al., 2018; Eriksen et al., 2019
Composites	Polymer matrix, thermoset or thermoplastic, fibre reinforced plastics (FRP), glass fibre reinforced plastics (GFRP), carbon fibre reinforced plastics (CFRP), glass fibre reinforced polypropylene (PP-GF)	Shuaib & Mativenga, 2016; Biron, 2018; Vollmer et al., 2020

As shown in Table 4-1, plastic waste streams can be mono or mixed plastic, clean or contaminated (Ragaert et al., 2017). Besides, recyclability also depends on whether the plastic is multi-layered, multi-material or composite plastic or whether it contains legacy additives (European Commission, 2018c). For instance, recycling composite materials can be challenging due to their inherently heterogeneous nature. Although industrial-scale mechanical recycling exists for composite materials, only short fibres and fillers can be recovered at a low market value (Shuaib & Mativenga, 2016). Currently, multi-layered plastics are not mechanically recycled (Vollmer et al., 2020).

Post-industrial waste is usually homogenous and of a higher quality than post-consumer waste. So, it could be recycled mechanically. Differently, post-consumer waste is mixed and contaminated, and its composition is often unknown. **Chemical recycling is often viewed as a promising management option for post-consumer plastic waste** (Solis & Silveira, 2020). For instance, the recyclability of heterogenous and mixed plastic from household waste in the European context has been assessed by Eriksen et al. (2019). The study evaluated many recovery scenarios, representing a broad range of sorting schemes, source-separation efficiencies and configuration and performances of material recovery facilities. The circularity potential revealed that only 42% of the plastic loop could be closed with current technology and raw materials demand (Eriksen et al., 2019). Chemical recycling technologies such as hydrolysis and pyrolysis have been successfully applied to treat mixed plastic waste affected by impurities (Faraca & Astrup, 2019).

In 2018, 29.1 million tonnes of post-consumer plastic waste were collected in the EU (PlasticsEurope, 2019). The importance of different relevant waste streams is shown in Figure 4-1.

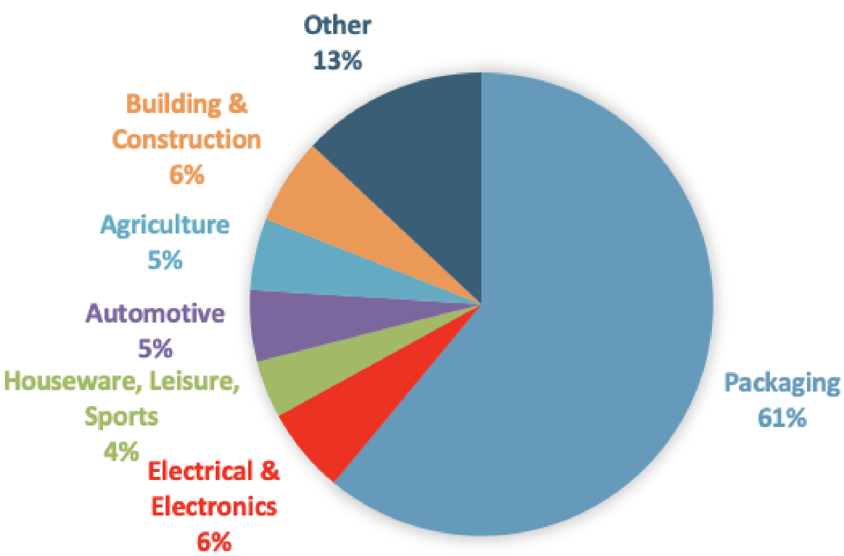

Figure 4-1: The EU plastic waste generation by a waste stream in 2018 - ***Source: PlasticsEurope, 2019***

Figure 4-1 shows that **plastic packaging waste** (household, industrial and commercial) **constituted the largest share** (61%, 17.8 million tonnes) of plastic waste. Waste from building & construction, electrical & electronics, agriculture, automotive and house, leisure & sports made up 26% of the total collected waste (PlasticsEurope, 2020; PlasticsEurope, 2019), while the remaining 13% were attributed to other waste.

It is important to note that some plastic products can be used for a long period, while others become waste after a single use.[3] The use phase of plastic products can range from less than one year to more than fifty years, depending on their application (PlasticsEurope, 2019a). For instance, packaging products are omnipresent and tend to have short lifetimes, whereas plastics in the automotive, building & construction sectors typically have longer lifetimes (Ragaert et al., 2017). Therefore, plastic waste volumes are much smaller than the total manufactured plastic parts or products put on the market for the same period (PlasticsEurope, 2019a).

[3] The EU is tackling the problems generated by single-use plastic products through Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment.

A typical composition of plastic waste in each plastic waste stream can be found in Table 4-2.

Table 4-2: Composition of post-consumer plastic waste streams		
Plastic waste stream	**Composition**	**Source**
Packaging	Poly(ethylene terephthalate) (PET), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), poly(vinyl chloride) (PVC), rubber, PS/acrylonitrile-butadiene-styrene (ABS), PA/poly(butylene terephthalate) (PBT), PE/PP (added), PE/PP, paper/fibre, metal/inerts	Meys et al., 2020; Dahlbo et al., 2018; Ragaert et al. 2017
Automotive	Polyethylene (PE), polypropylene (PP), polycarbonate (PC), acrylonitrile-butadiene-styrene (ABS), polyvinyl chloride (PVC), rubber, polyurethane (PU) foam (from seat padding), synthetic fabrics and covers	Pilát & Patsch, 2020; Liu et al., 2017
Agriculture	Polyethylene (PE), low-density polyethylene (LDPE), ethylene-vinyl acetate (EVA), polypropylene (PP), poly(vinyl chloride) (PVC) from covering films and nets, irrigation pipes, containers, bags	Vox et al., 2016; Horodytska et al., 2018
Building & Construction	ABS, PA, polycarbonate (PC), PE, PET, poly(methyl methacrylate) (PMMA), polypropylene (PP), polystyrene (PS), poly(vinyl chloride) (PVC)	Lahtela et al., 2019
Electrical & Electronics	Polycarbonate (PC), polypropylene (PP), acrylonitrile-butadiene-styrene (ABS), high impact polystyrene (HIPS), polystyrene (PS), polyamide (PA), poly(vinyl chloride) (PVC), poly(butylene terephthalate) (PBT), poly(plenylene ether) (PPE)	Kousaiti et al., 2020
Houseware, Leisure, Sports	Polypropylene (PP), poly(vinyl chloride) (PVC), polystyrene (PS), polyethylene (PE), acrylonitrile-butadiene-styrene (ABS), styrene-acrylonitrile resin (SAN), poly(methyl methacrylate) (PMMA), polyamide (PA), polycarbonate (PC), other	PlasticsEurope, 2020
Other	All polymers in different quantities	PlasticsEurope, 2020

All plastic waste streams consist of several common types of plastic polymers such as polyolefins (HDPE, LDPE and PP), PET, PS, PVC and PA. Nevertheless, most waste streams have other specific components like PU, ABS, EVA, PMMA or PC.

4.2 Trends in the management of plastic waste

To understand what will shape the management of plastic in the near and more distant future, waste scientists and research consultancies perform analyses of factors and trends influencing the management of plastic waste (Hestin et al., 2017; Simon et al., 2018) and/or develop future scenarios in waste management (see Borelle et al., 2020; Lau et al., 2020; Lebreton & Andrady, 2019; Hestin et al., 2017).

Available publications set out several trends that are shaping the management of plastic waste (with particular attention to chemical recycling):

- **The recycling rate of plastic waste is still insufficient, and it competes with incineration and landfilling** (Hestin et al., 2017; Simon et al., 2018). In 2018, 32.5% of post-consumer plastic waste collected in Europe was recycled, 42.6% or 12.4 million tonnes of all plastic waste was incinerated, and 24.9% - sent to landfills (PlasticsEurope, 2020). Although the recycling rates grow and landfilling practices decrease, they are still significant in plastics waste management. Incineration is still a prevalent practice in the management of plastic waste. For instance, in

2006-2018, the plastics recycling rates increased by 100%, while incineration – by 77%. In parallel, landfilling practices decreased from 50% of total plastic waste sent to landfills in 2006 to 24.9% – in 2018 (PlasticsEurope, 2020).

- **Chemical recycling is marginal compared to mechanical recycling** (Hestin et al., 2017; Simon et al., 2018). Out of 17.8 million tonnes of plastic packaging collected in 2018, 42% was recycled, 39.5% incinerated, and 18.5% sent to landfills. Most of the waste was recycled mechanically, and only very limited volumes (less than 0.1 million tonnes) were treated by chemical recycling processes (PlasticsEurope, 2019a; PlasticsEurope, 2020).
- **Export of waste to countries outside of the European Union plays a significant role in waste management** (Hestin et al., 2017; Simon et al., 2018). EU countries export waste to different destinations, mainly Asian countries. The export routes are affected by the changing import legislation of the destination countries, e. g., China's plastic waste import ban in 2017, which reduced plastic waste exports to China by approximately 96% and to Hong Kong by more than 70% (European Environment Agency, 2019). However, exports to other Southeast Asian countries, such as Malaysia and Indonesia, as well as Turkey, have been increasing since 2017. The fate of this plastic waste is not always clear. However, a significant negative correlation between a country's GDP per capita and mismanaged waste suggests that a greater amount of waste is not adequately disposed of in developing countries (Lebreton & Andrady, 2019). Amendments to the Basel Convention, which restrict the export of plastic waste from Europe to countries that do not meet high waste management standards for recycled plastic, should help the EU to boost the recycling industry (European Commission, 2018d) as large volumes of plastic waste now remains in the EU to be treated locally.

Future projections of managing plastic waste show the severity of the issue and the need to combine different strategies to achieve a satisfactory result. Table 4-3 provides examples of recent scenario exercises along with the main findings from these studies.

Table 4-3: Plastic waste management scenarios

Source	Scope	Key findings
Borelle et al., 2020	Emissions of plastic waste to water Worldwide, 173 countries Emissions scenarios by 2030 Starting point: 2016 statistics	'Business as usual' scenario: emissions to water of 90 Mt/y. Ambitious scenario (efforts based on global commitments*): from 20 to 53 Mt/y. Target scenario (> 8 Mt/y): plastic waste generation to be reduced by 25% to 40%**, levels of managed waste to reach 60% to 99%**; recovery of 40% environmental emissions by 2030 is needed.
Lau et al., 2020	Terrestrial and aquatic plastic pollution Worldwide (no. of countries is not specified) Plastic pollution by 2040 Starting point: 2016 statistics	Measure: the combined decrease in aquatic and terrestrial pollution (%) in comparison to BAU. 'Business as usual' scenario (BAU): decrease in aquatic and terrestrial pollution of 6.6% and 7.7%, respectively. 'Collect and dispose' scenario: 57%. 'Recycling' scenario: 45%. 'Reduce and substitute' scenario: 59%. Integrated 'System change' scenario: 78%.
Lebreton & Andrady, 2019	Mismanaged plastic waste (MPW) Worldwide, 188 countries MPW generation scenarios by 2060 Starting point: 2015 statistics	Scenario A ('business as usual'): 155 to 265 Mt/y of generated MPW. Scenario B (improvements in waste management infrastructure): 22 to 94 Mt/y of generated MPW. Scenario C (improvements in waste management infrastructure and reduction in household plastic

Table 4-3: Plastic waste management scenarios		
Source	**Scope**	**Key findings**
		use by 10% of municipal solid waste in 2040 and 5% - in 2060): 25 Mt/y of generated MPW.
Hestin et al., 2017	Implementation of the 55% plastic packaging recycling target European Union (basing on France, Germany, Italy, Spain, and the UK) Target scenario by 2025 Starting point: 2014 statistics	The penetration rate of recyclates should reach 30.2%. The collection rate for all packaging plastics should reach 74 %; 88% - for PETs and polyolefins. Policy measures: promotion and standardisation of product eco-design; development of the waste collection and deposit schemes; reduction of export to the non-EU countries; increase in sorting and recycling capacities; increase in end-use of recyclates.
*NOTE: *Global commitments are informed by G7 Plastics Charter, the European Union Strategy, the United Nations Environment Programme, Clean Seas, and the Our Oceans conferences. **Rates vary depending on the country income level*		

As stressed by all studies, **substantial efforts should be put into activities reducing the generation of plastic waste and its emissions to the environment**. Lebreton and Andrady (2019) advise a substantial reduction of plastic fraction in municipal solid waste. While in some countries it is a reality (e.g., in Denmark 1% of municipal solid waste was composed of plastics in 2016), others would need a substantial reduction effort (e.g., in the Netherlands, 19% of municipal solid waste was composed of plastics in 2016). Borelle et al. (2020) recommend high rates of management of plastic waste that should reach 99% in high-income economies and 60% - in low-income countries; reduction of waste generation by 40% in high-income and 25% in low-income economies in line with the recovery of 40% of aquatic emissions of plastics. Similarly, to reach not so distant goals of recycling 55% of plastic packaging waste in the EU, the collection rate, especially for PET and polyolefins, should increase up to 88% in line with better integration of recyclates into the market with 30.2% of recyclate penetration rate (Hestin et al., 2017).

The review of the scenarios makes it evident that **no one strategy would lead to a significant reduction in plastic waste both worldwide and in the European Union**. All research emphasised the need to combine pre-consumption (e.g., reduction of plastic use, eco-design of products) and post-consumption (e.g., waste collection and recycling) incentives. Lebreton and Andrady (2019) have shown that a combination of improvements in waste infrastructure and reducing the household use of plastics is necessary to significantly reduce mismanaged plastic waste that is currently a huge environmental pollution issue. Borelle et al. (2020) determined that to reach the target of 8 Mt/y emissions of plastic waste to water, the countries worldwide should apply a set of measures in building high waste management capacities combined with the reduction of plastic use. Hestin et al. (2017) extend this advice to cover the promotion of eco-designed products and the usage of recyclates. Lau et al. (2020) relied on an extensive analysis of eight types of interventions based on four classes of incentives in reducing plastics in the system, substituting it with other materials, maximising recycling capacities, reducing plastic waste leakage, and its export. The study has shown that only a mix of all these strategies would result in the substantial achievement of a 78% decrease in plastic pollution in the ‘System change’ scenario.

4.3 Trends in plastics production

Plastics are one of the most intensively manufactured and used materials in the world. According to the estimations by Geyer et al. (2017), 8,300 Mt of plastics were produced in the world in 1950-2015. Almost half of it (3,900 Mt) was produced in the last thirteen years of this period. It means that the volumes and pace of **production of plastics have increased substantially in the world**. The global production capacity for bio-based or biodegradable plastics constitutes only 4 Mt, so it is negligible in the general plastic flow (Geyer et al., 2017).

EU plastic production in 2019 was 58 million tonnes, which represented 16% of global production (368 million tonnes). Although globally the plastic production has been steadily increasing (see Figure 4-2), European production was relatively stable over the same period (PlasticsEurope, 2020). It is estimated that **the production of plastic globally can double by 2035 and quadruple by 2050** (Mrowiec, 2018).

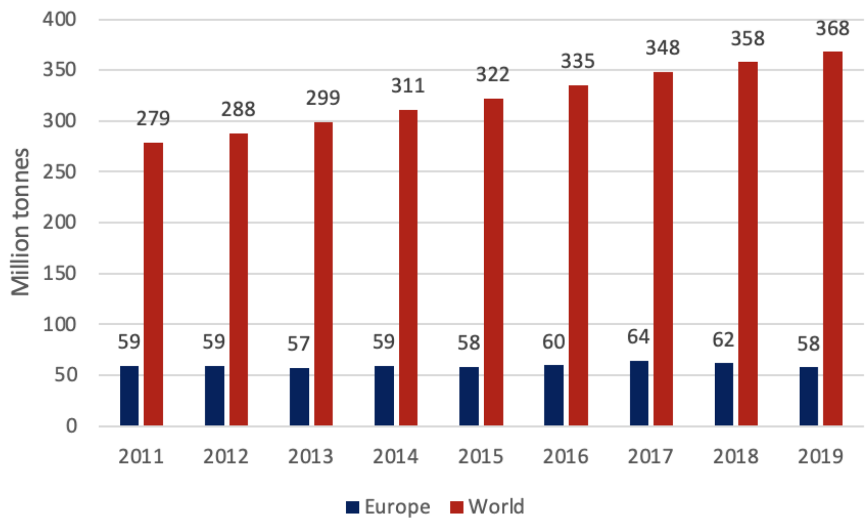

Figure 4-2: The plastic production in Europe and the World from 2011 to 2019
Sources: PlasticsEurope, 2016; PlasticsEurope, 2017; PlasticsEurope, 2018; PlasticsEurope, 2020

The demand by the European plastic converters (manufacturers of plastic products) has been gradually increasing over the same period.

In 2019, the demand for plastics by European (EU28+NO/CH) plastic converters was 50.7 million tonnes. **Almost 40% of the total demand was for packaging**, followed by building and construction (20.4%) and automotive (9.6%) industries (see Figure 4-3).

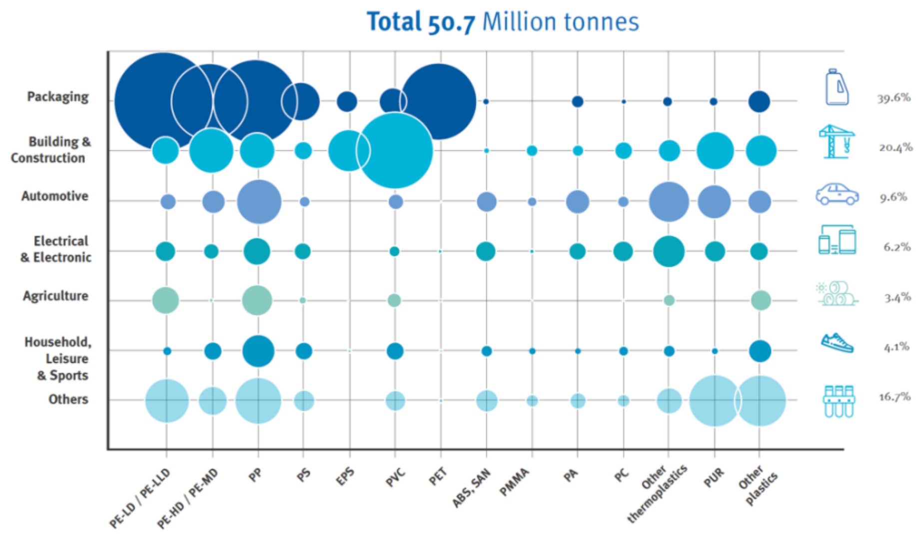

Figure 4-3: Plastic demand by segment and polymer type in 2019 - *Source: PlasticsEurope, 2020*

As shown in Figure 4-3, other sectors, including medical, mechanical engineering, appliances and furniture manufacturers, made up 16.7% of the total demand. The leading polymers with almost 50%

of the total demand were polyolefins (PE & PP), mainly used for packaging. PVC, which made up 10% of the total demand, was mainly used in building & construction. (PlasticsEurope, 2020).

Worldwide, the production of plastics is mostly focused not on durable but on single-use plastics (e.g., grocery bags, cutlery, containers, bottles etc.) that are intended to be used only once before throwing them away (Giacovelli et al., 2018). In this group, **plastic packaging** is a predominant product. According to the estimations by Geyer et al. (2017) adopted by Giacovelli et al. (2018), plastic packaging constituted 47% of all plastic produced in the world. The increase in demand and production of single-use plastics results in a growing share of such packaging in waste (Hong & Chen, 2017). To cope with this trend, governments worldwide introduce regulatory and economic measures to diminish the use of plastic packaging products (Giacovelli et al., 2018).

5 Chemical Recycling Technologies

This chapter **aims** to provide an overview of chemical recycling technologies that are commercially available or are at the stages close to industrial applications as well as emerging technologies.

Chemical recycling technologies have been widely discussed in the academic literature. A number of comprehensive scientific reviews distinguish several main commercially applied technologies such as **conventional pyrolysis, catalytic cracking** (Datta & Kopczynska, 2016; Lopez et al., 2017; Ragaert et al., 2017; Solis & Silveira, 2020; Vollmer et al., 2020), **conventional gasification** (Datta & Kopczynska, 2016; Ragaert et al., 2017; Solis & Silveira, 2020), **chemolysis** (Datta & Kopczynska, 2016; Ragaert et al., 2017; Vollmer et al., 2020), and several pilot or laboratory scale technologies, such as **hydrocracking** (Datta & Kopczynska, 2016; Lopez et al., 2017; Ragaert et al., 2017; Solis & Silveira, 2020; Vollmer et al., 2020), **pyrolysis with in-line reforming** (Lopez et al., 2018; Lopez et al., 2017; Solis & Silveira, 2020), **plasma pyrolysis** (Lopez et al., 2017; Solis & Silveira, 2020; Vollmer et al., 2020), **microwave-assisted pyrolysis** (Al Rayaan, 2021; Lopez et al., 2017; Solis & Silveira, 2020; Vollmer et al., 2020), and **plasma gasification** (Al Rayaan, 2021; Lopez et al., 2018; Solis & Silveira, 2020). Although plasma gasification has been commercially applied, the technology has mainly been used for the destruction of hazardous waste and not for the recycling of plastic waste. However, this technology has been mentioned as a promising method for recovering valuable products from plastic waste (Al Rayaan, 2021; Solis & Silveira, 2020).

Table 5-1 provides an overview of commercial and developing chemical recycling technologies and targeted plastic waste types. While some of these technologies can accept a wide array of plastics, others may not be so versatile. However, they still hold potential, as they excel in treating some types of plastic waste others cannot.

Table 5-1: Chemical recycling technologies overview

Technology	Scale of operation	Input materials	Source
Pyrolysis (conventional pyrolysis, thermal cracking)	Commercial	HDPE, LDPE, PP, PMMA, PS, HIPS, ABS, PU, mixed PE/PP/PS, fibre-reinforced composites, multi-layered plastic packaging	Datta & Kopczynska, 2016; Lopez et al., 2017; Ragaert et al., 2017; Solis & Silveira, 2020; Vollmer et al., 2020
Catalytic cracking	Commercial	HDPE, LDPE, PP, PS	Datta & Kopczynska, 2016; Lopez et al., 2017; Ragaert et al., 2017; Solis & Silveira, 2020; Vollmer et al., 2020
Conventional gasification	Commercial	All types of plastics, mixed plastics	Datta & Kopczynska, 2016; Ragaert et al., 2017; Solis & Silveira, 2020
Chemolysis	Commercial	PET, PU, PC, PA, PLA, PLLA	Datta & Kopczynska, 2016; Ragaert et al., 2017; Vollmer et al., 2020
Hydrocracking	Pilot	All types of plastics, mixed plastics	Datta & Kopczynska, 2016; Lopez et al., 2017; Ragaert et al., 2017; Solis & Silveira, 2020; Vollmer et al., 2020
Pyrolysis with in-line reforming	Pilot	PE, PP, PS, mixed plastics (PE/PP/PET)	Solis & Silveira, 2020; Lopez et al., 2018

Table 5-1: Chemical recycling technologies overview			
Technology	**Scale of operation**	**Input materials**	**Source**
Plasma pyrolysis	Laboratory	Mixed plastics	Lopez et al., 2017; Solis & Silveira, 2020; Vollmer et al., 2020
Microwave-assisted pyrolysis	Laboratory	Plastic waste, PS/PP mixtures	Al Rayaan, 2021; Lopez et al., 2017; Solis & Silveira, 2020; Vollmer et al., 2020
Plasma gasification	Commercial in decomposing hazardous waste	All types of plastics, mixed plastics	Al Rayaan, 2021; Lopez et al., 2018; Solis & Silveira, 2020

Table 5-1 shows that most of the considered chemical recycling technologies are at the stage of commercial application, while few of them are at the development stages.

5.1 Commercially applied chemical recycling technologies

Four technologies listed in Table 5-1 are commercially applied for the recycling of plastic waste. They include pyrolysis, catalytic cracking, conventional gasification, and chemical depolymerisation.

Pyrolysis (also known as conventional pyrolysis, thermal cracking) is one of the most widely known and commonly mentioned chemical recycling techniques in the literature. Pyrolysis is a thermal cracking reaction under the absence of oxygen that breaks down the macrostructure of polymer and leads to the formation of monomers or fuel-type products (Datta & Kopczynska, 2016; Ragaert et al., 2017). The process parameters, such as temperature, pressure, residence time, affects the final product (Solis & Silveira, 2020). Temperature is one of the most important parameters because it controls the cracking reaction of the polymer chain and influences the product composition. Higher temperatures of more than 500°C would yield more gaseous or char products, whereas lower temperatures of 300-500°C would produce liquid oil (Sharuddin et al., 2016). The pyrolysis process is a relatively simple technology suitable for recycling plastic waste that is difficult to depolymerise. The process can handle many types of plastics, as shown in Table 5-1; however, it has a low tolerance to PVC in the feedstock due to the formation of chlorinated compounds. This process is also known for high energy consumption, sensitivity to feedstock contamination and lower quality recyclates that need further upgrading (Solis & Silveira, 2020).

Solis & Silveira (2020) assigned pyrolysis a Technology Readiness Level (TRL) 9 that shows that the method is commercially applied and/or developed in large/medium/small-sized companies. Several functioning and pilot plants in the USA, Japan, China, Germany, and Spain are quoted by Solis & Silveira (2020) and Ragaert et al. (2017). Some of these examples are presented in Table 5-3.

Catalytic cracking is another version of pyrolysis that involves the use of catalysts, such as zeolites and silica-alumina, which reduces the activation energy of the process and increases the rate of reaction. Hence, the catalyst addition allows to carry out the process at lower temperatures (300-350°C) and reduce the energy consumption. Furthermore, it narrows the hydrocarbon distribution in the final products, allowing to obtain liquid oil with similar properties to conventional fuels (Lopez et al., 2017; Sharuddin et al., 2016; Solis & Silveira, 2020). The process generates higher oil yields if compared with conventional pyrolysis for most plastics, but only if the right catalyst is chosen. However, catalytic cracking is sensitive to the contamination of plastic because the presence of the chloride and nitrogen components in the plastic waste stream can deactivate the catalyst, and inorganic materials can block the pores of the catalyst (Solis & Silveira, 2020). Hence, thorough pre-treatment is required to protect the catalyst (Ragaert et al., 2017). The process is limited to pure polymers such as polyolefins and polystyrene (Datta & Kopczynska, 2016).

With a high technology readiness level (9), industrial facilities are available in different countries around the world. Some of them located in the USA, Japan, India, and Poland are mentioned by Solis & Silveira (2020) and Ragaert et al. (2017).

Gasification processes involve partial oxidation of plastic waste in the presence of an oxidation agent, which can be a mixture of steam and pure oxygen or simply air (Datta & Kopczynska, 2016; Ragaert et al., 2017). The process achieves detailed polymer breakdown and yields a mixture of hydrocarbons and syngas, which can be used to produce energy, hydrogen, or chemicals, and by-products, such as tars and chars (Solis & Silveira, 2020). The process is mainly used to produce petroleum fuel substitutes and combustible gases (Datta & Kopczynska, 2016). The gasification of plastic waste usually occurs at temperatures of 700-1,200°C and depends on the oxidation agent, which determines the composition of the syngas, and therefore its applications. Due to the higher tar content in the gas produced from plastic waste, the efficiency of the process is reduced, and the product needs upgrading before use. Furthermore, the process is energy-intensive and costly, hence requires high volumes of feedstock to be economically viable (Solis & Silveira, 2020).

The gasification process was assigned a high technology readiness level (9) by Solis and Silveira (2020). An example of a commercial gasification operation is the Enerkem plant in Canada (see Table 5-3), which produces 38 million litres of biofuel methanol, then ethanol, and ethylene from 100,000 tonnes of plastic waste. Enerkem is a part of the consortium that plans to build a chemical recycling plant in the Netherlands with the capacity to convert 360,000 tonnes of waste to chemicals per year (Solis & Silveira, 2020).

Chemolysis is the process of breaking down polymers into monomers, oligomers or other chemical substances that could be used as raw resources for manufacturing new materials and products. There are different types of chemical depolymerisation depending on the type of chemical agent involved: methanolysis, glycolysis, hydrolysis, alcoholysis, aminolysis, etc. (Ragaert et al., 2017; Datta & Kopczynska, 2016). The process is capable of obtaining monomers that can be purified by filtering out colourants and additives to produce virgin-grade quality material (Vollmer et al., 2020). Therefore, chemolysis opens up opportunities for different industrial applications where pure materials are important, e.g., food contact materials. This technology can only be applied to condensation polymers such as PET and polyamide (Ragaert et al., 2017) and is mostly suitable for homogeneous plastic waste (Solis & Silveira, 2020). To obtain a homogenous stream, mixed plastic waste can be separated and sorted based on shape, density, colour, size or chemical composition of plastics, which can be done by several techniques, such as flotation (sink-float), melt filtration, FT-NIR (Fourier Transform Near Infrared), magnetic density separation, tribo-electric separation, froth flotation, or X-ray detection (Ragaert et al., 2017). Several issues have been identified in chemolysis, such as separation of the liquid cleavage agent and other by-products, recovery of dissolved catalysts, and the small contact area between the cleavage agent and the polymer (Vollmer et al., 2020). Moreover, recycled materials are more expensive than virgin counterparts; hence, for the process to become economically viable, a vast amount of waste input is required (Ragaert et al., 2017).

Based on Solis and Silveira (2020) evaluation method on TRL, chemolysis can be assigned level 9 as it is a commercially available technology. Glycolysis is applied on a commercial scale by well-known companies, such as DuPont/DOW, Goodyear, Shell Polyester, Zimmer, and Eastman Kodak (Ragaert et al., 2017) and well as Garbo, IBM, Ioniqa, and PerPETual (Vollmer et al., 2020). Hydrolysis has also been applied on a commercial and pilot scale by companies such as Gr3n, Carbios and Aquafil, whereas methanolysis is applied by Loop Industries and in development by Eastman (Vollmer et al., 2020).

A summary of the advantages and disadvantages of each commercially applied chemical recycling technology is provided in Table 5-2.

<table>
<tr><th colspan="2">Table 5-2: Advantages and disadvantages of commercially applied chemical recycling processes</th></tr>
<tr><th>Advantages</th><th>Disadvantages</th></tr>
<tr><th colspan="2">Pyrolysis</th></tr>
<tr><td>• High calorific value fuel that can be used in gas engines to produce electricity (Antelava et al., 2019)
• Simple technology, in which the process parameters can be changed to optimize the product yield according to preferences and needs (Solis & Silveira, 2020)
• Suitable for difficult to depolymerise plastic waste, such as multi-layered plastic packaging (Solis & Silveira, 2020)
• Suitable for highly heterogeneous mixtures of plastics (Ragaert et al., 2017)
• Does not require intense feedstock sorting (Sharuddin et al., 2016)
• The technique can be executed at different parameters that result in different liquid oil yields and quality (Sharuddin et al., 2016)
• Less environmental pollution than in incineration and gasification (Al-Salem et al., 2017)</td><td>• High energy requirement (Solis & Silveira, 2020)
• Low tolerance to PVC as chlorinated compounds can be formed in the pyrolysis oil (Solis & Silveira, 2020)
• Products often need upgrading before further use (Solis & Silveira, 2020)
• Requires high volumes to be cost-effective (Ragaert et al., 2017)
• The complexity of reactions (Solis & Silveira, 2020)
• Demands relatively high temperatures (Miandad et al., 2016)</td></tr>
<tr><th colspan="2">Catalytic cracking</th></tr>
<tr><td>When compared to conventional pyrolysis:
• Lower operating temperatures (Solis & Silveira, 2020)
• Higher oil yields (Solis & Silveira, 2020)
• Shorter reaction times (Solis & Silveira, 2020)
• Reduced production cost and energy consumption (Solis & Silveira, 2020)
• Products with similar properties to fossil fuels (Solis & Silveira, 2020)
• Catalyst allows optimised product distribution and selectivity (Solis & Silveira, 2020)
• Possible 100% conversion of plastic waste (Solis & Silveira, 2020)
• Narrow product outcome (Ragaert et al., 2017)
• Less stringent reaction conditions favour economics (Ragaert et al., 2017)
• Reduced impurities in liquid oil (Miandad et al., 2016)
• Decreases char production (Miandad et al., 2016)</td><td>• Sensitive to contamination of the feedstock (Solis & Silveira, 2020)
• Often requires pre-treatment (Solis & Silveira, 2020)
• Nitrogen and chloride components can deactivate the catalyst (Solis & Silveira, 2020)
• Absence of suitable reactor technology (Ragaert et al., 2017)
• The presence of inorganic components can block the pores of the catalyst (Ragaert et al., 2017)</td></tr>
<tr><th colspan="2">Gasification</th></tr>
<tr><td>• Very detailed polymer breakdown (Solis & Silveira, 2020)
• Multiple applications of the product gas (Solis & Silveira, 2020)
• Suitable for mixed plastic waste (Solis & Silveira, 2020)</td><td>• The produced syngas needs further upgrading before use (Solis & Silveira, 2020)
• Requires high feedstock volumes to be feasible (Solis & Silveira, 2020)
• Tars and char in produced gas (Solis & Silveira, 2020)</td></tr>
</table>

Table 5-2: Advantages and disadvantages of commercially applied chemical recycling processes	
Advantages	**Disadvantages**
• Production of atmospheric nitrogen-free syngas via pure oxygen gasification (Solis & Silveira, 2020) • Production of nitrogen-free syngas via steam gasification that allows the use for synthesis applications and production of new plastic products (Solis & Silveira, 2020) • Possible hydrogen production from steam gasification (Solis & Silveira, 2020) • Syngas is a valuable intermediate (Ragaert et al., 2017) • Suitable for plastics mixed with other feedstocks (Lopez et al., 2018)	• Cost and energy intensive (Solis & Silveira, 2020) • Sensitive to some contaminants as they may poison downstream processes (Ragaert et al., 2017) • Produces noxious NO_x (Ragaert et al., 2017) • Gasification also requires large operational costs due to the feed pre-treatment, consumption of pure oxygen as well as syngas cleaning costs (Al-Salem et al., 2017) • Tar formation, which causes serious operational problems leading to a reduction in the overall process efficiency and applications of the gas produced (Lopez et al., 2018) • A very efficient gas cleaning system is needed to meet the requirements for the production of chemicals from syngas (Lopez et al., 2018) • Careful feedstock preparation by crushing, shredding and sieving with controlled moisture content has to be achieved (Al-Salem et al., 2017)
Chemolysis	
• Produces pure value-added products (Ragaert et al., 2017) • Operational for PET (Ragaert et al., 2017) • Already integrated into polymer production lines (Lee & Liew, 2020) • Requires lower energy input than other established chemical recycling processes, such as pyrolysis and gasification (Lee & Liew, 2020)	• Requires high volumes to be cost-effective (Ragaert et al., 2017) • Mainly suitable for condensation polymers (PET, PU, PC) (Lee & Liew, 2020; Simon et al., 2018) • Suitable for homogenous plastics only (Solis & Silveira, 2020) • Recycled polymers are more expensive than virgin polymers (Vollmer et al., 2020) • Susceptible to process contaminants such as heavy metals (Lee & Liew, 2020)

With reference to Table 5-2, it can be argued that the catalytic cracking process is better than conventional pyrolysis as it solves many drawbacks of the conventional process, such as lower temperature and energy requirements, which reduces the operational costs, better quality product with less char and impurities, and optimised product distribution and selectivity. Nevertheless, catalytic cracking still has some limitations, for instance, sensitivity to impurities and contamination, which can result in the deactivation of the catalyst. Although gasification can accept mixed plastic waste and offer a great polymer breakdown, the process is very energy and cost-intensive and requires high volumes of waste to be feasible. Chemolysis can generate virgin-like polymers, but the process requires high volumes to be economically feasible, can only accept homogenous waste streams, and is mostly suitable for condensation polymers such as PET, for which the operational plants already exist.

Table 5-3 complements the information provided in the descriptions of some technologies and gives an overview of parameters of selected commercial plants, which apply various chemical recycling technologies to recover plastic, and in some cases, energy or other by-products that may hold value.

Table 5-3: Examples of commercial plants along with inputs, yields and maximum capacities					
Technology	**Provider**	**Inputs**	**Yields**	**Capacity**	**Source**
Pyrolysis	Royco Beijing	PE, PP, PS, waste oils	87% oil, 10% gas, 3% solid residue	6 kilotons/year	Ragaert et al., 2017; Solis & Silveira; 2020
	Mogami-Kiko	PP, PE	79% oil, 12% gas	1 kiloton/year	Ragaert et al., 2017; Solis & Silveira; 2020
Catalytic cracking	Zadgaonkar	PE, PP, PS, PVC, PET	75% oil, 20% gas, 5% coke	12 kilotons/year	Solis & Silveira; 2020
	Thermofuel/Cynar	PE, PP, PS	Oil, gas, coke	6 kilotons/year	Solis & Silveira; 2020
Gasification	Enerkem	Plastic waste[4]	38 million litres of methanol, ethanol and ethylene	100 kilotons/year	Solis & Silveira; 2020
Chemolysis	Ioniqa Technologies	PET	BHET (an intermediate in PET production)	10 kilotons/year	Vollmer et al., 2020

Among the examples, the gasification operation is of the highest capacity, with the rest of the companies operating at much lower levels. Chemical depolymerisation is targeted to recover polymers of a single type of plastic, at the same time providing outputs that need less processing or refining to produce new plastics. Meanwhile, other technologies can process multiple plastic waste types, providing products that can be used as petrochemical feedstock and can yield both new plastics and energy.

5.2 Developing chemical recycling technologies

Five chemical recycling technologies are at the development stages (pilot or laboratory scale); see Table 5-1. They include hydrocracking, microwave-assisted pyrolysis, plasma pyrolysis, pyrolysis with online reforming, and plasma gasification.

Hydrocracking (also called hydrogenation) is achieved via the addition of hydrogen to the pyrolysis process. It occurs at temperatures ranging between 350 to 500°C while hydrogen is supplied at elevated pressure (70atm). The process reduces aromatics, olefins and coke formation, and the addition of hydrogen results in the removal of heteroatoms, such as bromine, chlorine, and fluorine, which may be present in plastic waste (Munir et al., 2018), resulting in higher quality pyrolysis products (Datta & Kopczynska, 2016; Ragaert et al., 2017). What is more, hydrocracking delivers highly saturated liquid products, which can be directly used as a transportation fuel or for energy production without further upgrading (Munir et al., 2018). In addition, the process can handle a mixture of plastic waste (Ragaert et al., 2017) (see Table 5-4). In this process, the plastic waste is first exposed to lower temperatures and gets liquified, in turn becoming free from non-distillable matter. The liquid is then mixed with the catalyst that reduces process temperature and improves the quality and yield of the resulting oil. However, the main challenges for this technology are the high costs of hydrogen and the

[4] Wastes such as non-recyclable plastics, textiles, or soiled food containers, and other non-recyclable waste destined for landfill (Enerkem, n.d.).

high capital expenditures and operational expenses, which limit the scaling up to industrial operation (Ragaert et al., 2017; Solis & Silveira, 2020). Finally, hydrocracking of some types of plastic (i.e., PVC) can also yield hazardous substances that would require additional costs to control and remove from the final product (Solis & Silveira, 2020). With a lower technology readiness level (7 – System prototype demonstration in operational environment), hydrocracking is mainly applied in the petroleum industry, while its application to plastics waste is still limited and only done at a pilot-scale (Solis & Silveira, 2020).

Pyrolysis with in-line reforming was developed to optimise the production of tar-free hydrogen from plastic waste, which usually reaches more than 30% (Solis & Silveira, 2020). The process involves the pyrolysis of plastic waste in the first reactor and the reforming of the pyrolysis product in the subsequent one. The advantages of the process include lower temperatures (500-900°C) when compared to gasification, which decreases the cost of production (Lopez et al., 2018), and the absence of contact between impurities in plastic waste and the catalyst, which minimise costs of catalysts needed for the reforming step (Barbarias et al., 2016). The main disadvantage of this technology is the absence of an industrial-scale application, as only pilot operations are available (Lopez et al., 2018; Barbarias et al., 2016). Therefore, this technology has been assigned TRL 4 by Solis and Silveira (2020), which indicates that the technology is in the development stage. Nevertheless, Barbarias et al. (2018) estimated that this process can be economically feasible and acknowledged the high flexibility of such a system to recycle different types of plastics, along with high conversion efficiencies and hydrogen production.

Microwave-assisted pyrolysis involves the addition of dielectric material or absorbents such as activated carbon, silicon dioxide or graphene to the plastic waste (Al Rayaan, 2021). It absorbs microwave energy to create adequate thermal energy to achieve the temperatures required for pyrolysis to occur (Arshad et al., 2017). Microwave irradiation can break heavier hydrocarbons in plastic waste into lighter hydrocarbons, producing high-quality oil or syngas (Al Rayaan, 2021). Microwave-assisted pyrolysis can address two major drawbacks of conventional pyrolysis – high energy requirements and slow reaction times (Rex et al., 2020). It achieves even heat distribution, offers more control over the process, higher heating rates and higher production speed (Solis & Silveira, 2020). The limitations of the process include imprecise temperature measurements, non-uniformity of the heating process, the difficulty to disperse the microwaves properly, requirements of large feedstock volumes, knowledge limitations on dielectric material roles in heating efficiency as well as limitations regarding the efficiency of microwave design (Arshad et al., 2017; Solis & Silveira, 2020). As a result, this technology has been developed at laboratory and pilot scales only, and the absence of a robust methodology for scaling up the process hinders its application potential (Aishwarya & Sindhu, 2016; Beneroso et al., 2017). Therefore, Solis and Silveira (2020) assigned this technology a TRL 4.

Plasma pyrolysis integrates thermochemical properties of plasma into conventional pyrolysis to completely break down plastic waste monomers to produce syngas, composed mainly of CO, H_2 and small amounts of higher hydrocarbons. The process is very fast (0.01 and 0.5 sec) and takes place at temperatures ranging between 1730 and 9730°C (Solis & Silveira, 2020). Flash depolymerisation takes place under these conditions yielding mainly gaseous products. High gas yields are achieved due to high process temperatures, which promote almost complete tar cracking (Lopez et al., 2017). In addition, the process is capable of high monomer recovery due to the efficient heating and ionisation of polymer chains (Vollmer et al., 2020). Furthermore, high temperatures are capable of decomposing toxic compounds that may be present in gas and prevent the formation of HCl (see Table 5-4). However, this technology has mostly been applied for the destruction of hazardous waste. Furthermore, although emissions of the process are low, the process has high energy requirements. As plasma pyrolysis technology for the recycling of plastic waste has only been investigated at a laboratory scale, the technology has been assigned a TRL 4 (Solis & Silveira, 2020).

Plasma gasification is an allo-thermal process where the heat is produced by thermal plasma, usually generated by direct current non-transferred arc plasma torches (Al Rayaan, 2021). The process temperatures can be very high and reach 14,000°C. The operating parameters, such as the reaction temperature, residence time, which ranges between less than 30min to 3h, and the flow rates of the oxidant, plasma gas, and steam streams affect the plasma gasification process (Munir, 2019). The process can handle all types of plastic waste, has a high tolerance to low-quality feedstock, and results in high purity syngas with low tar content (Solis & Silveira, 2020). However, there are still some challenges in transferring this technology to an industrial scale, such as the high investments and operating costs, high energy intensity, moderately low community readiness, the requirement for adequate waste sorting systems and limited understanding of the process (Munir, 2019). Although plasma gasification has been commercially applied, and Solis and Silveira (2020) assigned this technology a TRL 8, it has mainly been used for the destruction of various hazardous waste and not for the recycling of plastics. Therefore, we consider plasma gasification as an emerging technology for plastic waste recycling.

A summary of the advantages and disadvantages of each developing chemical recycling technology is provided in Table 5-4.

Table 5-4: Advantages and disadvantages of chemical recycling technologies in development

Advantages	Disadvantages
Hydrocracking	
• High quality product (Datta & Kopczynska, 2016) • Can handle a mixture of plastic waste (Ragaert et al., 2017) • No post-treatment required (Munir et al., 2018) • Lower process temperatures than pyrolysis (Munir et al., 2018) • Less coke formation in products (Munir et al., 2018) • Hydrogen allows the removal of heteroatoms such as chlorine, bromine, fluorine (Munir et al., 2018) • No production of toxic compounds such as dioxins (Ragaert et al., 2017)	• High cost of hydrogen (Solis & Silveira, 2020) • Hydrocracking of PVC has a poisoning effect (Solis & Silveira, 2020) • Initial and operational costs are also considered to be high (Ragaert et al., 2017)
Pyrolysis with in-line reforming	
• The process produces hydrogen (Solis & Silveira, 2020) • Tar-free gas products (Solis & Silveira, 2020) • Lower process temperature when compared to conventional gasification (Solis & Silveira, 2020) • Higher hydrogen production than from steam gasification (Solis & Silveira, 2020) • Lower production cost (Lopez et al., 2018) • High flexibility to recycle different types of plastics (Barbarias et al., 2016) • No contact between impurities and the reforming catalyst, which reduces the cost of catalyst (Barbarias et al., 2016)	• The catalyst deactivation issue still needs to be researched and resolved (Solis & Silveira, 2020) • Absence of an industrial-scale application (Lopez et al., 2018)

Table 5-4: Advantages and disadvantages of chemical recycling technologies in development	
Microwave-assisted pyrolysis	
• Suitable for MSW (Solis & Silveira, 2020) • Even heat distribution (Solis & Silveira, 2020) • Higher heating rates when compared to pyrolysis (Solis & Silveira, 2020) • More control over the process than conventional pyrolysis (Solis & Silveira, 2020) • Higher production speed when compared to pyrolysis (Solis & Silveira, 2020) • High quality oil or syngas (Al Rayaan, 2021)	• Sensitive to big fluctuations in waste composition (Solis & Silveira, 2020) • Large feedstock volumes required to be feasible (Solis & Silveira, 2020) • Efficient use of dielectric absorbent on an industrial scale is challenging (Solis & Silveira, 2020) • Imprecise temperature measurements (Solis & Silveira, 2020) • Non-uniformity of the heating process (Arshad et al., 2017) • The difficulty to properly disperse the microwaves (Arshad et al., 2017) • Knowledge limitations on dielectric material roles in heating (Arshad et al., 2017) • The efficiency of microwave design (Arshad et al., 2017)
Plasma pyrolysis	
• Toxic compound-free product gas due to high temperatures (Solis & Silveira, 2020) • Suitable for mixed plastic waste (Solis & Silveira, 2020) • Product gas with low tar content and high heating value (Solis & Silveira, 2020) • Very fast process (Lopez et al., 2017) • Limited formation of free chlorine from HCl (Solis & Silveira, 2020) • High gas yields (Lopez et al., 2017) • High monomer recovery due to efficient heating and ionisation of polymer chains (Vollmer et al., 2020)	• High energy requirements (Solis & Silveira, 2020)
Plasma gasification	
When compared to conventional gasification: • Less tar (Solis & Silveira, 2020) • Higher purity product gas (Solis & Silveira, 2020) • Suitable for low-quality feedstock (Solis & Silveira, 2020) • Can handle all types of plastic (Solis & Silveira, 2020) • Independent control of temperature (Solis & Silveira, 2020) • Well-established technology (Solis & Silveira, 2020)	• Very high energy requirements • High investment and operation costs (Solis & Silveira, 2020) • Moderately low community readiness (Munir, 2019) • Requirement for adequate waste sorting systems (Munir, 2019) • Limited understanding of the process (Munir, 2019)

As shown in Table 5-4, hydrocracking has many advantages that solve problems, such as the removal of chlorine or bromine, which can be found in some types of plastics, and also prevents the production of toxic compounds. Furthermore, it can be seen as a better treatment option than pyrolysis, as it requires lower temperatures and generates high-quality product, which does not require further post-treatment. Nevertheless, the investment, operational, and hydrogen costs are high, which is most likely the reason for this technology not reaching commercial levels of operation. Although microwave-assisted pyrolysis has some advantages, such as higher heating rates, more control over the process, and shorter production times compared to conventional pyrolysis, it has more disadvantages, which hinders its commercial application. Plasma technologies have many advantages over conventional processes; however, very high energy requirements make plasma pyrolysis and gasification very costly. Finally, pyrolysis with in-line reforming seems to be the technology that has a high potential as its limitations are related to the lack of research on the catalyst performance and the lack of industrial application.

5.3 State-of-the-art in comparative analysis of chemical recycling technologies

Most research literature reviews do not carry out a quantitative comparative analysis of chemical recycling technologies. In some cases, qualitative comparisons of the advantages or disadvantages of several technologies are given as a part of the review (e.g., see Table 5-2 and Table 5-4). However, a robust quantitative assessment of the advantages and disadvantages of chemical recycling technologies is still lacking. The literature search identified two methods with high potential for quantitative comparative analysis of chemical recycling technologies – **life cycle assessment** (LCA) and **techno-economic assessment** (TEA). The first method, LCA, is used for evaluating the environmental footprint, while the second, TEA, for assessing the economic viability of chemical recycling technologies. In the following sub-sections, each method, including its advantages and limitations, is presented with recent examples and insights from studies in chemical recycling.

5.3.1 Life cycle assessment of chemical recycling technologies

Life cycle assessment is a methodology used for a quantitative assessment of the environmental impacts of products or services. The use of life cycle assessment for environmental purposes is described in *ISO 14040: Environmental management – Life cycle assessment – Principles and framework* (International Organization for Standardization, 2006). The European Commission (2013) adopted life cycle assessment as a methodological framework for Product Environmental Footprint measurement and communication in its recommendation 2013/179/EU. In Europe, this method is used to assess the environmental performance of products, services, and organisations (Antelava et al., 2019; Zampori & Pant, 2019). Life cycle assessment provides an overview of complex waste management processes and a quantitative assessment of their effects on the environment (Brekke et al., 2019). This feature of the LCA methodology explains its high potential for use in policy-making and other decision-making contexts. LCA studies are often used to compare the environmental impacts of diverse waste management technologies. A typical LCA study contains four main steps as outlined in Figure 5-1.

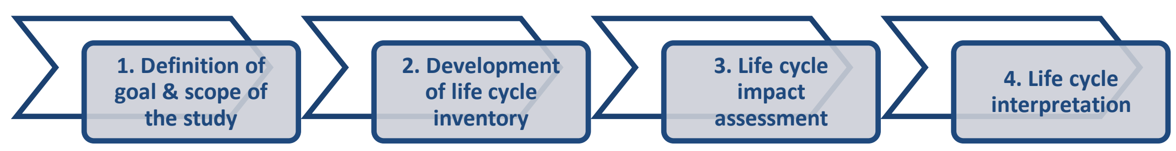

Figure 5-1: Main steps in a Life cycle assessment study - *Source: Antelava et al., 2019; Zampori & Pant, 2019*

All steps provided in Figure 5-1 are described in more detail by Antelava et al. (2019) and Zampori and Pant (2019):

- The **first step** is necessary to define the system that will be studied by applying the LCA approach. The system is defined through two main parameters – goal and scope. The goal sets the context and direction for the study and contains the intended application, target audience, analytical depth of the study, etc. The scope describes the system under analysis through several parameters: functional unit and reference flow, system boundary, environmental impact categories, limitations and other relevant information. The functional unit is a product/service studied within the system along with its qualitative and quantitative parameters (e.g., characteristics of a product/service, quality, duration etc.). The functional unit is complemented with reference flow information – quantities necessary for a product/service to perform its function within the system. Another important parameter is system boundary that covers parts of the life cycle, associated life cycle stages and processes of a product/service included in the study. Finally, environmental impact categories that embrace a set of quantitative indicators expressing specific effects of a product/service to the environment should be defined. Depending on the choices made and the availability of data, limitations should be reported.
- The **second step**, the development of life cycle inventory, is the basis for modelling the environmental footprint. It contains all inputs and outputs of material, waste and energy in the studied system, including emissions to air, soil and water.
- Having compiled the life cycle inventory, the **third step** – life cycle impact assessment is possible. At this stage, the calculation of the environmental performance of a product/service is possible by using the environmental footprint categories chosen at the first stage.
- The final **fourth step** involves the overall interpretation of the constructed LCA model and interpretation of findings.

The goal and scope definitions in LCA studies contain various sets of parameters that have a substantial impact on the findings of the study (Zampori & Pant, 2019). This peculiarity of LCA is the main source of limitations of the method and the main target for criticism to LCA (Antelava et al., 2019). Critics highlight the subjectivity in defining what should be measured (in other words, the list of variables specified in the scope of a system). It means that various LCA make different assumptions of what should be analysed, thus potentially omitting important aspects and their environmental consequences (Lazarevic, 2018). It substantially reduces the comparability of LCA studies due to different definitions and assumptions about the system that may even lead to contradictory results (Brekke et al., 2019; Antelava et al., 2019). This feature of LCA studies should be considered when using the findings. Importantly, transparency and explicit goals and scope definitions along with the data collected on various stages of LCA research are necessary for interpreting and using the results of such studies as well. The lack of access to the datasets in some LCA caused recent discussions about the transparency of the LCA research (e.g., see Tabrizi et al., 2020).

Nevertheless, LCA studies provide a picture, though still fragmented, of chemical recycling within the waste management system. This explains the constant interest of the researchers in comparing and analysing the results of the chemical recycling LCA studies. Recently, Davidson et al. (2021) and Antelava et al. (2019) conducted such analyses. According to both reviews, pyrolysis was the most analysed chemical recycling technology in LCA studies, although Antelava et al. (2019) point to some missing variables in these studies. Davidson et al. (2021) concluded from their analysis that **the potential of chemical recycling (mainly pyrolysis) as a complementary technology to mechanical recycling should be explored**. The increased attention to pyrolysis in the LCA studies indicated **the need to investigate chemical recycling technologies other than pyrolysis to avoid a biased approach to the chemical recycling domain** (Davidson et al., 2021).

The literature search allowed us to identify four recent LCA studies focusing on Europe as a region or specific European countries (see the summary in Table 5-5). All studies provided a detailed description of goals, the scope of their LCA studies and estimations, including supplementary materials.

Table 5-5: Overview of recent LCA studies in chemical recycling technologies		
Source	**Goal**	**Scope**
Jeswani et al., 2021	To compare environmental impacts of the chemical recycling of mixed plastic waste via pyrolysis to mechanical recycling and energy recovery.	Technologies compared: pyrolysis, mechanical recycling, energy recovery. Three perspectives: waste, product, combined waste and product. Plastic: polyethylene, polypropylene, polystyrene. Data sources: GaBi database and other sources representative for Germany. Temporal perspective: 2030. Environmental impact categories: EF* 2.0 and ReCiPe** 2016.
Schwarz et al., 2021	To assess the potential environmental performance of existing and innovative recycling technologies for 25 plastic polymers.	Technologies compared: 10 recycling technologies, including chemical recycling (different types of pyrolysis, gasification, glycolysis, hydrolysis), mechanical recycling (open-loop, closed-loop), quaternary recycling (incineration for energy recovery). Plastic: top 25 produced polymers in Europe. Data sources: European data where possible; otherwise – global datasets (Ecoinvent database). Environmental impact categories: ReCiPe** 2008, climate change (CO_2 emissions for treating 1 kg of plastic product).
Meys et al., 2020	To assess the environmental potential of 26 chemical recycling technologies for the major plastic packaging waste by comparing them to 18 benchmark waste treatment technologies.	Technologies compared: chemical recycling (pyrolysis, gasification, chemolysis), energy recovery in incinerators, energy recovery in cement kilns, mechanical recycling. Plastic packaging waste: PET, HDPE, LDPE, PP and PS. Data sources: Ecoinvent database, recycling professionals. Environmental impact categories: global warming, fossil resource depletion, terrestrial acidification, freshwater and marine eutrophication.
Qureshi et al., 2020	Climate impacts of pyrolysis of plastic waste for diesel and polymer production compared to the business-as-usual situation in Finland.	Technologies compared: pyrolysis, incineration for electricity/heat, mechanical recycling. Plastic waste, production of diesel and polyethylene. Data sources: Ecoinvent database, LIPASTO database, Plastics Europe, expert information, other sources from Finland. Environmental impact categories: carbon footprint.
*NOTE: *EF – environmental footprint categories advised for inclusion to the studies of a Product Environmental Footprint (European Commission LCA framework) (Zampori & Pant, 2019); **ReCiPe 2008 and 2016 – method for assessing the environmental impact that contains middle point and end point impact criteria. It was developed in 2008 by the National Institute for Public Health and Environment at the Ministry of Health, Welfare and Sport (The Netherlands) in collaboration with several partners and updated in 2016 (Huijbregts et al., 2017).*		

Table 5-5 shows that the identified LCA studies vary substantially in their goals and scope. Jeswani et al. (2021) and Qureshi et al. (2020) focused on pyrolysis and based their estimations on the data representative for specific countries – Germany and Finland, respectively. Schwarz et al. (2021) and Meys et al. (2020) cover more chemical recycling technologies and different types of plastic waste. Notably, all studies use different sets of environmental impact criteria and developed very specific system boundary definitions.

Schwarz et al. (2021) discovered that the **optimal choice of recycling technologies varies for different types of plastic waste**. It means that properly chosen recycling technology will result in optimal environmental performance. For instance, engineering and high-performance plastic benefit the most from mechanical recycling, while polyolefins – from gasification to monomers and plastic forming monomers – from pyrolysis to monomers. Yet, to reach the desired performance, each recycling technology should be combined with appropriate pre-treatment techniques. For instance, for mechanical recycling, it could be sorting and dissolution to remove additives, for gasification – sorting to remove PVC, PET and PS from plastic packaging materials, etc. (Schwarz et al., 2021).

Meys et al. (2020) concluded that in most cases choosing **chemical recycling technology can result in both negative and positive environmental impacts within selected five categories**. For instance, the environmental impacts of PET and PS chemically recycled or upcycled to monomers are smaller than when they are treated in municipal waste incinerators. However, mechanical recycling of PET and PS results in lesser environmental impacts than when they are used for refinery feedstock or fuel production. Other analysed cases of chemical recycling demonstrated trade-offs between various environmental impacts.

In the study by Jeswani et al. (2021), **pyrolysis, mechanical recycling and energy recovery methods demonstrated different environmental performance that depended on the assumptions about assigning credits to specific environmental impacts**. For instance, environmental impacts were higher for pyrolysis due to high energy demand in the process; however, the possible increase in carbon conversion efficiency in pyrolysis could change this situation in future. Additionally, the analysis revealed that the environmental impact of both mechanical recycling and pyrolysis depended on the quality and composition of plastic waste. It led the authors to conclude that **pyrolysis should be considered not as a competitive but as a complementary approach to mechanical recycling of plastic waste**.

Similarly to Jeswani et al. (2021), Qureshi et al. (2020) concluded that interpretation of results was very sensitive to the assumptions about the system (e.g., the type of electricity or heat replaced) and the quality of data. In scenarios analysing the treatment of separately collected post-consumer plastic by pyrolysis or incineration, the environmental impacts of both options were quite similar. However, when plastic is rejected/**refused from mechanical recycling and sent to incineration or pyrolysis, the latter could be a more favourable option in terms of environmental impacts**.

In summary, different LCA studies and reviews suggest treating chemical recycling as a complementary technique to mechanical recycling rather than a standalone option for waste management. There is still a lack of studies that would cover different chemical recycling methods and streams of plastic waste, as the effectiveness of the recycling method seems to be input dependent. Additionally, a number of variations in findings occur due to diverse assumptions about the systems under analysis.

5.3.2 Techno-economic assessment of chemical recycling technologies

LCA studies are often criticised for concentrating on environmental impacts and not covering the economic aspects of chemical recycling technologies (Antelava et al., 2019). **Techno-economic assessment** (TEA, also known as techno-economic evaluation and techno-economic analysis) is a methodology that emerged in cost engineering (Thomassen et al., 2019). TEA combines the analysis of technical performance and economic profitability of new technology and helps decision-makers to direct investments or take other decisions in developing the technology (Van Dael et al., 2015). Differently from LCA, TEA is not standardised, and methodological discussions on its application are still rare. TEA is used as an umbrella concept for various approaches and methodologies. Sometimes, TEA is combined with LCA or mass-flow analysis and other models (Thomassen et al., 2019; Van Dael et al., 2015). Van Dael et al. (2015) and Thomassen et al. (2019) defined four main steps of techno-economic assessment (see Figure 5-2).

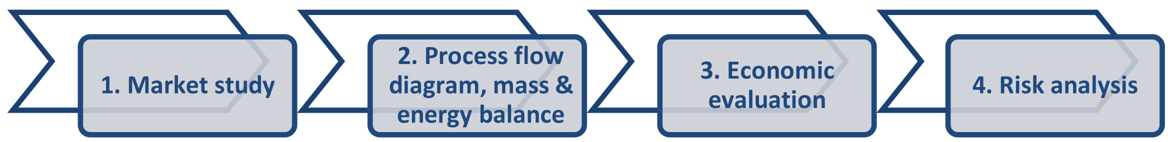

Figure 5-2: Main TEA steps - *Sources: Van Dael et al., 2015; Thomassen et al., 2019*

The **first step** involves a definition of the scope of technology development and conducting a market study to gather the input data. The data include market prices and volumes and could also cover the assessment of the market potential for the analysed technology. The **second step** is focused on the technology process design and mass and energy balance calculation. At this stage, inputs and outputs of a specific technology are determined as well as its performance parameters. Economic analysis that uses various investment indicators (e.g., net present value, internal rate of return etc.) follows in the **third step**. The **fourth step** evaluates the influence of uncertainty on indicators. The values used for estimations are usually found in literature and cross-checked with expert opinion. It means that uncertainty level is high in values used for modelling (Van Dael et al., 2015; Thomassen et al., 2019).

Similarly to LCA, TEA studies are based on a systems approach to technologies, where the scope and boundary of the system, as well as economic assessment parameters, are defined by a researcher. Input data for the analysis come from sources of different quality. So, LCA limitations and criticism are fully applicable to TEA studies.

A literature search identified four recent techno-economic assessment studies (see Table 5-6). All studies were focused on the economic feasibility of pyrolysis, with only one of them comparing it to other recycling technologies (see Volk et al., 2021). Volk et al. (2021) combined economic viability and environmental impact assessment. **All studies considered the production of petrochemical feedstock or fuel, while two studies also addressed plastic-to-plastic recycling** (Volk et al., 2021; Larrain et al., 2020).

Table 5-6: Overview of recent TEA studies in chemical recycling technologies

Source	Scope	Findings
Volk et al., 2021	Goal: to assess the costs, carbon efficiency, cumulative energy demand and global warming potential of primary plastic production, post-consumer plastic packaging sorting and recycling (mechanical, chemical – pyrolysis, and combined). Plastic considered: polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), and general-purpose polystyrene (GPPS). Data sources: Plastics Europe, German plastic packaging collection system and other German sources.	Mechanical recycling combined with the pyrolysis of mixed lightweight packaging waste shows cost-saving potential (0.14 €/kg input) compared to the business-as-usual mechanical recycling scenario in Germany.
Riedewald et al., 2021	Goal: to determine the economic potential of commercial-scale pyrolysis plant for reprocessing mixed plastic waste in Belgium. Data sources: EU statistics, Belgium statistics, literature.	Six aspects shape the economic viability of the pyrolysis plant: volume and quality of the processed plastic waste, feedstock costs, capital and operating expenditures, the revenues from

Table 5-6: Overview of recent TEA studies in chemical recycling technologies		
		the sale of the produced pyrolysis oil, the tipping fees and availability of a waste plastic sorting facility.
Larrain et al., 2020	Goal: to compare the potential economic returns of closed-loop versus open-loop pyrolysis of mixed polyolefin waste. Data sources: expert market studies, global data, data from Belgium, industrial references.	Open-loop pyrolysis is economically more profitable than the closed-loop counterpart. These findings strongly depend on oil prices, feedstock availability and other factors.
Fivga & Dimitriou, 2018	Goal: to analyse the technical and economic feasibility of a plastic waste pyrolysis plant to produce fuel oil as a heavy fuel oil substitute or as raw material for the petrochemical industry. Data sources: industry data, UK.	Fuel production costs in a pyrolysis plant are mostly influenced by fuel production rate.

All studies presented in Table 5-6 are case studies based on one country statistics and industrial references combined with global forecasts and data. They also use different assumptions about the prospective pyrolysis plants; therefore, the findings of these studies are not comparable. Interestingly, three studies (Riedewald et al., 2021; Larrain et al., 2020; Fivga & Dimitriou, 2018) emphasize the significance of the availability of large amounts of plastic waste for economically profitable chemical reprocessing activities.

5.4 Features and use of the recycled waste

Chemical recycling processes can be classified by the outputs that can be obtained from plastic waste, i.e. plastic-to-plastic (P2P) and plastic-to-fuel (P2F). The main contribution to the circular economy is P2P chemical recycling products, while P2F products are much less desirable as they do not result in recyclable resources (Rollinson & Oladejo, 2020). This chapter discusses commercially applied chemical recycling technologies with high technology readiness level: pyrolysis, catalytic cracking, gasification, and chemolysis.

Here the focus is on studying the main products and by-products of each chemical recycling process that could be usefully applied in various fields and their features. A summary of all findings is provided in Table 5-7.

Table 5-7: Chemical recycling technologies, products and their features		
Product / By-product	**Features**	**Source**
	Pyrolysis	
Gas, char, liquid oil (pyrolytic oil)	Pyrolytic oil – high calorific value and many potential applications (petroleum blends), requires upgrading before use	Solis & Silveira, 2020
Monomers, clean fuel, oil, gas, waxes, hydrocarbons: C_1-C_{50}	High calorific value products	Datta & Kopczyńska, 2016
Gas, liquid oil and solid residue	Different polymers give rise to completely different product spectra	Ragaert et al., 2017
Liquid oil	Contains some impurities such as sulphur, chlorine, solid residue, moisture, acids, which decrease the quality and limits commercial application, requires upgrading	Miandad et al., 2017

Table 5-7: Chemical recycling technologies, products and their features		
Product / By-product	**Features**	**Source**
Oil, gas, char	Quality depends on set up parameters, calorific value, density and viscosity comparable to those of commercial fuels	Sharuddin et al., 2016
Synthetic oil, diesel, wax, monomers	Oil and wax – rich in hydrocarbons, ideal raw material for the refinery	Qureshi et al., 2020
Catalytic cracking		
Oil (light, medium, heavy)	Similar properties to fossil fuels; light oil as feedstock for new products, medium fuel oil equivalent to diesel, heavy oil for electricity generation	Solis & Silveira, 2020
Fuel fractions (gas, liquid, waxy products), C_3-C_4: highly olefins, C_4-C_5: isoparaffins	Lighter liquid fuel fractions than in pyrolysis	Datta and Kopczyńska, 2016
Fuels	Transport grade	Ragaert et al., 2017
Gasification		
Mixture of hydrocarbons and syngas (hydrogen and methane)	Multiple applications, possible hydrogen production, free from atmospheric nitrogen (pure oxygen gasification), free from nitrogen and can be used for synthesis applications and production of new plastic products (steam gasification)	Solis & Silveira, 2020
Ethylene, methylene, heavy hydrocarbons and aromatics	Nitrogen in the air causes a reduction in the calorific value of the obtained product due to the dilution effect on fuel gases, high tar loads	Datta and Kopczyńska, 2016
Syngas, methanol, paraffinic hydrocarbons	A gaseous mixture containing CO_2, CO, H_2, CH_4 and other light hydrocarbons; use of air yields a higher amount of noxious NO_x; contains some impurities such as NH_3, H_2S, NO_x, alkali metals, and tars; purification step is the major contributor to the costs of producing the syngas	Ragaert et al., 2017
Chemolysis		
Monomers, polymers, oligomers	Suitable for food applications, pure value-added products, more expensive than virgin	Ragaert et al., 2017
Monomers	Virgin like quality	Vollmer et al., 2020
Original monomers or starting substances	High conversion to monomers can be further purified to remove additives	Datta and Kopczyńska, 2016

As revealed in Table 5-7 and by the subsequent detailed analysis presented below, **the technologies that are the most widespread commercially obtain different products and by-products, with part of them not contributing to the circular economy**. Pyrolysis, catalytic cracking and gasification converts plastic waste to fuel or energy and thus does not promote the circular use of plastic waste. Although chemolysis holds the promise for the recovery of plastics, the application of this technology is limited to homogeneous plastic waste streams and condensation polymers. What is more, the cost of the recycled polymer is higher than the virgin one, and the process requires high volumes of waste to be cost-effective. Hence, chemolysis processes need to be optimised and made economically viable in order to contribute towards the circular economy.

Further in the text, the findings are discussed in more detail, highlighting products, their qualities and market applications for each process (see the summary in Table 5-7).

5.4.1 Products and by-products of pyrolysis

Valuable products such as monomers or fuel-type oils (see the summary in Table 5-7) can be extracted from the pyrolysis of plastic waste, and they can be divided into non-condensable gas fraction, a liquid fraction (i.e., liquid oil or wax) and solid residue (char). The desired product is typically liquid oil or wax, which can be refined into chemicals or fuels, whilst gases and char are by-products (Datta & Kopczyńska, 2016; Almeida & Marques, 2016; Qureshi et al., 2020). Polymers such as PET and PVC produce very low yields of liquid oil compared to other plastics. Furthermore, PVC has not been preferred in pyrolysis due to the production of a harmful hydrochloric acid and possibly dioxins (Sharuddin et al., 2016). Therefore, PVC needs to be removed from plastic waste streams during the pre-treatment stage of the recycling process via separation and sorting, i.e. magnetic density separation, X-ray detection (Ragaert et al., 2017). Output yields of products from pyrolysis vary depending on the type and composition of the input feedstock, its contamination level, the temperature of the process, type of reactor, pressure, residence time and pre-processing treatment (Santaweesuk & Janyalertadun, 2017).

Some polymers like PS, PMMA and PA produce high yields of their **monomers** during the pyrolysis process, whereas collected plastic waste of municipal origin is often a mixture of various plastics and hence yields a mixture of products such as different hydrocarbons of various chain lengths (Qureshi et al., 2020). The hydrocarbons in C_1-C_5 range represent a gaseous stream, a liquid fraction consists of hydrocarbons in the C_5-C_{20} range, and products with a higher number of carbon atoms are waxes. For instance, pyrolysis of polyolefins can produce all types of products depending on process parameters. Moderate temperatures of 500°C with short residence time can produce more wax, BTX (benzene, toluene, xylene) aromatics can be produced at 650-800°C with moderate residence times, and light olefins can be produced at temperatures of more than 800°C with very short residence time (Lopez et al., 2017).

The produced **liquid oil** from different feedstock has different chemical and physical properties, such as density, viscosity, cold flow properties and High Heating Values (HHV). The density and the HHV of the produced liquid oil are very similar to that of conventional diesel. Thus, the pyrolysis liquid oil produced from various plastic wastes has the potential to be used as an alternative source of energy (Miandad et al., 2016a; Nisar et al., 2019). In the case of polyolefins, although the most feasible application of pyrolysis oil is fuel, the process can also produce a fraction of BTX. However, the selectivity of this product is usually below 20%; hence the process should be adjusted to produce not only BTX but also other good quality products (Lopez et al., 2017).

Lower temperatures of the pyrolysis process leave a **waxy product** that mainly consists of paraffin and carbonised char (Santaweesuk & Janyalertadun, 2017). Pyrolysis of polyolefins (PP, PE) yields wax as one of the main products under low temperatures (< 400°C) (Qureshi et al., 2020). For instance, in a study carried out by Miandad et al. (2017), the pyrolysis of PE under the temperature of 450°C did not produce liquid oil, but the wax was produced instead due to its long carbon chain structure, and the main yield was gas. The oil and wax obtained from the pyrolysis of plastic waste are rich in hydrocarbons; hence they can be used as a raw material in a refinery (Qureshi et al., 2020). For example, wax can be used to produce candles and lubricants (Miandad et al., 2017).

The liquid oil yield and **quality** depend on different parameters applied to the pyrolysis process. Efficiencies as high as 97 wt% have been achieved in pyrolysis of PS using conventional pressurised batch reactor and a temperature of 425°C. Polyolefins have achieved liquid oil yields ranging from 82.1 wt% for PP to 84.7-93.1 wt% for PE plastics when using optimised temperatures of 500-550°C. Pyrolysis of mixed plastic waste consisting mainly of PP, PE and PS has been reported to produce 46.6-48.4 wt% of liquid oil, however at much higher temperatures (650-730°C). Although the liquid oil yield is much lower for mixed plastic waste than single plastic, the quality of the produced oil was comparable to the single plastic pyrolysis (Sharuddin et al., 2016). Miandad et al. (2017) conducted a study on the effect of plastic waste types on the liquid oil and reported yields of 80.8% for PS, 42.0% for PP and 25.0-54.0% for various mixes of PS, PP, PE and PET at a temperature of 450°C (Miandad et al., 2017). Although the main goal of plastic waste pyrolysis is liquid oil, the process can be adjusted to optimise the production of wax and other components (Qureshi et al., 2020).

Some polymers lend themselves to the very high efficiency of monomer production when pyrolysed. For instance, the liquid product yields obtained from pyrolysis of model and commercial PMMA were high (99% and 98%, respectively) with monomer recovery of 98.3 wt% for model and 94.9 wt% for commercial PMMA. The produced PMMA polymer using a liquid fraction of pyrolysed PMMA was very similar to that obtained from the polymerisation of neat MMA (Datta & Kopczyńska, 2016).

Liquid oil from plastic waste pyrolysis usually requires post-treatment and upgrading (Miandad et al., 2017; Solis & Silveira, 2020) because sometimes it contains impurities such as chlorine, sulphur, moisture, solid residue, and acids, which decrease the quality of liquid oil and limits its **commercial applications**. The two main upgrading processes are refining and blending with conventional diesel, which depends on the targeted application (Miandad et al., 2017). For instance, several studies have simulated the integration of pyrolysis of plastic waste into the conventional refinery. It has been tested at a pilot plant scale oil refinery in Austria. However, the scale is insignificant compared with crude oil (Qureshi et al., 2020). After the upgrade, the oil can be used in modified diesel engines as transport fuel and for heat and energy generation (Miandad et al., 2017). On the other hand, pyrolysis of plastic waste into liquid hydrocarbons for the production of new polymers has been reported by Larrain et al. (2020). Companies such as BASF in Norway and Recycle Technologies in the UK have been running pilot and demonstration plants with the aim of producing liquid oil, which, after refinement, could be used as chemical feedstock for the manufacturing of new virgin-like plastics. Both companies are working on recycling mixed, multi-layered, or mechanically not recycled plastic waste (BASF, n.d.; Recycling Technologies, n.d.).

In pyrolysis, two by-products – gas and char – are obtained.

The composition of **gases** produced depends on the feedstock (Miandad et al., 2016a; Sharuddin et al., 2016). The gas contains hydrogen and is rich in hydrocarbons (methane, ethane, ethene, propane, propene, butane, butene, etc.) with a heating value of 25-45 MJ/kg (depending on the feed and conditions), which makes it suitable for the energy recovery; thus it is usually circulated back into the process for heating purposes (Sharuddin et al., 2016; Qureshi et al., 2020). On the other hand, pyrolysis of polyolefins can produce valuable light olefins as a gas under certain conditions, which recover polyolefin monomers ethylene and propylene as products (Lopez et al., 2017). Several parameters such as temperature, heating rate, pressure and residence time of the process affect the proportion of by-products. Optimal parameters for the production of more of the gaseous fraction are opposite to the parameters that are required to maximise the oil production (Sharuddin et al., 2016). It was estimated that the pyrolysis of plastic waste could produce 13-26.9 wt% of gases, depending on parameters (Miandad et al., 2016a). However, this may differ for the pyrolysis of polyolefins when the aim is to recover light olefins in the gaseous phase by adjusting process parameters to very high temperatures and very short residence time. In this case, the yield of 93% of the gaseous product has been reported in the literature (Lopez et al., 2017).

Gases from pyrolysis can be used as a heating source and in gas turbines to generate electricity without the need for flue gas treatment. Besides, propylene and ethylene can be used as a chemical feedstock to produce polyolefins. However, it requires separation from other gas components (Sharuddin et al., 2016).

Char is another by-product of pyrolysis, which can be described as an unburnt feedstock in the reactor. It consists of volatile matter, fixed carbon, ash, and moisture (Miandad et al., 2016). Char is produced in very low quantities (1.1-3 wt%), which depends on the temperature of the process (Miandad et al., 2016a). The slow heating rate at low temperatures and long residence time increase the char formation during the pyrolysis process, whereas the char production in fast pyrolysis is commonly low (Sharuddin et al., 2016).

Char can be used in water treatment as an absorbent to remove heavy metals from municipal and industrial wastewater and toxic gases (Miandad et al., 2016a). Besides, there is a potential to use the pyrolysis char as a feedstock to produce activated carbon as a solid fuel for boilers (Sharuddin et al., 2016).

5.4.2 Products and by-products of catalytic cracking

Catalytic cracking produces the same products and by-products as conventional pyrolysis; however, the qualities and quantities of products are different and can vary depending on the catalyst used. Catalysts are widely used by industries and research to optimise product distribution and increase the selectivity of the product (Sharuddin et al., 2016). Furthermore, introducing a catalyst to pyrolysis can help to reduce productions costs and increase the quality and yield of materials with a higher added value (Solis & Silveira, 2020).

Compared to conventional pyrolysis, the use of catalyst in the process decreases the liquid yield production (including the heavy oil) and produces the liquid oil that contains low chain compounds in the gasoline range with high octane number (Miandad et al., 2016). Generally, catalytic pyrolysis products are grouped as hydrocarbon gases ($<C_5$), gasoline (C_5-C_9), liquids, and residues (Datta & Kopczyńska, 2016). Hence, catalytic decomposition of plastic waste can be seen as a better alternative to conventional pyrolysis due to a narrower product spectrum obtained from the process. Furthermore, the range of products can be directed towards fuel, commodity chemicals and fine chemicals, depending on the process conditions (Ragaert et al., 2017). For instance, if transportation fuel range hydrocarbons are preferred, zeolite catalysts can be used for the process due to the corresponding properties from the zeolitic framework, such as developed micro/meso porous structure, relatively high surface area, and strong acid sites (Dai et al., 2021). Temperature can also be adjusted depending on the required product – an increase in temperature results in shorter chain compounds (Miandad et al., 2016). The **liquid oil** derived from catalytic cracking has similarities to commercial fuels. For instance, Miandad et al. (2019) reported HHV values of 41.7-44.2 MJ/kg, which is similar to that of conventional diesel. Furthermore, the viscosity and density of the liquid oil obtained from catalytic cracking have also been reported to be similar to that of the commercial fuel (Budsaereechai et al., 2019). Hence, the oil has the potential to be used for energy production and as a transport fuel.

In most cases, the use of catalyst in the pyrolysis process increases gas production and decreases the liquid yield but improves its quality (Miandad et al., 2016). The use of different catalyst produces different yield. For instance, catalytic pyrolysis of mixed post-consumer plastic waste (PP/PE/PS/PVC) had a gaseous yield ranging from 83.56 wt% to 90.65 wt% and a conversion rate of 88.7-93.7%, depending on the catalyst used. The catalyst also determined the proportion of hydrocarbon gases and gasoline, which can be attributed to the microstructure of the catalyst; hence the catalytic cracking process can be adjusted to produce the desired product (Datta & Kopczyńska, 2016). Furthermore, liquid oil yields as high as 91.2 wt% were achieved for HDPE, 92.3 wt% for PP, and 96.7 wt% for PS using a different catalyst (Sharuddin et al., 2016). The conversion rate of almost 100% was achieved during the catalytic cracking of LDPE with a yield of liquid product ranging from 41% to 89% depending on the catalyst used (Datta & Kopczyńska, 2016).

Several commercial catalytic processes are available with the main goal to produce high yields of transport grade fuels such as gasoline and diesel (Ragaert et al., 2017). Although the use of catalyst improves the quality of the liquid oil, it can only be used for **energy production and as a transport fuel** after refining/blending with conventional fuels (Miandad et al., 2019).

5.4.3 Products and by-products of gasification

The gasification of plastic waste leads to the production of a **synthetic gas** (syngas) made up mainly of H_2, CO, and a lesser amount of CO_2, CH_4, N_2 and other light hydrocarbons. It can be used to produce energy, energy carriers (i.e., hydrogen) or chemicals from the produced syngas (fuels, methanol, DME, etc.). The composition and the application of the syngas are determined by the agent used in gasification, such as air, steam or plasma (Ragaert et al., 2017; Lopez et al., 2018; Solis & Silveira, 2020).

The **quality** of the syngas depends on the type of gasification. Air gasification produces gas with an average lower heating value in the 6-8 MJ m^{-3} range, which can be used for energy production. On the other hand, steam gasification allows the production of H_2 rich syngas, which can be used for synthesis and energy applications. Besides, the absence of nitrogen increases the heating power to values above 15 MJ m^{-3} and allows the syngas to be used to produce new plastic products (Lopez et al., 2018; Solis & Silveira, 2020). In both processes, the main challenge is the formation of tar, which causes operational problems that lead to the reduction in the efficiency of the process and application of the produced syngas (Lopez et al., 2018). However, the plasma gasification process results in higher purity of the product gas with fewer tars compared to conventional processes (Solis & Silveira, 2020). **Char** can also form during the gasification process, but the yield is often very low, and higher production only occurs when the plastic waste is mixed with fibres or biomass. The syngas can also contain some impurities such as NH_3, H_2S, NO_x and alkali metals (Ragaert et al., 2017).

Syngas can be used to produce methanol or paraffinic hydrocarbons. Methanol is one of the most produced chemicals globally, and it is used as a reactant to produce several chemicals such as formaldehyde, methyl amine and acetic acid. The produced methanol can be further used as a commodity chemical or deployed to produce olefins or petroleum-like products via methanol-to-olefin (MTO) and methanol-to-gasoline (MTG), respectively (Ragaert et al., 2017).

Steam gasification of polyolefins can produce syngas with hydrogen concentration of up to 40%, with H_2 production being 4 wt% for PE and 3 wt% for PP. The high concentration of methane, 30 and 40%, and ethylene, 11-15%, has also been observed in the gasification of PE and PP, respectively. The high concentration of hydrocarbons can increase the heating value of the gas to 25 MJ m^{-3}. However, the high concentration of CH_4 and light hydrocarbons indicates the presence of tar (Lopez et al., 2018).

The gasification process leads to the production of **syngas** (hydrogen, carbon monoxide, et.), which then **can be used to produce biofuels** such as methanol (Solis & Silveira, 2020). The gas needs to undergo several cleaning processes to remove HCL, HF and other impurities, after which clean and dry syngas consisting mainly of CO and H_2 is produced (Ragaert et al., 2017). The process has been successfully applied by Enerkem in Canada and Texaco in the US (Ragaert et al., 2017; Solis & Silveira, 2020).

5.4.4 Products and by-products of chemolysis

Chemical depolymerisation processes reproduce the original monomers or starting substances from plastics such as PET, PU, PC, PA and polyesters (Datta & Kopczyńska, 2016). The advantage of this process is the possibility to recover monomers that can be further purified by filtering out colourants and additives, allowing for re-polymerisation to virgin-grade quality. However, if the quality or purity of the recovered monomers is not as good as the original monomers, they can be mixed with conventionally produced monomers for polymer synthesis (Vollmer et al., 2020).

Depolymerisation of plastics via chemical routes delivers **high conversion** to their monomers. However, different chemical depolymerisation processes and conditions produce different yields of monomers. For instance, depolymerisation of PET can recover 65-100% of monomer depending on the process. PU chemolysis can yield 70-95% of the original monomer, PC can achieve yields of 80-

100% andPA – 78-90% (Datta & Kopczyńska, 2016). Purification steps are usually required following the chemolysis process, which adds to the production costs (Barnard et al., 2021). It is important to address that monomers obtained from chemically recycled polymers are more expensive than virgin material due to raw material costs, capital investment and the scale of operation (Ragaert et al., 2017). Table 5-8 summarises different depolymerisation processes, obtained products and their yields.

Table 5-8: Summary of chemical depolymerisation processes for PET, PU, PC and PA, products and yields

Characteristics	Hydrolysis	Glycolysis	Alcoholysis	Methanolysis	Aminolysis
PET waste					
Products	TPA, sodium or potassium terephthalate, EG	BHET, DMT, EG	Dioctyl terephthalate (DOTP), EG	DMT, EG	BHETA, N, N'-bis allyl terephthalamide
Yield	70-100%	85-99%	95-100%	65-90%	75%
PU waste					
Products	Polyols, amine intermediates, toluene diamines	Polyols, aromatic carbamates, ureas, amines	Polyol, amine	4,4'-methylene diphenyl carbamate, DMA, MDC, BDO, amines, THF	Polyol, aromatic amines, DETA, MDA
Yield	70-90%	80-95%	No data	App. 95%	No data
PC waste					
Products	BPA, phenol	Monohydroxyethyl ether, bishydroxyethyl ether, ethylene carbonate	BPA, DEC	BPA, DMC, phenol, 4-tertbutylphenol	BPA, DMDEA
Yield	80–100%	50–80%	90%	90–95%	Over 80%
PA waste					
Products	ε-caprolactam, ε-aminocaproic acid	β-hydroxyethylester, bis (β-hydroxyethyl) hexanoate, δ-valerolactone	n/a	n/a	n/a
Yield	78-90%	No data	n/a	n/a	n/a
Source: Datta and Kopczyńska, 2016					

According to the literature review by Datta & Kopczyńska (2016), aminolysis and methanolysis are common processes for depolymerisation of PET, and hydrolysis is often used for both PET and PU decomposition. However, glycolysis has been identified as the most appropriate chemolysis reaction for these polymers as it gives high yields without the need of very special conditions, such as high pressure (Datta & Kopczyńska, 2016), and technologies employing glycolysis are currently the most advanced in regards to demonstrating commercial viability on a larger scale (Barnard et al., 2021). Glycolysis is also a typical method for depolymerisation of PA (nylons) and polyesters. Methanolysis in sub- and supercritical conditions is a very efficient way to depolymerise PC (Datta & Kopczyńska, 2016).

The **only commercially available depolymerisation** of polyester into its virgin quality ingredients is done in Japan, at the Teijin plant, where a closed-loop recycling system 'ECO CIRCLE' has been started together with sportswear and apparel manufacturers. During the methanolysis process, PET is converted to its ingredients: dimethyl terephthalate (DMT) and ethylene glycol (EG) at a reported stoichiometric relation of 69% and 31%, respectively. The process involves cutting, washing and dissolving the material in EG at its boiling point under the pressure of 1 bar to depolymerise polyester to bishydroxyethyl terephthalate (BHET), which is then reacted with methanol to produce DMT and EG by ester exchange reaction at the methanol's boiling point. The obtained DMT and EG are then purified via distillation (Schmidt, 2016). Furthermore, Aquafil developed ECONYL® Regeneration System to recycle nylon, which is a thermoplastic material that can be 'infinitely' recycled in a closed-loop system due to its great recycling properties. The depolymerisation and repolymerisation process can produce Nylon 6 from marine plastic waste, fishing nets and textile fabric waste without affecting its qualities (Hahladakis & Iacovidou, 2018; Luo & Deng, 2021).

Glycolysis is currently the most important PU recovery process, which has achieved the commercial scale with a few successful examples that use single-phase glycolysis. However, most of them are not operative at present because the process recovers polyols, which can only substitute virgin polyols in semi-rigid and rigid foams and not in flexible ones. Split-phase glycolysis processes obtain much higher quality products, but the high cost associated with the amount of cleavage agent required has resulted in the development of the technology only at a pilot scale. The recovered products can be reused as a raw rigid polyether polyol replacement to synthesise new rigid foams or produce adhesives, coatings, elastomers, and sealants (Simón et al., 2018).

6 Substances of Concern in Chemical Recycling

This chapter **aims** to discuss substances of concern (SoCs), their presence in plastic waste streams, the behaviour and fate of SoCs in chemical recycling processes and emissions of SoCs from chemical recycling of plastic waste.

6.1 The concept of substances of concern

To effectively implement waste management and circular economy goals, there is the need for a definition of 'substances of concern'. The Commission listed two options: the first option considers the REACH and CLP Regulations only, while the second option provides a detailed overview of substances of concern in all regulations relevant to the recyclers. For the purpose of this study, we will use the second option: "**substances of concern** are those identified under REACH as substances of very high concern, substances prohibited under the Stockholm Convention (POPs), specific substances restricted in articles listed in Annex XVII to REACH as well as specific substances regulated under specific sectorial/product legislation" (European Commission, 2018b: p. 9). Figure 6-1 provides a summary of various groups of substances of concern (SoCs).

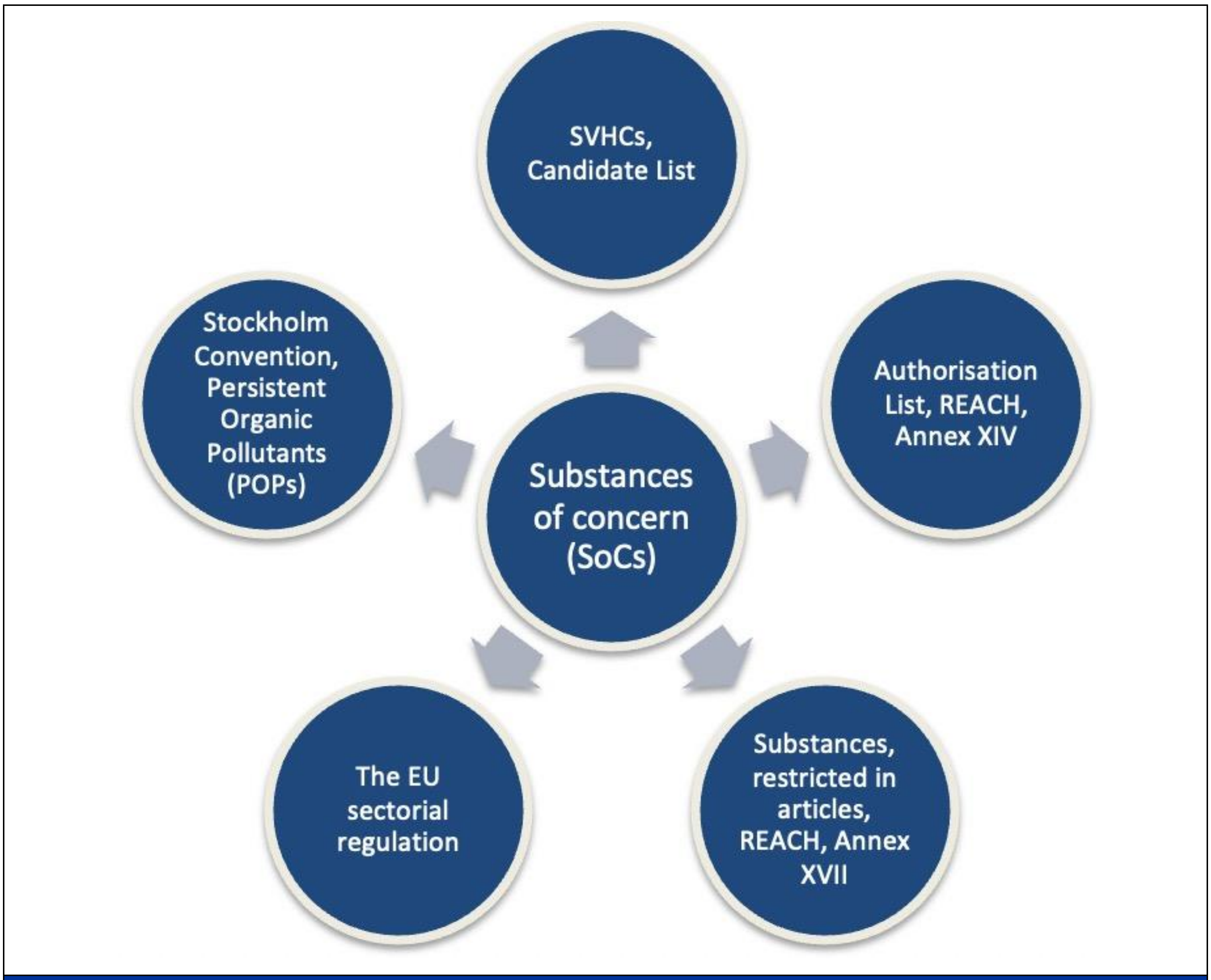

Figure 6-1: Substances of concern in various legislation and reports

As shown by Figure 6-1, there are five groups of substances of concern.

The first group contains substances of very high concern. The concept **of substances of very high concern (SVHCs)** is defined in the EU REACH Regulation (Article 57) and includes substances that are carcinogenic, mutagenic, and toxic for reproduction (CMR); persistent, bioaccumulative and toxic (PBT); very persistent and very bioaccumulative (vPvB), have endocrine-disrupting properties (ED) or those for which there is scientific evidence for serious effects to human health or the environment that give rise to an equivalent level of concern to those substances listed in Article 57 ((a) to (e)). The latter are identified on a case-by-case basis as outlined in Article 59 (European Parliament, 2006a).

In addition to the EU Candidate List of SVHCs, the **EU Member States introduce their national requirements**. For instance, The Netherlands introduced a non-exhaustive list of 1,400 substances that, according to various international laws and treaties, meet the SVHC criteria. The Dutch Government aims to substitute or prevent and minimise exposure to these substances (Wassenaar et al., 2017).

The list of SVHCs is provided in the **Candidate List of Substances of Very High Concern for Authorisation**, which is maintained by the European Chemicals Agency (ECHA) and based on the proposals for inclusion of a particular substance on the list submitted by the EU Member States or by ECHA itself at the request of the Commission. Currently, there are over 200 substances on the Candidate List for Authorisation. Upon the inclusion of a substance as SVHC in this list, suppliers of that substance must provide safety data sheets, communicate on its safe use, respond to consumer requests related to its presence in articles within 45 days and notify ECHA if the articles they produce contain the SVHC in quantities above one tonne per producer/importer per year and if the substance is present in those articles above a concentration of 0.1% (w/w) (ECHA, n.d.).

SVHCs from the Candidate List could be included in the **Authorisation List** (REACH, Annex XIV) based on their intrinsic properties, wide dispersive use, and high volumes. Authorisation aims "to ensure that the risks related to substances of very high concern (SVHCs) are properly controlled throughout their life cycle and to promote the progressive replacement of SVHCs by suitable alternatives (less dangerous substances, new technologies and processes), where technically and economically feasible alternatives are available" (ECHA, n.d.d).

Another measure to protect human health and the environment from substances of concern is adding a substance on its own, in a mixture or in articles on the **Restriction List** (REACH, Annex XVII). This list specifies conditions that substantially limit or prohibit the use of certain substances on the EU market and contains 69 unique entries as of May 2021 (ECHA, n.d.a).

The sectorial EU legislation regulates substances with adverse effects on human health and the environment. For instance, the RoHS Directive restricts the use of hazardous substances in electrical and electronic equipment (European Parliament, 2011). Currently, the use of ten substances that include heavy metals (used as stabilisers), flame retardants and plasticisers is restricted. Only very low concentrations (lower than 0.1% weight by weight for most of the restricted substances, with the exception of cadmium – 0.01%) are allowed in electrical and electronic equipment. The Regulation on materials and articles intended to come into contact with food (1935/2004) (European Parliament, 2021) and accompanying regulations, e.g., the Plastic Implementation Measure (10/2011) (European Parliament, 2011a), sets out specific requirements for food-contact plastic articles and materials. Similarly, the Toy Safety Directive (2009/48/EC) restricts the use of substances of concern in toys (European Parliament, 2009).

Another group of substances of concern – **Persistent Organic Pollutants (POPs)**, is regulated by the Stockholm Convention, which aims to eliminate or drastically reduce the manufacture and use of these substances globally. POPs include organic chemical substances that are peculiar for their persistency, bioaccumulation and transport in the environment. These substances are toxic to humans and wildlife.

They include pesticides, industrially produced chemicals and chemicals produced unintentionally in industrial processes, e.g., through combustion or degradation. They are listed in different annexes: Annex A – POPs that are subjected to elimination; Annex B – POPs for which production and use must be restricted; and Annex C – chemicals for which unintentional releases must be reduced (United Nations Environmental Programme, 2019). The provisions of the Stockholm Conventions are implemented in the EU by the POPs Regulation, which aims to eliminate and restrict POPs and ensure the safe management of stockpiles and waste streams (European Parliament, 2019).

Some studies identify substances that disrupt the performance of waste treatment and reduce the quality of recyclates as substances of concern (see Ökopol et al., 2020). Such substances pose challenges for chemical recycling itself. For instance, the presence of PVC in the plastic waste leads to the formation of chlorinate compounds in the pyrolysis oil; these compounds also have negative effects on pyrolysis equipment (Ragaert et al., 2017; Solis & Silveira, 2020). Chloride and nitrogen components deactivate catalyst in catalytic pyrolysis, while chemolysis methods are sensitive to contaminants in waste streams, such as heavy metals (Lee & Liew, 2020). However, these substances are identified as SoCs without any reference to their harm to human health and/or the environment, as in the regulatory definitions. While recognising that the knowledge about the presence of such substances in plastic waste streams is important to chemical recyclers, we do not include such substances in the definition of SoCs.

6.2 Substances of concern in waste streams

SoCs have been identified in many plastic product groups, such as consumer goods (e.g., plastic shoes, mattresses, pets' toys), products for children, construction materials (e.g., floors, pipes, wallpaper), electronics including TVs, mobile phones and kitchen appliances, furniture, vehicles including upholstery and fittings, packaging and food packaging, and recycled plastics (Stenmarck et al., 2017).

However, the most common plastic waste streams containing hazardous substances are plastics from **waste electric and electronic equipment** (**WEEE), end-of-life vehicles (ELV) and construction & demolition (C&D) waste** (Wagner & Schlummer, 2020). The substances have been found in articles made of or containing PVC, PES, PA, PUR, EPS, HIPS, ABS, PC, PS, PE, PP, PET, epoxy resins, rubber, and other plastics. However, it does not mean that hazardous substances are always found in these types of products (Stenmarck et al., 2017).

SoCs have been used in plastic articles as **stabilisers, colourants, plasticisers, blowing agents, catalysts, flame retardants, monomers, cross linkers, chain modifiers, hardeners, antioxidants, antimicrobial substances, solvents, and others** (Stenmarck et al., 2017; Wassenaar et al., 2017). These substances can be used at different concentrations in products (Wassenaar et al., 2017).

Most of these substances are used as **additives** in the manufacturing of plastic articles. They are used to improve processability and modify the physical or chemical properties of the final plastic material to achieve the desired properties. The **Plastics additive initiative by ECHA and partners from the industry** has listed over 400 functional additives or pigments used in plastics, registered under REACH at above 100 tonnes per year. The project focused on flame retardants, plasticisers, stabilisers, antioxidants and other additives and did not include additives or pigments never or no longer used in the EU, but that may be present in the imported goods (ECHA, n.d.b). The summary of all categories of additives and how many different substances have been identified in each category can be seen in Figure 6-2.

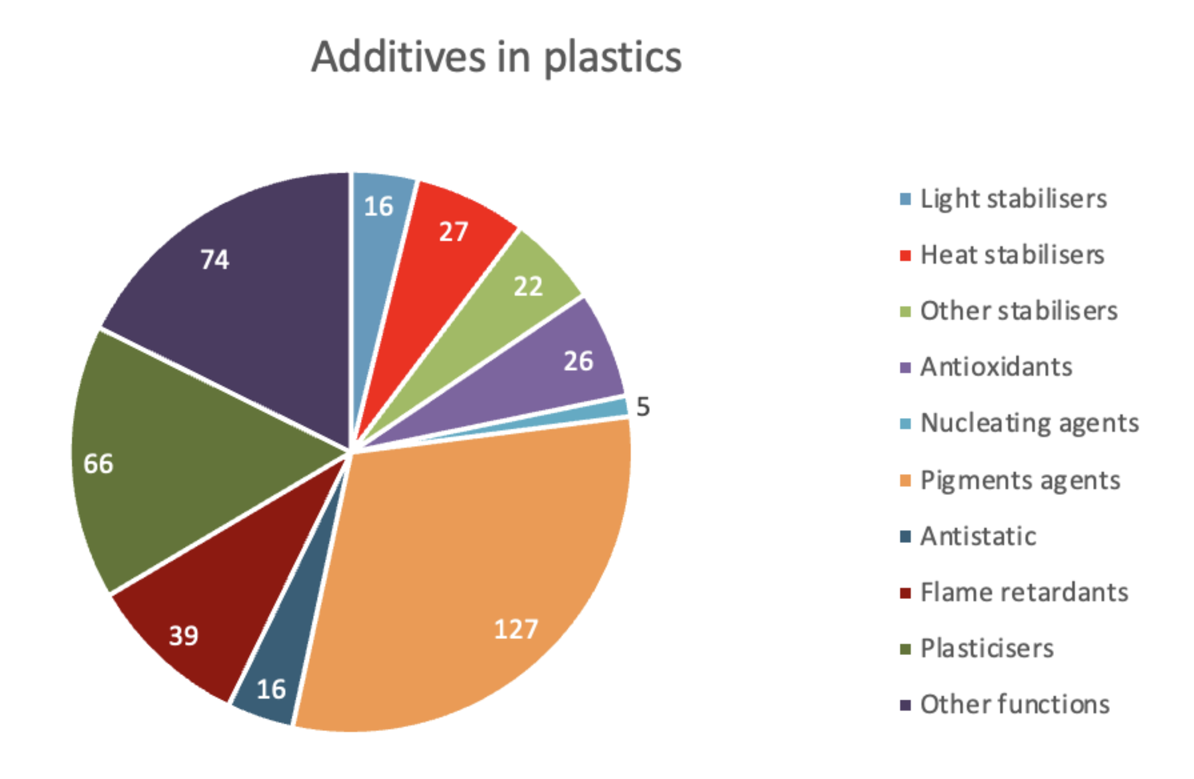

Figure 6-2: Additive categories and quantities of different substances in each category - *Source: Plastic additive initiative (ECHA, n.d.b)*

Additives may be present in a polymer as substances by themselves or react in the polymer matrix. In the latter case, reactive additives do not leach from the plastics because of stronger bonds with the molecules in the polymer matrix. In the former case, however, additives interact with the polymers via weaker, non-covalent bonds. As a result, they can leach into the environment during the intended life cycle and the waste phase of the plastic product (Wagner & Schlummer, 2020). However, leaching only through molecular diffusion is considered a very slow process, and most SoCs are released to the environment due to wear-and-tear and pulverisation (Sun et al., 2016). Though additives have been used for decades, many have been identified as hazardous to human health and the environment (Linares et al., 2015; Zarean et al., 2016).

Additives that often cause numerous health and safety hazards are plasticisers (phthalates)**, flame retardants** (brominated and chlorinated), **and heavy metal stabilisers** (cadmium and lead) (Janssen & van Broekhuizen, 2017). Phthalates have been found to be carcinogenic and influence neurodevelopment, reproductive, and respiratory systems (Zaraen et al., 2016). Brominated flame retardants are associated with reproductive, endocrine, behavioural, and neurodevelopmental effects and may even cause cancer (Linares et al., 2015; Lyche et al., 2015). Exposure to heavy metals, such as lead, can affect nervous, digestive, reproductive, and respiratory systems and disrupt the performance of enzymes and normal DNA function (Ab Latif Wani & Usmani, 2015). These additives are also substances that may cause problems during the recycling processes (Janssen & van Broekhuizen, 2017). Phthalates, stabilisers (lead and cadmium) and flame retardants that are currently on the REACH Candidates List of SVHCs are presented in Table 6-1. Limits for substances on the REACH Restriction List are also provided.

Table 6-1: Plasticisers (phthalates), stabilisers (lead & cadmium), and flame retardants on REACH Candidates List of SVHCs and Restriction List 2020 (REACH Annex XVII)

Substance Group	Substance name	EC Number	Application	Limit
Cadmium	Cadmium (Cd)	231-152-8	Colour pigment and stabiliser in plastic products	The concentration of cadmium (expressed as Cd metal) in plastic material **<=0.01%**
Lead	Lead (Pb)	231-100-4	Stabilisers in construction materials, flooring, furniture, toys, curtains, paints, electronic equipment, footwear	**<0.05%** *The limit shall not apply where it can be demonstrated that the rate of lead release from such an article or any such accessible part of an article, whether coated or uncoated, does not exceed 0,05 µg/cm^2 per hour*.
Phthalates	DEHP	204-211-0	Plasticisers in soft plastic toys, plastic bottles, raincoats, shoes, food packaging	DEHP+DBP+BBP<=0.1%
	BBzP	201-622-7		
	DnBP	201-557-4		
	DiBP	201-553-2		
	DnPeP	205-017-9		
	DCHP	201-545-9		
	DiPeP	210-088-4		
	DHNUP	271-084-6		
	DnHP	201-559-5		
	DMEP	204-212-6		
Flame retardants	BDE-209	214-604-9	Electronics, textiles & furnishings, building insulation, automobiles and other vehicles, flooring, ducting, appliances	BDE - banned as a substance. Less than 0.1% in article or its part. Exemptions: spare parts of aircraft, vehicles or machines, electrical and electronic equipment
	HBCDD	221-695-9, 247-148-4		
	TCEP	204-118-5		
	DDC-CO	236-948-9		
Sources: ChemSafetyPRO, 2021; HBM4EU, 2021				

Plasticisers used to improve the flexibility of the plastics are mainly found in PVC plastic waste; heavy metal stabilisers used to protect the material from thermal degradation are also often found in PVC plastics (Hahladakis et al., 2018; Wagner & Schlummer, 2020). Brominated flame retardants used for fire resistance in plastic products are often found in plastics from WEEE (Wagner & Schlummer, 2020). If not removed, these SoCs can further circulate in the environment, they may degrade into smaller and likely toxic, persistent, and bio-accumulative molecules and can be taken up by animals and plants and eventually enter the food chain (Bouwmeester et al., 2015; Hahladakis et al., 2018).

The Swedish Chemical Agency had investigated the presence of restricted substances such as plasticisers, flame retardants, lead, cadmium, and dimethylformamide/methylacetamide, in plastic articles. Samples were collected from over fifty companies and contained articles that can be found in a home environment, such as garden equipment, bathroom products, sports equipment, bags, and working gloves. Out of 160 articles, more than 50% contained restricted substances to various levels, with 14 articles containing restricted substances above the limit values (KEMI, 2015). However, in this investigation, not all plastic products were analysed for all restricted substances; hence these statistics are not definite and only illustrative of the extent of the presence of various restricted substances in consumer products.

The presence of restricted hazardous substances in plastic waste streams can pose technical and legal challenges for recycling of such waste to various stakeholders within the plastic waste recycling chain, including the producers of products from recyclates (Janssen & van Broekhuizen, 2017), because hazardous substances may be released during various recovery and recycling processes (Hahladakis et al., 2018; Hahladakis & Iacovidou, 2018). For instance, the study by Leslie et al. (2016) revealed that toxic flame retardants were identified in high concentrations in certain plastic waste streams destined for recycling. More importantly, they were found in various new consumer products made of recycled plastics. What is more, substances that are not permitted in new plastic articles today might still be present in plastic waste streams as **legacy additives** from long-lived products added to the market in the past, for example, PVC flooring or plastics from WEEE (Stenmarck et al., 2017). In addition, restricted substances may enter plastic waste streams from **products imported from outside the EU/EEA**. For instance, annual imports of articles based on rigid PVC stabilised by lead (e.g., pipes, window frames, fittings, shutters, etc.) have been steadily increasing over the last decade, mainly from Asian countries where lead is not restricted in PVC applications. Furthermore, based on the consultation between WTO countries in early 2016, the manufacturing of articles made of rigid PVC stabilised by lead will not cease, and imports of such articles to the EU countries are expected to continue (ECHA, 2018). Hence, recyclers will have to deal with these legacy additives and additives in imported articles for years to come.

6.3 SoCs behaviour and fate in chemical recycling

Plasticisers, flame retardants, and stabilisers have been named as additives posing the highest risk to human health and the environment. Chemical recycling of plastic wastes containing brominated flame retardants (BFRs) has been mostly discussed in the academic literature to date.

The literature search demonstrated that research on substances of concern in chemical recycling is scarce and mostly focuses on pyrolysis. Occasional mentions of the lack of studies about the behaviour and fate of substances of concern were given in the literature reviews of a broader scope. For instance, Barnard et al. (2021) recognised the lack of information about technical details, effectiveness and efficiency of chemolysis of PET waste in the industry. According to the review, there is a general lack of understanding of the processes, the capacity of chemolysis technologies to handle hazardous/contaminated inputs and the possibility of hazardous outputs (Barnard et al., 2021). Several literature reviews investigated the chemical recycling of **plastics from WEEE containing BFRs** (Charitopoulou et al., 2020; Das et al., 2021; Ma et al., 2016). The main processes reviewed were **pyrolysis** (Das et al., 2021; Ma et al., 2016), **catalytic pyrolysis** (Charitopoulou et al., 2020; Das et al., 2021; Ma et al., 2016), **co-pyrolysis** (Charitopoulou et al., 2020; Ma et al., 2016)**, pyrolysis with pre-treatment** (Charitopoulou et al., 2020), **two-step pyrolysis, microwave-assisted pyrolysis** (Charitopoulou et al., 2020), and **pyrolysis with catalytic upgrading** (Charitopoulou et al., 2020; Ma et al., 2016). All reviews covered a substantial number of studies over a long period: Charitopuolou et al. (2020) reviewed 66 studies published in 2003–2019; Ma et al. (2016) – 96 studies, published in 1986 (only a few instances) – 2016 and Das et al. (2021) – 85 studies, published in 1986–2020. Despite being valuable resources, these reviews contain several limitations. None of them discusses criteria for inclusion of studies in the review or develops any method for evaluating the quality of evidence. Furthermore, it is unclear if the reviewed chemical recycling technologies have actually been applied in the industry. These limitations should be taken into account when using the findings of these extensive reviews.

Several more **recent experimental studies** have also been identified, which studied WEEE containing BFRs and the fate of brominated compounds during pyrolysis processes. All these studies were performed at a laboratory scale. In their study, Chen et al. (2020) investigated the effect of the catalyst on pyrolysis products and the removal of bromine from these products. Evangelopoulos et al. (2020) studied the fate of bromine during the pyrolysis of WEEE and the performance of the continuous auger reactor. Finally, Oleszek et al. (2021) investigated the distribution of brominated compounds in the products obtained during pyrolysis and catalytic pyrolysis of polycarbonate (PC) plastics from WEEE.

Table 6-2: Summary of studies on chemical recycling of plastic waste containing brominated flame retardants

Plastic waste	Additive	Chemical recycling technology	Type of source	Source
WEEE	BFRs	Pyrolysis with pre-treatment; catalytic pyrolysis; co-pyrolysis; two-step pyrolysis; pyrolysis-catalytic upgrading; microwave-assisted pyrolysis	Review	Charitopoulou et al., 2020
WEEE	BFRs	Pyrolysis; catalytic pyrolysis; co-pyrolysis; pyrolysis-catalytic upgrading	Review	Ma et al., 2016
WEEE	BFRs & heavy metals	Pyrolysis; catalytic pyrolysis	Review	Das et al., 2021
WEEE (computer casing plastics)	BFRs	Two-stage (pyrolysis and catalytic pyrolysis)	Experiment	Chen et al., 2020
WEEE	BFRs	Pyrolysis	Experiment	Evangelopoulos et al., 2020
WEEE (PC plastics)	BFRs	Pyrolysis; catalytic pyrolysis	Experiment	Oleszek et al., 2021

According to Table 6-2, pyrolysis has been the most widely studied chemical recycling technology to treat plastic waste containing BFRs. Therefore, it is important to understand the behaviour of these additives during the pyrolysis process as they may undergo transformations that could determine their fate. However, although the fate of BFRs in the combustion process has been investigated, the thermal behaviour of BFRs during the pyrolysis process has not been well studied. Compared to the combustion process, pyrolysis takes place in an oxygen-free atmosphere; hence BFRs may experience very different transformations (Ma et al., 2016). Nevertheless, although the behaviour of such substances is not well understood, the quality and composition of products and by-products from pyrolysis of waste plastics containing BFRs have been widely investigated, which can provide useful insight into the fate of hazardous substances during various pyrolysis processes. For instance, toxic substances such as brominated organic compounds are often transferred to secondary by-products such as solid residue or gas instead of liquid oil, improving the quality of the product (Das et al., 2021).

Pyrolysis of two common BFR-plastics, namely, Br-ABS and Br-HIPS, which were flame retarded with decaBDE and TBBPA, respectively, and containing Antimony(III) oxide (Sb_2O_3) synergist, resulted in the production of both organically and inorganically bound bromine in the final product. The amount of organobromine and inorganic bromine ($SbBr_3$) in liquid oil and wax products varied depending on the type of pyrolysis (conventional, slow, and fast) and the type of plastic (Ma et al., 2016). What is more, the degradation of brominated plastics can produce HBr at higher temperatures (>500°C), which can result in the choking and corrosion of downstream pipes (Das et al., 2021). For instance, in their experimental study on WEEE plastic waste pyrolysis, Evangelopoulos et al. (2020) found that the highest fraction of bromine was transferred to gas when process temperature increased, and the main compound was HBr, the formation of which is explained by increased hydrogen radicals in the gas phase. In the same study, the bromine collected in the oil product was generated mainly through synergist reaction of Antimony (Sb), producing $SbBR_3$. The presence of metallic copper in this type of plastic waste resulted in the production of $CuBr_3$ in the solid residue due to the reaction with HBr (Evangelopoulos et al., 2020).

In addition, the presence of BFRs can generate other brominated compounds, such as bromomethane, bromophenol, bromobenzene, etc. The presence of brominated organic compounds in the liquid oil may act as precursors to the toxic dioxins and furans (PBDD/Fs) during the utilisation of oil as fuels (Das et al., 2021). The bromine content in the oil produced via pyrolysis of plastics from WEEE is above the permitted levels for commercial application according to the EU standards (Directive 2011/65/EU), as the presence of organic and inorganic bromine would cause problems during the combustion of the final product (Ma et al., 2016). Therefore, the presence of bromine in products would require further treatment. Nevertheless, the process conditions could be adjusted to allow the bromine to be transferred in different products depending on the post-processing available in the plant for the most efficient removal (Evangelopoulos et al., 2020).

Catalytic pyrolysis has been seen as a suitable solution for the simultaneous degradation and dehalogenation of plastic waste containing BFRs (Das et al., 2021). In their reviews, Charitopoulou et al. (2020), Das et al. (2021), and Ma et al. (2016) discussed the addition of various catalyst for the debromination of liquid oil. Catalysts such as zeolites (HY, Hβ, HZSM-5, ZSM-5, Y-zeolite), mesoporous (all-silica MCM-41, activated Al_2O_3), and natural catalysts such as limestone, red mud and natural zeolite were all effective in reducing or eliminating bromine component from the liquid oil of pyrolysis of BFR-plastics, but some catalysts performed better than others (Charitopoulou et al., 2020; Das et al., 2021; Ma et al., 2016). Organobromine components were successfully removed from the liquid oil produced from the pyrolysis of Br-HIPS and Br-ABS in the presence of ZSM-5 and Y-zeolite catalysts. However, they were not as effective in the elimination of inorganic bromine. Furthermore, the oil yield was reduced, and the oil composition was significantly altered (Ma et al., 2016). Catalysts such as red mud and natural zeolite decreased the production of oil and increased the yield of gases. But all natural catalysts were effective in removing bromine from the liquid fraction of the product. What is more, besides the removal of organobromine compounds, red mud was capable of fixing HBr formed by Br-HIPS degradation (Charitopoulou et al., 2020; Ma et al., 2016).

In their recent experimental study, Oleszek et al. (2021) investigated the pyrolysis of brominated PC from WEEE. They found that catalytic conditions using Cu_2O reduced the amount of organic bromine compounds in the condensate and substantially reduced the formation of HBr in the gas phase due to an effective bromine fixation by oxides and the formation of CuBr, which is stable and does not vaporise at temperatures up to 600°C. What is more, a significant reduction of brominated organic compounds in the condensate was related with their involvement in coupling reactions, which result in the intermolecular cross-linking by copper compounds (Oleszek et al., 2021). Although catalytic cracking can be seen as a promising solution to remove BFRs from waste plastic, coke accumulation on the catalyst, the expense of the catalyst, and the catalyst deactivation or poisoning are seen as main drawbacks that have prevented the commercial success of this technology (Ma et al., 2016).

Pyrolysis with catalytic upgrading appeared useful when dealing with raw WEEE waste that usually contains other impurities and metals that may deactivate the catalysts during catalytic pyrolysis. In this case, the pyrolysis process is used to decompose brominated plastics. The second step involves catalytic upgrading of the pyrolysis products to reform them into bromine-free products (Charitopoulou et al., 2020). In their recent experiment, Chen et al. (2020) studied the effectiveness of the Fe-Ni bimetallic MCM-41 catalyst with different ratios of Fe and Ni to remove bromine from the liquid phase in two-stage pyrolysis of computer casing plastic containing BFRs. The catalyst was remarkably effective in eliminating bromine from the oil, with Fe-based catalyst reaching the highest efficiency. The key mechanisms responsible for debrominations were thought to be reactions between metal oxides and $SbBr_3$/HBr, direct elimination and dissociative adsorption coupled with β-H elimination of organobromines with metal oxides, and the deposition of organobromines on the catalysts due to high carbon solubility of metal oxides (Chen et al., 2020).

Pyrolysis with pre-treatment has also been discussed in the literature. Solvent extraction as a pre-treatment has been used to remove BFRs from plastic waste (Charitopoulou et al., 2020; Evangelopoulos et al., 2019). Different extraction techniques are performed for this method, from traditional Soxhlet extraction to more advanced techniques such as pressurised liquid extraction (PLE), supercritical fluid extraction (SFE), microwave-assisted extraction (MAE), etc. Furthermore, different solvents can be used for this method, namely, isopropanol, toluene, methanol, ethanol, and acetone (Charitopoulou et al., 2020). For instance, Evangelopoulos et al. (2019) investigated the removal of flame retardant TBBPA from real WEEE plastics through Soxhlet extraction using isopropanol and toluene as solvents for a pre-treatment step prior to the pyrolysis process. The results showed that isopropanol was more efficient in removing bromine from the solid material, whereas the analysis of the effluent solvent indicated that toluene was more efficient in removing TBBPA specifically, although complete removal was not achieved. The study has indicated that the subsequent pyrolysis of treated plastic can affect the production of brominated compounds due to the higher ratio of available H radicals and the bromine, which increases the production of HBr instead of brominated organic compounds. Nevertheless, in their experiment, the process led to a reduction of bromine content from the waste and not complete removal, although some bromine compounds were eliminated (Evangelopoulos et al., 2019).

Debromination using supercritical or near supercritical fluids has been gaining importance due to great debromination efficiency (Soler et al., 2017). Supercritical fluids, including water or other organic solvents, such as acetone, ethanol, and methanol, can be used to degrade brominated plastics with high effectiveness (Charitopoulou et al., 2020). The extraction of bromine using fluids in such conditions is much faster and more efficient than using liquid solvents as low viscosity of supercritical fluids favours penetrability into the pores of the polymeric matrix and mass transfer phenomena (Soler et al., 2017).

The pre-treatment of brominated plastic waste using chemical reagents has also been investigated. The pre-treatment of a non-metallic fraction of waste printed circuit board with NaOH followed by pyrolysis resulted in the fixation of Br in the char due to the reaction between produced HBr and NaOH, which resulted in NaBr generation (Shen et al., 2018). Similar results were obtained by Wajima et al. (2015) when the pyrolysis of Br-ABS with the addition of NaOH resulted in effective removal of bromine from pyrolysis oil, which was captured in the solid residue instead of a gaseous product.

Other types of pyrolysis, namely, two-step pyrolysis, co-pyrolysis, pyrolysis-catalytic upgrading, and microwave-assisted pyrolysis, have also been analysed in literature reviews. **Co-pyrolysis** with other polymers, for example, PP, helped reduce bromine content in the liquid oil, whereas the co-pyrolysis of WEEE and biomass blend transferred bromine to the char instead of oil (Ma et al., 2016). In **two-step pyrolysis**, bromine components simply remained in the first step liquid oil, leaving the oil from the second phase free from the brominated compound. Although **microwave-assisted pyrolysis** for brominated plastic waste has been mentioned, it has not been well researched (Charitopoulou et al., 2020).

A summary of effective solutions to reduce concentrations of hazardous substances during pyrolysis and gasification of plastic wastes or in their products are listed in Table 6-3. Besides the already mentioned processes, other solutions such as the addition of transition oxides (see Ji et al., 2020), use of adsorbents (see Torres et al., 2020), and the selective decomposition of unsaturated hydrocarbons with the application of catalytic sorbent in the simultaneous dechlorination of non-condensable gas have been investigated in the academic literature.

Table 6-3: Solutions for a reduction of hazardous substances in the pyrolysis process			
Process	**Plastic waste**	**Control**	**Source**
Pyrolysis	PVC	Addition of transition metal oxides	Ji et al., 2020
Pyrolysis	E-waste plastics	HCl leaching/Alkali pre-treatment	Shen et al., 2018
Pyrolysis	PVC	Use of adsorbents	Torres et al., 2020
Pyrolysis	Mixed plastics	Selective decomposition of unsaturated hydrocarbons with simultaneous dechlorination of non-condensable pyrolysis gas using a catalytic sorbent	Veksha et al., 2018
Pyrolysis	E-waste	Debromination in subcritical water	Soler et al., 2017
Pyrolysis	E-waste	Co-pyrolysis with biomass	Ma et al., 2016
		Use of catalyst	
		Catalytic hydrodebromination or pyrolysis with catalytic upgrading	

Overall, the chemical recycling of plastic waste containing BFRs, mainly from WEEE, has been widely discussed in the academic literature. However, the behaviour of halogen compounds during the pyrolysis process still needs to be fully understood to allow the optimisation of process parameters that would prevent the formation of hazardous substances. The presence of stabilisers and plasticisers in PVC wastes mainly affects the temperature of the dehydrochlorination step in pyrolysis. Chemical recycling of other types of plastic waste in the presence of these additives has not been well studied and would require more research.

6.4 Emissions of substances of concern

The EU Directive 2010/75/EU on industrial emissions defines **emissions** as "direct or indirect release of substances, vibrations, heat or noise from individual or diffuse sources in the installation into the air, water or land" (European Parliament, 2010, pp.12).

The literature search identified research focused on the emissions from gasification and pyrolysis processes. Hazardous substances can be found in liquid, solid residue, and gas fractions of the pyrolysis process (Das et al., 2021) or solid residue and gases of the gasification process (Weiland et al., 2021). Liquid oil is a product of pyrolysis; hence the presence of substances of concern in this fraction will not be considered in this section.

For the purpose of this chapter, the gas fraction of these thermal recycling processes is considered, as hazardous substances may be released into **the air** either via **flue gases** or during the accident, which can cause the exposure of harmful substances to workers (see Paladino & Moranda, 2021) and/or have negative effects on the population and the environment in the nearby areas of the plant. It is important to mention that flue gas emissions from gasification are lower than from straight combustion, and emissions from pyrolysis are considered very low (Joint Research Centre, 2019). Furthermore, **emissions to water from wet processes are also considered** when discussing emissions control. Finally, the **treatment and disposal of solid residues** is also discussed because toxic compounds are often transferred to these by-products during thermal treatment processes (Das et al., 2021).

Pyrolysis and gasification of complex plastic waste such as e-waste or mixed plastics can result in the formation of various hazardous compounds, including **polycyclic aromatic hydrocarbons (PAHs), oxygenated monoaromatic hydrocarbons (MAHs), polychlorinated biphenyls (PCBs), volatile organic compounds (VOCs), chlorinated/brominated dioxins and furans** (Das et al., 2021; Dogu et al., 2021; Garrido et al., 2016; Paladino & Moranda, 2021), **hydrogen halides and halogens, and other brominated** (Das et al., 2021; Soler et al., 2017) **and chlorinated compounds** (Garrido et al., 2016). The gasification of solid plastic waste can also produce heteroatoms containing compounds such as

HCN and NOx (Dogu et al., 2021). The summary of hazardous substances emitted from the thermal recycling of various plastic wastes identified in the research literature can be found in Table 6-4.

Table 6-4: Emissions of substances of concern from thermal recycling processes of various plastic wastes

Process	Plastic waste	Substances	Source
Pyrolysis/gasification	Solid plastic waste	Oxygenated MAHs	Dogu et al., 2021
		PAHs	
		VOCs	
		Brominated phenols	
		Dioxins/furans	
		Sulphur oxides (SOx)	
		Hydrogen halides	
Gasification		Heteroatoms containing compounds such as HCN and NOx	
Catalytic pyrolysis	Mixed plastic waste	Dioxins/furans	Paladino & Moranda, 2021
		PCBs	
		VOCs	
		MAHs	
		PAHs	
Pyrolysis	E-waste	Dioxins/furans	Das et al., 2021
		Hydrogen halides, halogens	
		PCBs	
		PAHs	
		Brominated compounds	
Pyrolysis with and without debromination in subcritical water	E-waste (printed circuit boards)	Hydrogen halides, halogens	Soler et al., 2017
		PAHs	
		Semi volatile compounds	
		Brominated compounds	
Pyrolysis	Flexible polyurethane foam (FPUF)	PAHs	Garrido et al., 2016
		VOCs	
		Semi volatile compounds	
		Dioxins/furans	
		PCBs	
		Chlorophenols	
		Chlorobenzenes	
		Ammonia	
Gasification	Plastic reject (PR) & automotive shredder residue (ASR)	Dioxins/furans	Weiland et al., 2021
		Halogen halides	

Emissions of certain substances during pyrolysis or gasification of plastic waste depend on its composition, molecular structure, the presence of additives and contaminants. For instance, the thermal treatment of e-waste plastics can result in the formation of hydrogen halides, halogens, dioxins, and brominated compounds due to the presence of brominated flame retardants in waste (Das et al., 2021; Soler et al., 2017). Pyrolysis of polymers containing various additives (plasticisers, UV stabilisers, antioxidants) can produce high concentrations of VOCs (He et al., 2015). The presence of PVC in the mixed plastic waste can result in the generation of HCl or chlorinated hydrocarbons (Dogu et al., 2021), whereas monoaromatics are derived from the treatment of ABS and PS plastics and oxygenated VOCs from the pyrolysis of PVC and PA (Paladino & Moranda, 2021). The type of thermal process (e.g., conventional or catalytic pyrolysis), process parameters or the addition of the pre-treatment step can also influence the composition of emissions from the process.

The **gas fraction of the pyrolysis** of mixed plastic waste consists of **un-condensable phase**, which is typically composed of hydrogen, methane, nitrogen, oxygen, hydrocarbons, VOCs, with small amounts of PAHs (mainly from the evaporator), and **flue gas**, which contains main combustion products such as carbon dioxide and nitrogen oxides, unburnt hydrocarbons, **dioxins, furans, and PCBs** (Paladino & Moranda, 2021). Monoaromatic hydrocarbons (MAHs) like benzene, styrene, and toluene are also produced, which are considered valuable products; however, benzene and oxygenated MAHs may cause some concerns if released in the exhaust gases from the pyrolysis or gasification processes (Dogu et al., 2021).

Many **PAHs** such as phenanthrene, anthracene, fluoranthene, pyrene, benz(a)anthracene, chrysene, benzo(k)fluoranthene, benzo(g,h,i)perylene are on the Candidates List of SVHC, and some are REACH Annex XVII restricted substances, for example, benzo(b)fluoranthene, benzo(k)fluoranthene, dibenzo(a,h)anthracene (ChemSafetyPRO, 2020). These substances are not only toxic but also known as precursors for the formation of harmful particulate matter (Dogu et al., 2021). **PCBs, dioxins, and furans** are on the list of persistent organic pollutants (POPs). Dibenzo-p-dioxins and dibenzo-p-furans are highly persistent in the environment and tend to bioaccumulate in organs and tissues. Several PCBs called coplanar that have similar physical, chemical and toxicological properties to dioxins and furans are called dioxin-like PCBs. They have similar effects on human health and organisms as dioxins and are classified as carcinogenic for humans (Paladino & Moranda, 2021). **MAHs are rich sources of VOCs**, which can pose non-cancer and cancer risks to human health (He et al., 2015).

The thermal degradation of e-waste plastics can also generate **hydrogen halides such as HBr, halogens (Br_2), bromophenols and other brominated compounds due to the presence of brominated flame retardants** in such waste (Das et al., 2021; Soler et al., 2017). In their study, Soler et al. (2017) investigated the emissions of various pollutants from pyrolysis of printed circuit boards with brominated flame retardants at 850°C. They found that the main bromine product was inorganic bromine, with HBr emissions being much higher than Br_2. Hydrogen halides are highly corrosive and may have an adverse impact on the downstream processes (Das et al., 2021). The emissions were also analysed for sixteen priority PAHs, and the presence of compounds such as naphthalene, acenaphthylene, phenanthrene and fluorene was identified. Naphthalene was the most abundant PAH formed during the pyrolysis. Semi volatile compounds also were formed but to a much lesser extent due to the high temperatures of the process. Finally, other brominated compounds, including 9- bromo-9H-fluorene, bromobenzene and 5-bromobenzofuran, were also detected (Soler et al., 2017). Similarly, in their review on the thermochemical treatment of contaminated e-waste plastics, Das et al. (2021) identified HBr and bromomethane as the main bromine compounds in the gaseous fraction of the pyrolysis of waste plastics (ABS/HIPS, printed circuit boards).

In their study, Garrido et al. (2016) characterised **emissions from the pyrolysis of flexible polyurethane foam (FPUF)** found in mattresses and upholstered furniture. They found that thermal degradation yielded VOCs, including toxic acrylonitrile and acetonitrile, and all sixteen priority PAHs with benzonitrile, styrene and naphthalene being most abundant, although seven most carcinogenic PAHs were only detected in the pyrolysis at 850°C and in relatively low levels. Furthermore, chlorobenzenes, chlorophenols and more than 180 other semi-volatile compounds were also detected as well as the presence of PCDD/Fs and dioxin-like PCBs. However, less toxic congeners were dominant for the latter compounds (Garrido et al., 2016).

The **pyrolysis of PVC plastics or plastic wastes containing PVC results in the formation and release of hydrogen chloride (HCl)**, which can deactivate the catalyst, affect the mechanism of the pyrolysis, reaction, cause equipment corrosion, and affect the quality of the product (Ji et al., 2020). The emissions of other hazardous substances in the thermal treatment of PVC were detected by Torres et al. (2020) in their study. The pyrolysis of PVC at 550°C, besides HCl, generated benzene, toluene, naphthalene, and chlorinated aromatic hydrocarbons (mainly chlorobenzene). The char was also produced with the presence of chlorine derivatives (Torres et al., 2020).

The **gasification of chlorine containing plastic waste can generate PCDD/Fs**, however, to a much lesser extent when compared to combustion/incineration (Weiland et al., 2021). The PCDD/Fs can form either because of the presence of PCDD/Fs in the waste or from chlorinated hydrocarbons already in or generated in the furnace (Joint Research Centre, 2019). Furthermore, copper, which may be present in some plastic wastes, can act as a catalyst for the formation of PCDD/Fs. The gasification process takes place in fuel-rich conditions, where all oxygen is consumed in the conversion process. The syngas is essentially free of oxygen when it cools down to temperatures associated with PCDD/F formation. Since oxygen is required for the formation of PCDD/Fs, the lack of it inhibits the generation of these toxic compounds (Weiland et al., 2021). Nevertheless, the emissions of these substances from gasification, although to a much lesser extent compared to incineration, still occur and need to be controlled.

6.5 Emissions control and best available techniques (BATs)

Currently, the **emissions control and Best Available Techniques (BATs) for pyrolysis and gasification processes are covered within BAT Reference Document for Waste Incineration**. The document highlights that it is more common for all these three processes to be combined as part of an integrated process and often on the same site. In this case, the plant recovers energy rather than feedstock to produce chemical products (Joint Research Centre, 2019). A separate reference document for the emissions control and BATs for pyrolysis and gasification processes has not been identified.

Emissions to air are controlled by applying flue gas cleaning (FGC) systems. They are usually constructed as a combination of separate process units, the balance of which depends on the waste stream. This combination of units provides an overall treatment of the pollutants in the flue gas. **The reduction of acid gases such as HCl** is generally achieved by injecting alkaline reagents, where the reaction products are dry or dissolved salts depending on the technique. There are three main processes for flue gas cleaning from acid gases: wet, semi-wet and dry processes. **Emissions of organic carbon compounds** such as PAHs, halogenated aromatic hydrocarbons, PCDD/Fs etc., can be reduced by applying oxidising catalysts, adsorption processes and further dust and aerosol deposition due to preferable pollutant adsorption onto the fine fraction of dust. Techniques such as adsorption on activated carbon reagents, SCR systems, catalytic filter bags, reburning of carbon adsorbents, the use of carbon-impregnated plastics for the adsorption, static or moving bed filters, or rapid cooling of flue gases are being used (Joint Research Centre, 2019).

Several main principles apply for the control of **emissions to water**:

- the optimisation of the thermal process provides effective control of emissions to the water where the wet processes are applied;
- the reduction of water consumption and the discharge of wastewater, which can be achieved by recirculation of polluted water for wet or semi-wet FGC processes, cooling of wastewater from wet FGC systems, application of FGC technology that is wastewater-free (e.g., dry sorption systems), water reuse and recycling, etc.;
- compliance with relevant water emissions standards;
- optimised operation of wastewater treatment system (Joint Research Centre, 2019).

The wet FGC process generates wastewater that contains a wide range of polluting compounds. The recirculation of polluted wastewater in a wet FGC system can generate lower volumes of wastewater, however higher concentrations of pollutants as a consequence. The wastewater from wet FGC systems is treated by three main methods: physio-chemical treatment, evaporation in the waste incineration process line, and separate evaporation (Joint Research Centre, 2019).

Solid residues, such as fly ashes or FGC residues, may also contain various hazardous substances, hence need to be properly treated. Fly ashes that are entrained with flue gas are often collected with flue gas treatment equipment (Joint Research Centre, 2018). Residues from the FGC system are a mixture of pollutants that are present in flue gas and also substances that are used for the removal of those pollutants (Joint Research Centre, 2019). The residue can be treated by stabilisation and solidification processes, either on site or in waste treatment facilities. These processes are usually used before landfilling. For instance, FGC residues solidified with cement are landfilled in either surface-level or underground deposits, and it is a very common method for the treatment of FGC residues, widely used in Europe. The release of pollutants from the solidified output in the short-term is considered low; however, long-term leachability is not well understood. However, the time required for a total release from stabilised output is expected to be in the range of several hundred to thousand years. Methods such as vitrification, purification, and recycling of some components are also applied to treat FGC residue. Furthermore, these residues may also be used to substitute raw materials in waste treatment or construction applications after further treatment (Joint Research Centre, 2018).

Finally, **safety devices and measures deal with the prevention of accidents** that could result in pollution emissions. The aim of protective systems installed in safety-relevant parts of the plant is to prevent the occurrence of malfunctions or accidents that could potentially cause harm or reduce the effects if malfunction or accident occur. Protective systems include systems for controlling the release of pollutants, systems for protection against fire and explosions, systems for protection against sabotage, pollution detection, etc. In addition, components for the discharge, removal or retention of hazardous substances, warning, alarm and safety systems are also important. The reaction of a protective system to a malfunction or an accident can cause an increase in pollution emissions, so the purpose of all safety measures must be to keep the duration of these elevated emissions to a minimum (Joint Research Centre, 2019).

Currently, **Best Available Techniques (BATs) for emissions control to air and water in pyrolysis and gasification plants** are included within BAT for waste incineration. The BATs for the treatment of fly ash and FGC residue are covered by the BAT for Waste Treatment (Joint Research Centre, 2018).

For channelled **emissions to air of dust, metals and metalloids**, BAT is the application of one or a combination of the following techniques: bag filter, electrostatic precipitator, dry sorbent injection, fixed- or moving-bed adsorption (mainly used to adsorb metals, metalloids and organic compounds such as PCDD/Fs), and wet scrubber. For **emissions of HCl, HF and SO_2**, BAT is the use of one or a combination of the following techniques: wet scrubber, semi-wet scrubber, dry sorbent injection, boiler sorbent injection, and direct desulphurisation. Furthermore, for reduction of peak emissions of these substances while limiting the consumption of reagents and the generation of residues from dry sorbent injection and semi-wet absorbers, optimised and automated reagent dosage needs to be used with an option to recirculate reagents. Finally, to reduce **emissions to air of organic compounds PCDD/Fs and PCBs**, optimisation of the thermal process, control of the waste feed, on-line and off-line boiler cleaning, and rapid flue-gas cooling need to be used with either one or a combination of the following techniques: dry sorbent injection, fixed- or moving-bed adsorption, selective catalytic reduction (SCR), catalytic filter bags and/or carbon sorbent in a wet scrubber. The advancements in the design and operation of thermal processes and FGC systems have resulted in a very effective reduction of emissions of these harmful compounds into the air (Joint Research Centre, 2019).

There are several **BATs for controlling emissions to water**. Firstly, BAT is to separate wastewater streams depending on their characteristics and treat them separately to prevent the contamination of uncontaminated water, increase resource efficiency, and reduce emissions to water. To reduce water consumption and the generation of wastewater, BAT is to use wastewater-free FGC techniques, injection of wastewater from FGC, dry bottom as handling, and water reuse/recycling. For reduction of emissions to water from FGC, BAT is to use an appropriate combination of the primary (optimisation of the thermal process and/or of the FGC system) and secondary (preliminary and primary treatment, physio-chemical treatment, and final solids removal) techniques, and use the secondary techniques as close to the source as possible to avoid dilution (Joint Research Centre, 2019).

BAT for the treatment of FGC residue is covered under the BAT for the physico-chemical treatment of solid/or pasty waste. Firstly, BAT is to monitor the waste input to improve the overall environmental performance. Secondly, to reduce emissions of dust, organic compounds and NH_3 to air, BAT is containment, collection and treatment of diffuse emissions using adsorption, biofilter, fabric filter and wet scrubbing or a combination of these techniques (Joint Research Centre, 2018). BATs for emissions control to land or soil via leaching from landfills have not been considered in BAT for Waste Treatment.

7 Regulatory Issues in Chemical Recycling

In the EU, **waste recycling is subject to different regulations**. The feedstock for recycling is waste, and this is governed by waste legislation. However, the output of recycling falls under the regulation of chemical substances and articles, product safety and other sectorial legislation. In turn, the role of recycling is twofold: it is a means for achieving both the circular economy goals and efficient waste management. Historically, EU policies on waste and chemicals management did not contain the circular economy dimension and were mainly oriented toward creating a non-toxic environment and efficient waste management. Circular economy policies focus on maximum re-use and recyclability of materials to safeguard natural resources and produce less waste. Many researchers emphasise that regulatory and technical issues in recycling arise due to the lack of reconciliation between the objectives and means for their achievement in these regulatory areas (Wagner & Schlummer, 2020; Alaranta & Turunen, 2021; Friege et al., 2019; de Römph & Calster, 2018). The European Commission recognised the need to consolidate the circular economy and waste management objectives and develop effective means for their implementation in *Communication on the implementation of the circular economy package: options to address the interface between chemical, product and waste legislation* (European Commission, 2018a).

Recyclers are both waste managers and manufacturers of new substances/producers of articles who must comply with waste management and chemicals legislations. The summary of legal obligations of chemical recyclers under different types of legislation is provided in Figure 7-1.

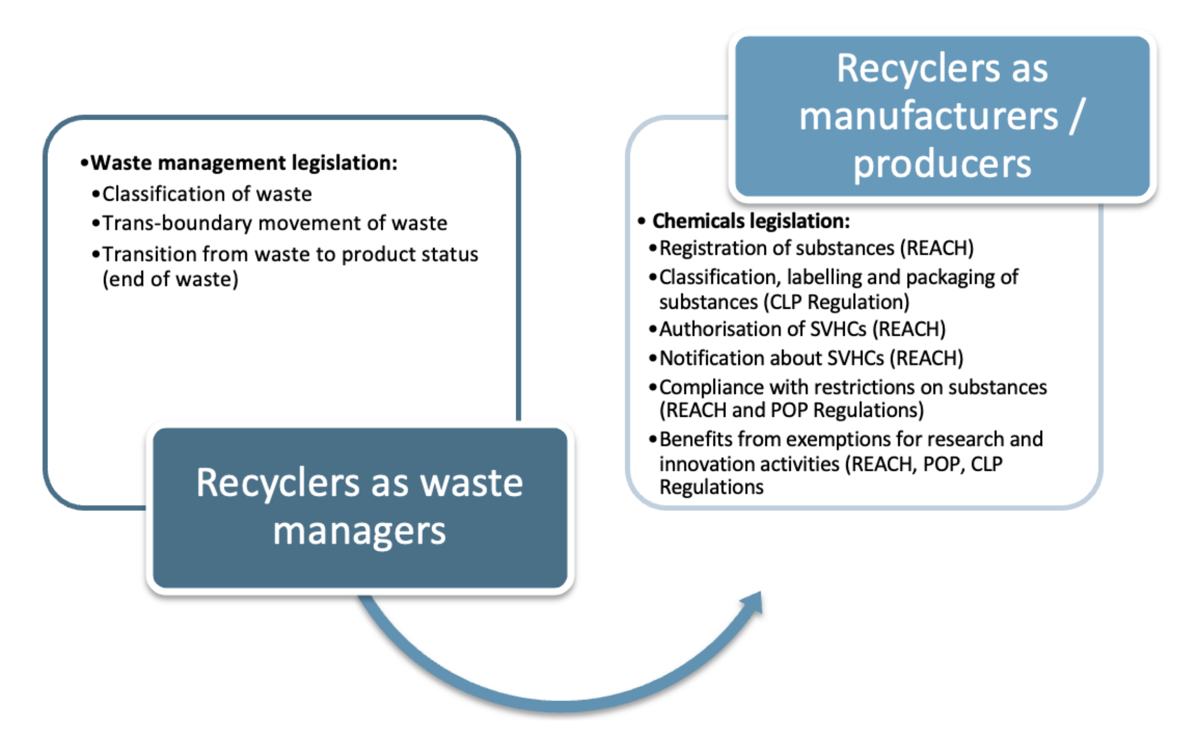

Figure 7-1: Overview of legal obligations of chemical recyclers - *Sources: Friege et al., 2019; Alaranta & Turunen, 2021; de Romph & Van Calster, 2018*

This chapter **aims** to discuss the obligations of recyclers as waste managers and manufacturers of substances or producers of articles and covers uncertainties and complexities that emerge in the implementation of legal obligations.

Importantly, most research on the regulatory issues in recycling is focused either on recycling in general or mechanical recycling. Based on the content of section 6.2, *SoCs Behaviour and Fate in*

Chemical Recycling, it is assumed that challenges faced in mechanical recycling can be relevant to chemical recycling in those cases when chemical recycling technology is not capable of destroying SoCs. However, it should be noted that the issues discussed here are relevant to chemical recycling technologies only in those cases where SoCs remain in the recycled substances. In other cases, SoCs can be emitted during the treatment and managed by the technologies for emission control or remain in the residues of chemical recycling and handled through appropriate treatment.

Before the detailed analysis of the regulatory concerns, it should be mentioned that in research and grey literature, chemical recycling is often positioned as an alternative way to manage SoCs (Wagner & Schlummer, 2020; Friege et al., 2019; Norin et al., 2020; Janssen et al., 2016). It is seen as a method for eliminating SoC in reprocessing waste into new substances or products. Seeking alternative methods to destroy SoCs in recycling is prominent in different reports (e.g., see Beekman et al., 2020; Janssen et al., 2016; Norin et al., 2020). However, the mentions of chemical recycling prospects are concise and provide examples rather than extensive evidence-based discussions. For instance, many publications refer to the CreaSolv® process – a solvent-based technology that is suitable for the recycling of thermoplastics, construction and demolition waste containing hazardous brominate flame retardant hexabromocyclododecane (HBCD) (e.g., see Wagner & Schlummer, 2020; Norin et al., 2020; Alaranta &Turunen, 2021; Friege et al., 2019; Janssen et al., 2016). However, solvent-based purification (or dissolution) is not a chemical recycling technology (see the discussion in section 3.1 *Defining Chemical Recycling*). As mentioned by Norin et al. (2020), the assessment of chemical recycling is complicated by the lack of harmonised terminology that results in giving a different meaning for the same terms. Therefore, in this study, the definition of chemical recycling provided in Section 3.1 is used to make judgements about chemical recycling.

7.1 Chemical recycling under waste management regulation

Management of waste is covered by the Waste Framework Directive (WFD) and related regulations that implement international agreements (e.g., Stockholm Convention, Basel Convention, etc.). Waste management regulation covers obligations of recyclers in the classification of waste as hazardous or non-hazardous, conditions for transboundary movement of waste and prevention of accidents and criteria when waste ceases to be waste (see the summary of relevant legislation in Table 7-1).

Table 7-1: The EU legislation relevant for the classification of waste

Legislation	Provisions
Waste Framework Directive 2008/98/EC	• Provides the definitions of waste (Article 3(1)), hazardous waste (Article 3(2)), recovery (Article 3(15), and recycling (Article 3(17)). • Outlines conditions for managing hazardous waste (Articles 17, 18 and 19). • Sets out the basis for the List of Waste and its application for waste classification (Article 7).

European List of Waste (Commission Decisions: 2000/532/EC, 2014/955/EU)	• Sets out further provisions for classification of waste and provides a detailed list of waste sub-divided into chapters, sub-chapters and entries.
	• Categorises waste into:
	  ○ absolute hazardous entries – cannot be allocated to non-hazardous entries and are hazardous without any further assessment;
	  ○ absolute non-hazardous entries – cannot be allocated to hazardous entries and are non-hazardous without any further assessment;

Table 7-1: The EU legislation relevant for the classification of waste	
Legislation	**Provisions**
	○ mirror entries – can be allocated to non-hazardous and hazardous entries depending on a specific case and the composition of waste.
Waste Shipment Regulation (EC) (No. 1013/2006)	• Sets out the procedure of prior written notification and consent for shipment of any waste (Article 4). • Provides general information requirements that apply to shipments for the recovery of waste listed in Annex III, so-called 'green list of waste' (Article 18).
POP Regulation (EC) (No. 850/2004)	Specifies that POPs listed in Annex IV that are present in waste above 'low POP-content limit value' must be disposed of or recovered without any undue delay and in accordance with POP Regulation, to ensure that POP content is irreversibly destroyed so that remaining waste and emissions do not exhibit POP characteristics (Article 7)*.
Seveso III Directive (2012/18/EU)	• Aims to prevent major accidents that involve dangerous substances and limit their consequence for human health and the environment. The Directive also applies to waste. • Obliges the operator who handles dangerous substances to take necessary measures to prevent and limit the consequence of major accidents. Measures include the provision of information to the public likely affected by an accident, provision of safety reports, establishing a safety management system and internal emergency plan.
Source: European Commission, 2018 *NOTE: *Waste containing POPs in amounts exceeding low POP-content limit values is not automatically considered hazardous. Classification must follow the general rules set out by WFD.*	

Table 7-1 provides a general overview of legal acts with a brief explanation of their role in the management of waste. Further in the text, the focus is on issues related to the implementation of legislation highlighted in the literature.

Main principles for the classification of waste are prescribed by WFD (Alaranta & Turunen, 2021). Under WDF, hazardous waste is a subject of certain additional obligations on monitoring and tracking, packaging and labelling and treatment to protect human health and the environment. Hazardous waste cannot be mixed with other types of waste. Classifying waste as hazardous is based on the properties listed in Annex III of the WFD. Further guidance for waste classification is given in the List of Waste (Commission Decision 2014/955/EU) that provides an extensive list of waste categorised according to its hazards (European Commission, 2018). With some deviations, Classification, Labelling and Packaging (CLP) Regulation principles are applied in the European List of Waste (Friege et al., 2019). Differently from CLP Regulation, where a substance is a subject of classification, in waste management, waste as a whole is a subject of classification. It means that waste that contains hazardous substances is not necessarily classified as hazardous (Bernard & Buonsante, 2017).

The classification of waste is complicated. Apart from post-industrial waste, where the composition is known, other – post-consumer streams of plastic waste are mixed and contaminated. The composition of mixed and contaminated post-consumer plastic waste is not stable and varies from batch to batch. With the presence of so-called 'mirror entries' in the List of Waste, the same category of waste could be classified as hazardous or non-hazardous based on the presence of certain hazardous substances (Alaranta & Turunen, 2021; Friege et al., 2019). **The complexity of plastic waste streams may result in the misclassification of waste**. The misclassification issues were highlighted by the European Commission (2018b): if hazardous waste is misclassified as non-hazardous, it will lead to contamination of recycled products with hazardous substances, while if non-hazardous waste is misclassified as hazardous, it will affect waste management costs and economic viability of recycling.

Furthermore, the **situation is complicated by the presence of different hazard classification principles in various regulations**. For instance, the EU Waste Shipment Regulation implements the Basel Convention on the transboundary movements of hazardous waste and its disposal. This regulation provides principles for classifying waste as hazardous (European Parliament, 2006; Friege et al., 2019) that differ from those listed in WFD. The difference in classification approaches results in different interpretations of what waste should be classified as hazardous. For instance, according to Friege et al. (2019), spent car catalysts are classified on the so-called 'Green list' (no notification is required for shipment) under Waste Shipment Regulation, but it is hazardous in the List of Waste.

Additionally, **waste classification methodologies are applied differently in the EU Member States**, which leads to substantial uncertainty among recycling operators on the legitimacy of their waste movement practices across the borders. Alaranta and Turunen (2021) provided a useful example of waste transportation between two European Union Member States that resulted in the refusal of entry. In their research on the recyclers opinion on managing waste containing SoCs, Janssen and van Broekhuizen (2017) discussed the uncertainties about waste transport across the borders resulting from various interpretations as well. Finally, similar concerns were emphasised by the European Commission (2018).

In practice, waste classification as (non)hazardous consists of collecting the relevant information about the properties of waste as prescribed by the List of Waste. Completion of this task requires knowledge of the presence and content of hazardous substances in waste. The relevant information could be collected by several methods: from the existing information sources on the manufacturing process of substances that contribute to waste, on the substances or articles and their composition (e.g., safety data sheets), databases on waste analysis, and sampling and chemical analysis of waste (European Commission, 2018). The collection of such information is crucial for the **classification of waste and clarifying the prospects for recycling**.

Identification of hazardous substances in waste streams could be complicated due to the following reasons:

- Plastic waste streams could be incidentally contaminated with various substances during their active use. Usually, there are no sources for clarifying this type of information.
- According to the REACH Regulation, EU producers and suppliers of goods are obliged to inform customers about the presence of SVHCs in the articles in the concentration of more than 0.1% w/w; however, this information does not reach waste managers. The SCIP database of SVHCs maintained by ECHA aims to contribute to closing this information gap.
- Information on substances of very high concern in certain articles may no longer be available for products that become waste after a long period of use (e.g., construction waste).
- Incomplete or missing information on the substances of concern in goods imported to the EU from other countries. The EU importers of such goods are obliged to provide information about SVHCs in the products; however, restrictions for certain substances provided in REACH do not apply to the suppliers of goods from non-EU countries. For instance, in a pilot project carried out in collaboration with the customs of the fifteen EU Member States, the ECHA inspected a selection of 682 imported articles and found that 89% and 56% of the inspected goods contained SVHCs above 0,1% w/w and were non-compliant with the REACH Articles 33(1) and 33(2) respectively. It means that in those cases, the EU importers did not fulfil their duty to communicate information on substances in articles to the users of substances down the supply chain. In many cases, the supplier of goods from the non-EU country did not inform the EU importer about the presence of SVHCs (ECHA, 2019).
- The lists of various SoCs in different regulations (e.g., SVHCs, POPs, substances that are banned or restricted by inclusion to REACH Annex XVII) are constantly updated with new substances. These substances have been used in many products that were legitimately produced and disseminated on the market before such change in the status of the substances

(Alaranta & Turunen, 2021; de Römph & Van Calster, 2018; Friege et al., 2019; European Commission, 2018b). So, information on the products that circulated legitimately on the market in the past may be missing as well.

Procedures and standards that define conditions and test methods for a **transition of waste to the secondary product stage** (i.e., end-of-waste) are crucial for introducing the recyclates on the market. The CEN and CENELEC Working Group on Sustainable Chemicals (BTWG 11) reviewed the current standardisation activities and initiatives in the field of plastics. BTWG 11 concluded that current standards on plastic waste do not provide specific guidance on the quality of recycled waste material and contaminants. However, **specific end-of-waste criteria and guidance on their implementation are crucial for the confidence in the quality and safety of recyclates and their uptake on the market** (CEN-CLC BTWG 11, 2018). Currently, the WFD specifies the conditions when waste ceases to be waste in Article 6 where it outlines four general end-of-waste criteria:

a) the use of a substance/object for a specific purpose;

b) the existence of market demand for a substance/object;

c) compliance of a substance/object with relevant legislation, technical requirements or standards applicable for the products;

d) absence of adverse impact on human health and the environment due to the use of a substance/object (European Parliament, 2008).

The WFD delegates the task of determining the end-of-waste status to the EU Member States while mentioning that the EU wide end of waste criteria could be developed where relevant (European Commission, 2018b). The European Commission (2018b) noted that currently, it is not clear what measures are taken in the Member States to ensure that the recycled materials meet the end-of-waste criteria and whether they are sufficient and effective. **Different regulatory end-of-waste regimes across the EU may lead to difficulties in introducing the recycled materials on the EU market and safety concerns** due to various interpretations of the end-of-waste in the Member States (Alaranta & Turunen, 2021).

7.2 Chemical recycling and REACH

Research and grey literature analyse the following aspects of chemicals legislation as relevant for recycling:

a) registration of substances under REACH;

b) classification of substances according to the CLP Regulation and links to REACH;

c) notification on SVHCs, authorisation and restriction of substances under REACH (de Römph & Van Calster, 2018; Friege et al., 2019; Bernard & Buonsante, 2017; Alaranta & Turunen, 2021); and

d) exemptions for scientific and innovation activities (de Römph & Van Calster, 2018).

However, specific issues relevant to chemical recycling, such as registration and classification of intermediate substances, UVCBs, i.e., substances of unknown or variable composition, complex reaction products or biological materials, are not covered. In the following sections, the four aspects outlined above are discussed based on the review of ECHA guidance materials. However, the latter does not include an assessment of potential complexities that could be encountered by chemical recyclers. These gaps in the literature were sought to be filled through stakeholder consultation. An online survey focusing on the regulatory challenges with chemical legislation faced by chemical recycling facility operators was carried out in July 2021 to complement the information gathered through expert interviews. The results of the survey are presented in Annex 5.

7.2.1 Substance features and REACH registration

A recycler who recovered chemical substances by means of a selected chemical recycling technology becomes a manufacturer of substances and a REACH duty-holder (de Römph & Van Calster, 2018). According to REACH, **manufacturers of substances should register their substances** on their own or in a mixture (Article 3(1)) if they are manufactured in quantities larger than one tonne per year (Article 3(2)).

Requirements for registration documentations are laid down in the REACH Annexes VI – XI. For the purposes of registration, the registrant should collect all freely available information about the properties of substance for registration purposes. Information requirements to registration dossiers differ depending on the quantities manufactured per year and intrinsic substance properties.

All **registration dossiers** must contain the following information: general information on the registrant, identification of the substance, information on the manufacture and use(s) of the substance, classification and labelling of the substance, guidance on safe use, exposure information for substances registered in quantities of 1 to 10 tonnes. If the substance is manufactured in amounts over 10 tonnes per year, additional information should be provided as well as a chemical safety report. The latter includes an assessment of the hazards and risks to human health and the environment as well as appropriate risk management measures to control them. This report is submitted as a part of the registration dossier. Furthermore, the manufacturer of a substance should communicate information provided in a chemical safety report to other users of a substance down the supply chain through extended safety data sheets (ECHA, 2017).

Some chemical recycling technologies produce substances that need additional processing to be used. For instance, this is the case of pyrolysis oil or waxes produced in pyrolysis that are usually upgraded in refineries (see section 5.1 for discussion of chemical recycling technologies and their products). They meet the criteria of **intermediate** substances under REACH. According to REACH Article 3(15), intermediate is a "substance that is manufactured for and consumed in or used for chemical processing in order to be transformed into another substance" (ECHA, 2017). For instance, in the REACH Registered substances portal, pyrolysis oil from waste rubbers and tires (EC / List no.: 948-949-8) is registered as an intermediate used at industrial sites and in manufacturing only (see Figure 7-2).

Figure 7-2: A snapshot of substance info card for 'pyrolysis oil from waste rubbers and tires'
Source: ECHA Registered substance portal, https://echa.europa.eu/substance-information/-/substanceinfo/100.266.554, accessed 28/05/2021 - NOTE: This snapshot is presented to illustrate the text and does not contain full information about the substance

However, it should be noted that following the judgement of the Court of Justice of the European Union C-650/15P on acrylamide (2017), open discussions about the definition of intermediate are still in place.[5]

The lifecycle of an intermediate starts with its manufacture and ends with its use for the synthesis of another substance. Intermediates are sub-divided into:

- Non-isolated intermediates that are not intentionally removed from the synthesis equipment (except for sampling) (Article 3(15)(a)).
- On-site isolated intermediates that do not meet the definition criteria for non-isolated intermediates (Article 3(15)(b)) and are manufactured and used for the synthesis of (an)other substance(s) at the same site, i.e., a single location equipped with appropriate infrastructure.
- Transported isolated intermediates that do not meet the definition criteria for non-isolated intermediates and are transported or supplied between sites (Article 3(15)(c)) (ECHA, 2010).

For the use of a substance as a **non-isolated intermediate,** there are no obligations under REACH (Article 2(1)(c)). According to Article 2(8), **on-site isolated intermediates** and **transported isolated intermediates** are exempted from the general registration regime referred to in chapter 1 of Title II of REACH. A manufacturer of on-site isolated intermediates and/or transported isolated intermediates can register their substance in quantities of 1 tonne or more per year under a different regime, as specified in chapter 3 of Title II of REACH, provided that they confirm that these substances are used under strictly controlled conditions. For **monomers that are used as either on-site isolated intermediates and/or transported isolated intermediates in the production of polymers, the reduced registration provisions do not apply** (see Article 6(2)). So, the chemical recyclers who synthesise monomers and use them for producing polymers must follow the standard procedure for registering a substance under REACH (ECHA, 2010).

Despite the exemption from registration applying to non-isolated intermediates (Article 2(1)(c)), **monomers used as non-isolated intermediates** in the manufacturing of polymers are subject to registration if the conditions of Article 6(3) of REACH are met (Court of Justice of the European Union, 2009). This is because the obligation to register monomer substances, which are less numerous than polymers, makes information available not only on the risks specific to those substances but also on those of monomers found as residues after polymerisation or in monomer form after the possible degradation of the polymer.

Under REACH, **polymers** are subject to registration exemptions laid out in Article 2(9). It means that a manufacturer is not obliged to provide ECHA with any information about the intrinsic properties of a polymer, except its classification and labelling where appropriate. According to REACH Article 3(5), a polymer is "a substance consisting of molecules characterised by the sequence of one or more types of monomer units. Such molecules must be distributed over a range of molecular weights wherein differences in the molecular weight are primarily attributable to differences in the number of monomer units. A polymer comprises the following:

[5] The Court has indicated that three conditions have to be simultaneously satisfied for the use of a substance to be considered an intermediate under REACH (paragraph 33):

*"The first of those conditions concerns **the intended purpose** at the time of the manufacture and use of a substance as an intermediate, which consists **of transforming that substance into another**. The second condition concerns the technical means by which that processing takes place, namely **a chemical process known as 'synthesis'**. The third condition restricts the scope of the definition of 'intermediate' to uses of **a substance which remains confined to a controlled environment**, which may be either the equipment within which synthesis takes place, or the site in which the manufacturing and synthesis takes place or to which that substance is transported, 'site' being defined in Article 3(16) of the REACH Regulation as a 'single location' in which infrastructure and facilities are installed"* (The Court of Justice of the European Union, 2017).

- a simple weight majority of molecules containing at least three monomer units which are covalently bound to at least one other monomer unit or other reactant;
- less than a simple weight majority of molecules of the same molecular weight" (European Parliament, 2006a).

However, according to Article 6(3) of REACH Regulation, a **manufacturer must submit a registration** to ECHA for the monomer substance(s) or any other substance(s) that have not already been registered by an actor up the supply chain **if both the following conditions are met**:

- the polymer consists of 2% weight by weight (w/w) or more of such monomer substance(s) or other substance(s) in the form of monomeric units and chemically bound substance(s);
- the total quantity of such monomer substance(s) or other substance(s) makes up 1 tonne or more per year (the total quantity in this context is the total quantity of monomer or other substance ending up chemically bound to the polymer) (ECHA, 2017).

It is important to note that the study commissioned by the European Commission to provide 'scientific and technical support for the development of criteria to identify and group polymers for Registration/Evaluation under REACH and their impact assessment' has recently been published. It suggested criteria for the identification of polymers requiring registration under REACH, laid out possible registration requirements and assessed the costs and benefits of registering polymers requiring registration. The report also proposed how to adapt the REACH registration information requirements to be more suitable for polymers (Bougas et al., 2020).

REACH also offers **an exemption from registration for substances on their own, in mixtures or in articles** that have been already registered and are recovered (Article 2(7)). The exemption is applied if the recovered substance is the same as the registered one and if the recycling operator has access to information required by REACH Articles 31 or 32. To enjoy the benefits of this exemption, the recyclers should be aware of the previous registration of the substance and provide analytical information justifying the sameness of the previously registered and recovered substance (ECHA, 2017a). It is important to note that some substances, such as pyrolysis oil mentioned above (see Figure 7-2), are not manufactured otherwise than from waste. For some chemical recycling technologies, e.g., chemolysis, this exemption could be relevant because it deals with a plastic waste of known composition (Lee & Liew, 2021). However, for other technologies that produce UVCBs benefitting from this exemption would require more efforts to justify the sameness of the UVCBs with the previously registered and recovered substances. Additionally, access to information required in Articles 31 and 32 in practice is difficult. Usually, the recyclers do not receive such information with incoming waste. Moreover, when such information is compiled by the manufacturer of the substance, it may be subject to intellectual property rights (Alaranta & Turunen, 2021; de Römph & Val Calster, 2018).

Under REACH, the **composition of a substance** plays an important role in the registration process. Substances can be defined by chemical and physical parameters. Chemical composition aspects are especially important in the context of the chemical recycling of plastic waste; therefore, the discussion is further focused on the chemical composition of substances. According to the chemical composition, several types of substances are divided into well-defined substances and UVCB substances. **Well defined substances** are those for which qualitative and quantitative aspects of the composition could be sufficiently identified by using identification parameters set out in REACH Annex VI Section 2. In turn, based on constituents, well-defined substances can be mono constituent with one main constituent present in concentration over 80% w/w and multi constituent with more than one constituents present in concentration less than 80% w/w. **UVCB** stands for Substances of Unknown or Variable composition, Complex reaction products or Biological materials. These substances cannot be identified by using the above-mentioned identification parameters. See Figure 7-3.

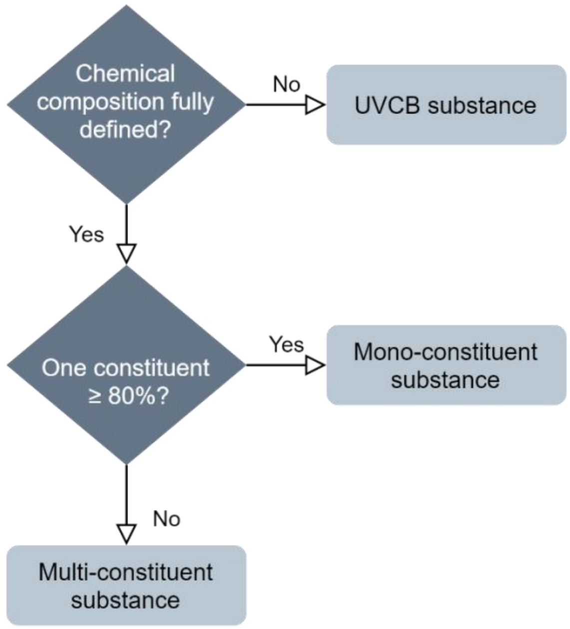

Figure 7-3: Substances according to their chemical composition, adapted from ECHA, 2017a

In well-defined substances, unintentional constituents in concentration less than 20% w/w for mono-constituent substances and equal or less than 10% for multi-constituent substances are considered impurities. Intentionally added substances to stabilise a substance are called **additives** and treated as a part of the same substance. Only the minimum amount of additive necessary to preserve the stability of the substance is considered as part of the substance composition. Other intentionally added substances (e.g., additives that are common in plastic products and considered in previous chapters of this study – flame retardants, plasticisers, colourants etc.) are not treated as a part of the same substance (de Römph & Van Calster, 2018). Such a blend of substances is regarded as a mixture or an article, depending on the case (ECHA, 2017a; ECHA, 2012). Importantly, mixture refers to a physical blend of two or more substances without a chemical reaction. As the mixture is not considered a substance, each individual substance must be separately registered (ECHA, n.d.c; ECHA, 2016).

In the case of **UVCB substances**, identification of chemical composition is complicated because of the large number of constituents, the composition being unknown to a significant part, high variability and poor predictability of the composition. UVCB substances could be a relevant outcome of the application of some chemical recycling technologies, e.g., pyrolysis or gasification. For instance, pyrolysis oil (e.g., pyrolysis oil from waste rubbers and tires, provided as an example in Figure 7-1) and waxes obtained in pyrolysis are UVCBs. Sources of UVCBs and processes used to make them are the main identifiers for UVCBs. They are important for the justification of the UVCB sameness. Change in the sources and processes may lead to a different substance that may require a new registration. However, as long as the composition of a UVCB stays within a pre-defined range, new registration is not required (ECHA, 2017a).

The registrant should provide spectral and analytical information proving qualitatively and quantitatively the composition, concentration and range of constituents in mono- and multi-constituent substances as well as UVCBs by using relevant spectroscopic and analytical methods. If certain information could not be given, a sound justification should be provided (ECHA, 2017a; ECHA, 2016).

7.2.2 Recovered substances, SoC and exemptions to stimulate innovation

The REACH and POPs Regulations provide several mechanisms for gradual phasing out of substances of concern and substituting them with non-hazardous substances. The relevant provisions include:

- Candidate List of Substances of Very High Concern, maintained by the ECHA.
- List of Substances Subject to Authorisation, Annex XIV of REACH.
- REACH Annex XVII Restrictions on the Manufacture, Placing on the Market and Use of Certain Dangerous Substances, Mixtures and Articles.
- POP Regulation Annex I that lists substances for which manufacturing, placing on the market and use on their own, in mixtures or in articles, are prohibited in accordance with Article 4.

If SVHCs are listed in the Candidate List of Substances of Very High Concern and are present in concentrations above 0.1% weight by weight in articles that are produced or imported in the EU in quantities over 1 t/y, the producer/importer of the articles should notify ECHA about the presence of SVHCs. In accordance with Article 33 of the REACH Regulation, any supplier of an article where SVHCs are present in concentrations above 0.1% w/w should communicate information on SVHCs to the recipients and consumers of an article to ensure safe use of these goods (European Parliament, 2006a). From 5 January 2021, all suppliers of articles containing SVHCs from the Candidate List in a concentration above 0.1% weight by weight should submit information about SVHCs to the **SCIP** (Substances of Concern In articles as such or in complex objects (Products)) database. The SCIP database containing information on the SVHCs in articles supplied on the EU market has been established and maintained by the ECHA (European Parliament, 2018).

The inclusion of substances on the Candidate List of SVHCs is an initial step to their authorisation and gradual elimination from the EU market (ECHA, n. d.a). The substances under Annex XIV should be progressively eliminated from the market and substituted with safe counterparts, however, without causing undesired disruptions to the EU market. Companies may apply for authorisation to start or continue using such substances. The authorisation procedure is described in Title VII of the REACH Regulation. Certain exemptions from the authorisation requirement also apply (see the ECHA (2021) and ECHA (2015) for the lists of general exemptions for certain uses of substances and exemptions specific to certain intrinsic properties). Following the so-called "sunset dates", the use of such substances is only allowed if authorisation for the specific use has been granted by the European Commission. If adequate control of the substance used can be proven, or the socio-economic benefits of these uses outweigh the risks to human health or the environment, an authorisation can be granted. (ECHA, 2017b). While recognising the importance of the authorisation process, some researchers highlighted that the authorisation procedure and subsequent restrictions apply only to the EU companies but not to imported goods. It diminishes its efficiency and sets different conditions for the EU producers and importers of non-EU goods (Alaranta & Turunen, 2021). The problem was recognised by the European Commission (2018b) that also emphasised that imported goods become waste in the EU, thus producing waste streams containing SoCs.

Restrictions for the substances are listed in Annex XVII. According to REACH Article 67(1), substances on their own, in a mixture or in articles for which Annex XVII contains a restriction shall not be manufactured, placed or used on the market unless they comply with the restriction conditions of the relevant Annex XVII entry. REACH restrictions are complemented by POP Regulation that sets conditions for production, placing on the market and use of POP substances. The production, placing on the market, and use of POP substances listed in Annex I of POP Regulation is prohibited in accordance with Article 3 of the Regulation. However, there could be exemptions applicable to this list (Article 4). Inevitably, products containing restricted substances will reach recycling facilities. So, there is a need for recycling technologies and/or cost-effective sorting, pre- and post-treatment solutions to eliminate these substances (de Römph & Van Calster, 2018). These circumstances could influence the cost of recycling and recyclates.

It is also important to note that REACH and related legislation provide certain **exemptions to encourage innovation** and could be potentially used for experimenting with recycling technologies (de Römph & Van Calster, 2018). These are exemptions for the use of substances for **scientific research and development** (SR&D) and **product and process-oriented research and development** (PPORD). In terms of volumes and the definition, SR&D are applicable to laboratory activities, while PPORD is suitable for improvements at pilot plants.

According to Article 3(23) of REACH, SR&D involves "any scientific experimentation, analysis or chemical research carried out under controlled conditions in a volume less than one tonne per year". **Substances that are used for SR&D** are exempted from authorisation and restriction. As the volume of substances used for SR&D is less than one tonne per year, such substances are not subject to REACH registration. According to Article 1(2)(d), the CLP Regulation does not apply to substances and mixtures used in SR&D which are not placed on the market, given that they are used under controlled conditions. For any other substance or mixture within the scope of the CLP Regulation, it applies to any quantity, including those below one tonne per year (ECHA, 2017c). Similarly, the POPs Regulation sets an exemption from restrictions laid out in Article 3 for "a substance used in laboratory-scale research" (Article 4(1)(a)) (European Parliament, 2019).

PPORD covers "any scientific development related to product development or the further development of a substance, on its own, in mixtures or in articles in the course of which pilot plant or production trials are used to develop the production process and/or to test the fields of application of the substance" (Article 3(22)). Substances that are used for **product and process-oriented research and development (PPORD)** in an amount over one tonne per year can be exempted from the obligation to register for five years with the opportunity to extend this period upon request. Substances used in PPORD must not be made available to the general public on their own, in a mixture or an article. The remaining quantities of substances must be re-collected after the end of the exemption period, and controlled conditions of the activity must be ensured in accordance with the legislation on the protection of workers and the environment. To use PPORD exemption, the manufacturer must submit to ECHA information as outlined in Article 9(2) of REACH.

8 Technical Issues in Chemical Recycling

Analysis of literature in previous chapters highlighted several issues relevant to chemical recycling: a) heterogeneity of plastic waste and relative sensitivity of chemical recycling technologies to specific substances in waste (e.g., chemolysis, pyrolysis, see chapter 5); b) the presence of substances of concern in plastic waste and varying potential of different chemical recycling to eliminate them (see chapter 6). Digital technologies hold the potential to solve these issues. In recent literature, **digitalisation is seen as an enabler of the circular economy** (see Kristoffersen et al., 2020; Sarc et al., 2019). Similarly, the European Commission recognized **digitisation and digital innovation as cross-cutting actions to achieve the circular economy goals** in the New Circular Economy Action Plan (European Commission, 2020a). The plan focuses on those digital technologies that 'can track the journeys of products, components and materials and make the resulting data securely accessible'.

Heterogeneity of plastic waste and the presence of substances of concern in waste streams requires solving several technical tasks:

- gaining knowledge about the composition of waste streams;
- detection of substances of concern in waste streams;
- quantification of substances to comply with provisions of legal regulations;
- screening waste streams to eliminate products containing substances of concern.

This chapter **aims** to review the current state-of-the-art and future prospects for the application of digital technologies for solving technical issues in chemical recycling. The review focuses on existing technical solutions: databases that facilitate gaining knowledge about the composition of plastic waste and waste screening technologies for detection and quantification of various substances in plastic waste streams. Furthermore, it outlines emerging solutions, such as smart tags, digital product passports, blockchain technologies and robotic sorting applications for solving the technical issues in chemical recycling.

8.1 Databases on substances and materials

Databases can facilitate the collection of information about substances (including SoCs) in plastic waste. Access to such information is a helpful way to understand the possible composition of waste and decide about waste screening and sorting. The collection of information is an initial step in identifying the presence of SoCs in waste streams, which should be complemented by waste screening and/or chemical analysis.

There are several types of databases that contain information about substances. These are databases maintained by industries, the SCIP database maintained by the ECHA, and environmental product declaration databases.

Businesses share information prepared to comply with legal requirements on the safety of their products and materials. Several **databases maintained by industries** are available to support the collection of information about substances in plastic waste streams (see Table 8-1).

Table 8-1: Examples of databases containing information about substances in plastic waste

Database	Scope	Developer
SCIP Database	Articles containing SVHCs in a concentration above 0.1%	The European Chemical Agency

Table 8-1: Examples of databases containing information about substances in plastic waste		
I4R: Information for Recyclers Platform, https://i4r-platform.eu/	Components and materials in electric and electronic equipment, SoCs	APPLIA, DigitalEurope, WEEE Forum
International Material Data System (IMDS), https://public.mdsystem.com/en/web/imds-public-pages	Materials present in automobile parts, including SoCs	Automotive manufacturers, full list: https://public.mdsystem.com/en/web/imds-public-pages/community
Global Automotive Declarable Substance List (GADSL), https://www.gadsl.org/	Substances in automotive parts, including SoCs	Global Automotive Stakeholders Group (GASG)
Safety Data Sheets Service for Plastic Recycling, https://www.polymercomplyeurope.eu/pce-services/sds-r-tool-service	SoCs in polymers	Polymer Comply Europe
Building Material Scout, https://app.building-material-scout.com/app/en-us/search?term=	Materials used in construction products, including SoCs	Building Material Scout Ltd.
Source: Friege et al., 2021; BAMB, 2020		

Table 8-1 shows that the need to comply with various regulatory requirements encouraged various industries to build collective digital resources for materials and substances, including SoCs. Notably, all databases can be used to collect information on plastic products because plastic is widely used in construction, electrical and electronic equipment, and the automotive industry. The SCIP database should offer the broadest source of information on the presence of SoCs; however, it is the most recent data source and is still being populated.

In accordance with Article 9(2) of the WFD, the **SCIP** (Substances of Concern In articles as such or in complex objects (Products)) database containing information on the SVHCs in articles supplied on the EU market has been established and maintained by the ECHA. From 5 January 2021, all suppliers of articles containing SVHCs from the Candidate List in a concentration above 0.1% weight by weight should submit information about SVHCs to the database. The early assessment of the SCIP database in the research literature by Friege et al. (2021) focuses on understanding its benefits to recyclers. The researchers evaluated SCIP based on case studies of products that undergo recycling (e.g., PVC floor coverings, plastics from waste electric and electronic equipment, waste footwear, etc.). It was concluded that a substantial information gap relates to so-called 'legacy' SVHCs that are no longer used on the market but are abundantly present in the discarded products. Additionally, more detailed information on the identity of the product (e.g., producer, production year, etc.) is necessary to recyclers but is missing in SCIP (Friege et al., 2021).

Digital information about substances could also be obtained from **Environmental Product Declarations** (EPDs). An EPD describes the environmental performance of a product and provides quantitative and qualitative environmental information about it following the guidance of *ISO 14025:2006 Environmental labels and declarations – Type III environmental declarations – Principles and Procedures* (International Organization for Standardization, 2006b). Lifecycle assessment (LCA) is a basis for completing EPDs. Such declaration also includes content declarations where materials and substances contained in a product are specified. This information also covers substances that have an adverse impact on human health and the environment (Minkov et al., 2015). Environmental declarations are verified by independent experts and published online on dedicated platforms, for instance, the International EPD system (https://www.environdec.com/home), ECO-Platform (https://www.eco-platform.org/home.html, for construction EPD).

8.2 Technologies for detecting substances of concern

Various **technologies** are used **for screening waste** streams and identifying substances of concern. In scholarly literature, the accuracy of various sorting technologies in identifying different substances in plastic waste has been analysed. Occasional case study publications have been focused on the identification of bromine and brominated flame retardants (Hennebert & Filella, 2018; Sharkey et al., 2018) or other plastic additives (Wu et al., 2020) in waste electrical and electronic equipment. For instance, Hennebert and Filella (2018) studied bromine and brominated flame retardants in electrical and electronic equipment and waste samples identified by handheld X-Ray Fluorescence from different periods. The researchers determined the highest bromine and brominated flame retardants concentrations in "old" waste, while the lowest – in recent products and discussed detection and sampling methods to comply with the international and EU regulation. Sharkey et al. (2018) evaluated the efficacy of the X-Ray Fluorescence tool for the detection of brominated flame retardants in waste electrical and electronic equipment from eight waste and recycling sites in Ireland by comparing results to mass spectrometry measurements. The researchers concluded that X-Ray Fluorescence tools could be used to comply with POP Regulation requirements; however, due to some inconsistencies in detecting precise concentrations of brominated flame retardants, other complementary measures may be required. Wu et al. (2020) examined the application of Near-Infrared Spectroscopy for sorting waste electrical and electronic equipment based on waste samples. Classification methods for effective sorting were the focus of this study. Wu et al. (2020) concluded that despite good accuracy, Infrared Spectroscopy has several limitations. It cannot detect black plastics that are common in electrical and electronic equipment. To decrease chances for waste misclassification sufficient volume of training samples from diverse sources should be used in the system's software. Despite examples of testing sorting technologies, there are no synthesis studies focused on the efficiency and accuracy of different technologies for sorting plastic waste that would provide a comparative analysis and critically evaluate the results of experimental evaluations.

So far, the most extensive overview of sorting technologies, including a brief discussion of their advantages and shortcomings, was provided by Norin et al. (2020). However, it should be noted that Norin et al. (2020) based their review on grey literature analysis and the results of an expert consultation. Data from Norin et al. (2020) was used for summarising the available sorting technologies. This information was complemented by information provided by Stenmarck et al. (2017) and Wagner & Schlummer (2020). The overview of screening technologies is provided in Table 8-2.

Table 8-22: Overview of waste screening technologies

Detected SoCs	Advantages	Disadvantages	Cost
Energy-dispersive X-Ray fluorescence			
Heavy metals, bromine, chlorine	Detects bromine and chlorine < 1%; Uses in-built software to compare identified values with allowed limits in regulation (e.g., RoHs); Used for indirect identification of different plastic materials (e.g., PVC); Relatively cost-effective technology for small volumes of waste.	Difficulties in detecting very low concentrations; Cannot distinguish between various brominated flame retardants; Dirt and coatings affect detection accuracy.	
Wavelength-dispersive fluorescence			
Heavy metals, bromine, chlorine and fluorine	Detects bromine and chlorine <1%; Uses in-built software to compare identified values with allowed limits in regulation (e.g., RoHs); Used for indirect identification of different plastic materials (e.g., PVC);	Difficulties in detecting very low concentrations; Cannot distinguish between various brominated flame retardants; Expensive technology;	

Table 8-22: Overview of waste screening technologies			
Detected SoCs	**Advantages**	**Disadvantages**	**Cost**
	Has high resolution and low detection limits for lighter elements.	Dirt and coatings affect detection accuracy.	
X-Ray transmission			
Heavy metals and brominated flame retardants	Can be used for the qualitative detection of brominated flame retardants; Can be used to detect and sort plastic materials like PP, PE and PET and HDPE; Detection accuracy is < 1%.	Difficulties in detecting very low concentrations (lower than 0.5%); Emits radiation and requires special training for use; Limited information on accuracy; High costs of equipment.	
Near-infrared spectroscopy			
Brominated flame retardants and PVC	Cost-efficient technology; Can quickly carry out detection procedures.	Possibly limited accuracy in detecting of SoCs in low concentrations; Unable to detect mixtures; Cannot detect black plastics; Possibly unable to detect substances beneath material's surface.	
Fourier transform infrared spectroscopy			
Brominated flame retardants, phthalates	Fast and easy method for qualitative detection.	Cannot detect SoCs in low concentrations; Unable to detect mixtures; Cannot detect black plastics; Possibly unable to detect substances beneath material's surface.	
Sliding spark spectroscopy			
Brominated flame retardants, fillers and stabilisers, chlorinated flame retardants, perfluorinated substances	Accurately quantifies bromine and chlorine concentrations down to approximately 1%; Can be used to detect chlorine-containing plastics (e.g., PVC); Detects low concentrations of organofluorine (such as PFOS) down to approximately 0.1% Inexpensive technology.	Decrease in accuracy in measuring low concentrations of substances (0-1%); Measured material should be clean and have a flat area for good contact; Provides information only about the surface of measured material.	
Laser-induced breakdown spectroscopy			
Potential to detect all SoCs	Very low detection limits up to 0.0001% in some versions of LIBS equipment; Low energy consumption.	Sensitive to moisture and contamination of material surface; Expensive technology; Long data acquisition.	
Raman spectroscopy			
Detection of brominated flame retardants, phthalates	Potential future technology for detecting SoCs in recycling.	Complicated in use than other spectroscopic techniques; Costly technology.	
Sources: Norin et al., 2020; Stenmarck et al., 2017; Wagner & Schlummer, 2020			

Table 8-2 shows a wide selection of different screening technologies that have been already available to recyclers or will be available in the near future. Screening technologies enable detecting heavy metals, flame retardants, phthalates, and other substances relevant to chemical recyclers (e.g., PVC).

However, the available technologies experience difficulties in detecting substances of concern in sufficiently low concentrations to comply with legal requirements of allowed concentrations of SoCs. Due to insufficient sensitivity of available screening technologies, some waste streams potentially complying with legislative requirements could not be directed to appropriate recycling facilities (Wagner & Schlummer, 2020). Technologies that can detect low concentrations of SoCs, such as laser-induced breakdown spectroscopy, are expensive. Many technologies are available for the detection of brominated flame retardants, heavy metals, while much less for identifying other SoCs. Furthermore, the accuracy of the measurement depends on various external factors, such as moisture, dirt, absence of flat area on waste objects, etc. (Norin et al., 2020; Stenmarck et al., 2017).

8.3 Trends in digitalisation of recycling

Recent extensive literature reviews on digitalisation and the circular economy and digital developments in the waste management sector suggest several technological solutions to identify waste composition and ensure effective treatment and quality of recyclates. These are tracking the entire life cycle of products from manufacture to recycling and applying advanced waste screening and sorting technologies in recycling facilities (Kristoffersen et al., 2020; Sarc et al., 2019; Berg et al., 2020). The solutions and supporting technologies are outlined in Figure 8-1.

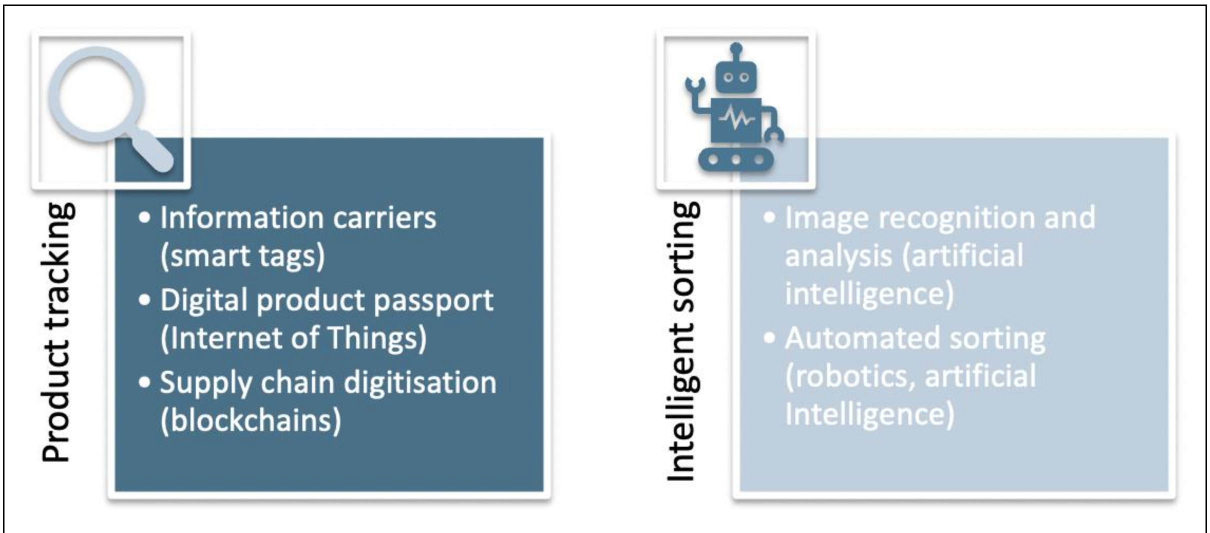

Figure 8-1: Overview of digital solutions for recycling - *Sources: Kristoffersen et al., 2020; Sarc et al., 2019; Berg et al., 2020*

As shown in Figure 8-1, differently from databases that allow simple search for information about substances, the proposed tools **link substances and other information to a physical product and monitor its entire lifecycle**. This can be done by employing Internet of Things technologies, when information carriers (e.g., tags or tracers) are embedded in or attached to physical products to allow exchanging data between physical objects and other devices or systems on the Internet (e.g., digital product passports) (Gligoric et al., 2019). Furthermore, information carriers can exchange data with sophisticated information systems that monitor transactions between different players during a product's lifecycle (e.g., manufacturing, supplying, selling the product, collecting end-of-life products at waste management facilities). For building such systems, blockchain technologies could be used (Taylor et al., 2020).

Information carriers allow following the products at various stages of their lifecycle. They include tags that are physically attached to an object or tracers integrated into a material matrix and contain information about its identity and properties. They provide various information about SoCs, ranging from information on their presence (present or not), identifying from one to several SoCs, linking to databases with detailed information of the product, including SoCs (Ökopol et al., 2020). Information carriers range from simple printed labels to sophisticated solutions. Some promising information carriers have not been applied for recycling purposes yet, although they are widespread in other sectors. These are RFID (Radio Frequency Identification) and QR (Quick Response) codes that could keep any type of information on SoCs. Both technologies have been applied in retailing, education, transportation sectors. However, their application in the recycling sector is estimated in 5-10 years (Norin et al., 2020). The main challenges in the application of information carriers include their wear and tear and detachment from products during their lifecycle, the loss of the link of information to the object (e.g., if an object is dismantled, but the carrier information refers to the whole, but not specific parts of an object), the loss of meaning of information in case of changed conditions (e.g., if an object is mixed with other objects in a stream of waste that results in its contamination with other substances) (Ökopol et al., 2020).

Information carriers can be used to link physical objects to their **digital product passport**. This is a database providing structured information about a product, data related to different lifecycle stages and materials the product is composed of. Sometimes other terms, such as 'digital material passport' or 'circularity passport', are used when speaking of the same or similar digital information systems. Usually, product/material passports provide information about the physical, chemical properties of a material, as well as its safety information. Some systems include information about substances of concern as well. Product and material passports are jointly developed by different players, contributing to the product – manufacturers of substances, producers and/or suppliers of various product components. Digital product passports could be integrated into other digital information systems. For instance, in the construction sector, digital material passports could be part of building information systems. Various digital tools and solutions could be used for developing such databases. They include product tags or tracers, blockchain technologies and artificial intelligence tools. The construction industry is one of the most active sectors in developing digital material/product passports. However, most attention has been drawn to physical properties, different events in the product lifecycles and less to substances of concern. Recent initiatives, such as the BAMB (Buildings as Material Banks) project, considered the inclusion of substances of concern into digital product passports (Hoosain et al., 2021; Rašković et al., 2020).

Tracking of materials should be supported by databases where records about important product transactions are kept. Therefore, information carriers are often used in combination with databases. **Blockchain** is an instance of distributed ledger technology (DLT) – a decentralised database of ledgers, records of digital events or transactions shared by the network of users without centralised management (with different degree of decentralisation in different DLT). ISO 22739 Blockchain and distributed ledger technologies – Vocabulary defines blockchains as "distributed ledger with confirmed blocks organized in an append-only, sequential chain using cryptographic links" (International Organization for Standardization, 2020).

In blockchains, a transaction is created autonomously by each user without any approval or involvement of a third party. The transaction is copied to multiple nodes of the system and stored there for security and verifiability. Storing data in independent blocks allows better verification, where automatic comparison of a data unit with copies kept in various nodes makes data less prone to falsification and minimises the need for human involvement (Saberi et al., 2019; Wuppertal Institute et al., 2019). Blockchains have been applied for different purposes in waste management. For instance, the blockchain platform of the social enterprise *The Plastic Bank* uses virtual currency to encourage recyclers in poor communities to contribute to reducing the stream of plastic waste. The French National Railway Company, SNCF, used blockchain for monitoring the amount, type and frequency of waste collected in waste bins of railway stations to optimise waste management (Taylor et al., 2020; Wuppertal Institute et al., 2019). When used together with the unique identifiers of plastic products (i.e., digital tags that could be screened and link to the database with information that identifies a product), blockchains allow tracking the whole lifecycle of a good and screen waste to get information on its composition. So, blockchains have the potential for digitising entire supply chains of certain goods with benefits for the recyclers and waste management. *RecycleGO* (https://recyclego.com/) and *Circularise* (https://www.circularise.com/) are examples of blockchain platforms used for the purposes of recycling and tracking products through the entire supply chain. The main advantages of applying blockchains in recycling are summarised in Table 8-3.

Table 8-3: Advantages and disadvantages of blockchains in recycling

Advantages	Disadvantages
Used with unique identifiers, blockchain is a powerful tool in tracking different life stages of products to waste	Losses of information due to wear and tear of information carriers, the infeasibility of tracking individual waste components
Trustworthy transactions reducing the risk of manipulation of data and cheating	Barriers in collaboration and coordination originating from challenges in reconciling different information sharing, privacy practices, information management cultures
Centralised management is not necessary (although it could be the case in some applications)	Lack of involvement of different actors due to costs, lack of skills and organisational policies
Allows collaborative creation of data by multiple users	Unclear roles and responsibility for waste of different actors
Sources: Saberi et al., 2019; Taylor et al., 2020	

As shown in Table 8-3, blockchain advantages can also become a source of disadvantages. First of all, digital identifiers may wear out and break during the use of products or collecting waste. So, the identifying information would be lost. To make blockchains functional for waste management, there should be a community of committed contributors to the system. Organisations sharing information in the blockchain should invest in software, information management practices and solve privacy and information sharing issues. These solutions should be coordinated among the users of blockchain. Manufacturers, suppliers and other players may become less involved due to costs associated with a blockchain, lack of organisational policies and skills. Roles and responsibilities for waste are not always shaped by transactions due to specific legislation. For instance, extended producer responsibility obliges producers to take care of the waste collection, although the product owner is a consumer. It can generate uncertainty in using the system. So, a necessary adaptation of the system should take place (Saberi et al., 2019; Taylor et al., 2020). In general, blockchain is a technology solution, but to make it work, a lot of collaboration and coordination of efforts is necessary. It is clearly shown in the example of *reciChain* – a pilot project for the application of blockchains for recycling (see Box 8-1).

Box 8-1: reciChain project by BASF - *Source: BASF, 2021*

In 2019 BASF launched *reciChain* project in Brasil to fight waste certificate fraud. Based on the first results, in 2020, it expanded the project to Canada, where together with two other partners Deloitte and Security Matters, they worked on developing blockchain solutions.

The project aims at contributing to a circular economy in the management of plastic packaging. *reciChain* will provide a solution for tracking plastics from manufacturing to recycling stages, enhancing sorting and creating trusted data about the supply and demand of plastics. Overall, the project seeks to encourage producers' social responsibility and commitment to sustainability and to demonstrate the circularity of plastics.

Implementation of the project is organised into five phases. Phase I and II have been completed, while the rest are ongoing.

In the first two phases of the project, BASF involved two partners – Deloitte and Security Matters. Together the partners developed a consortium of eight stakeholders, implemented the pilot design of the digital plastic ecosystem and run two products through the whole life cycle chain. Solutions for tracking the physical movement of plastic products within the entire supply chain were developed by using tracers. The traceability of plastic products in the blockchain was enabled by digital handshakes and data records.

The ongoing Phase III (January 2021 – January 2022) is dedicated to exploring the economics and regulation of the digital ecosystem as well as requirements to support its continuous functioning. At this phase, stakeholders in the plastics supply chain will be sought for expanding the blockchain project.

Phase IV (January 2021 – January 2023) goes in parallel with Phase III and aims at industrial scaling of the system in the plastic packaging industry, involving different players, such as brand owners, extruders and processors. The auditability and key metrics of the platform will be explored.

The final Phase V is planned for 2023 and beyond and will be focused on commercial scaling – expansion of the initiative's geography and inclusion of different types of plastics.

Solutions enabling **intelligent sorting of waste** at recycling facilities have been explored in two main directions (see Figure 8-1): image recognition and analysis and robotic sorting. Sarc et al. (2019) report about research that aims to apply artificial intelligence to recognise waste objects based on visual information and classify them according to type and composition. Research on image recognition and analysis by applying artificial intelligence is evolving. It aims to enhance the quality of waste classification accuracy by "training" artificial intelligence tools to recognise waste objects using image databases and classify them by various criteria (e.g., material). Different levels of classification accuracy were reported by different studies, ranging from 22% in earlier experiments to 95% in more recent research (Zhang et al., 2021).

Robotics is another rapidly developing field where robots powered by artificial intelligence can detect certain waste objects, dismantle them and eliminate "undesirable" objects from the processed waste stream (Alvarez-de-los-Moros & Renteria, 2017). Sarc et al. (2019) provided abundant examples of robotics applications for various waste streams. Several of them are equipped with artificial intelligence and are used for sorting plastic waste. For instance, Max-AI Autonomous Quality Control (MAX-AI AQC), produced by the U.S. company BHS is applied for PET waste sorting. It uses optical data to recognise recyclable objects and separate up to six fractions of waste. SamurAI is a robot developed by the Canadian company Machinex that is extensively used for sorting plastic waste. The customers can use the database by the manufacturer and compile their own databases of plant-specific waste materials to enhance their recognition and classification (Sarc et al., 2019).

8.4 Digital data about products/substances in the construction sector: a case study

The **aim** of this case study is to illustrate the developments and challenges in managing digital data about products and substances that could be relevant to recyclers based on the example of the construction sector.

Construction and demolition waste constitutes the **largest fraction of waste** (36%) generated in the European Union (Eurostat, 2020) and uses a lot of raw extracted materials. Therefore, the New Circular Economy Action Plan (European Commission, 2020) lists the **construction and buildings sector among the key value chains where circularity should be improved**. Plastic materials are abundantly used in construction for various purposes. The sector generates 6% of plastic waste in Europe (see section 4.1). Management and recycling of plastics in construction waste is challenging because it enters waste streams after a long period of time that may last for decades. It is assessed that the building stock in Europe is older than 60 years, with the current life expectancy of buildings reaching 100 years (Rašković et al., 2020). Therefore, **construction and demolition waste is likely to contain legacy substances of concern**. Information about substances, especially SoCs, in plastic construction waste is lost and cannot be easily accessed by recycling operators (Friege et al., 2021).

In the construction sector, demolition decision requires a thorough assessment of building parameters, including the materials and substances used. Such analysis requires both desktop and field research and access to various analytical documentation about the building. To solve the issues of extensive data collection and promote re-use of the building data for sustainable management of buildings, including construction waste, the field of **building information modelling** (BIM) has been evolving rapidly. The developments include geographic information systems for monitoring and visualisation of buildings, complemented with analytical databases on building information that also covers material properties and the presence of SoCs (Rašković et al., 2020). A high number of publications in the BIM field proves the relevance of development datasets in the construction sector. For instance, Li et al. (2017) identified 1,784 BIM research papers published in 2004-2015.

In the BIM field, two approaches to digitising the data that are relevant to recyclers are prominent: a) developing digital material (product) passports and b) digital building logbooks. The high potential of both approaches for combining circularity and sustainability perspectives is recognised in the New Circular Economy Action Plan (European Commission, 2020).

According to the New Circular Economy Action Plan, **digital material (product) passports** (DMPs) allow benefiting from digitalisation for increasing sustainability and circularity of products (European Commission, 2020). DMPs can be universally used for describing products and substances contained in them. **DMP** is a structured set of data about the components and materials that an individual product contains to enhance its use, recovery and reuse in future (Debacker & Manshoven., 2016). Such data provide a wide range of properties of the product and its constituents that enable its safe management and recycling (Pagoropoulos et al., 2017). Information in DMPs can be structured on different hierarchy levels, where materials integrate into components, products and systems. Digital technologies allow the exchange and integration of such data from multiple players. For each material, a dataset describing its physical, chemical and other properties is developed. An important part of data on material properties contains the description of SoCs (if present) and other safety information collected by the manufacturers/suppliers/importers to comply with legislative requirements (Heinrich & Lang, 2019).

An instance of the international DMP initiative is the EU Horizon-2020 project **BAMB** (Buildings As Material Banks, https://www.bamb2020.eu/) that was focused on increasing the circularity of the construction sector by using digital tools. Fifteen partners from seven European countries joined their efforts to develop digital material passports. In the project, 428 digital passports were created with 345 passports for construction products from 94 manufacturers in 14 countries. Analysis conducted during the development of DMPs pointed out fragmentation and varying approach to data in the current DMPs initiatives and the need for standardised data formats. Many questions about validation/audit of the data in digital passports were raised as well. The project research concluded that multiple data types needed for digital passports put a substantial burden on manufacturers to collect them (Luscuere et al., 2019). Additionally, Westerholm (2020) highlighted that data collection and maintenance should be carried out for long periods of time to preserve data and extend their use.

Similarly, national initiatives are focused on using digital material passports to increase the circularity of the construction sector. One example of such initiative is **Platform CB'23** (https://platformcb23.nl/english) launched by the Dutch Ministry of Infrastructure and Water Management, the Dutch Central Government Real Estate Agency, Construction Campus and The Netherlands Standardization Institute in 2018. One of the main tasks of the initiative is to develop digital product passports for the Dutch construction sector. While developing the guidance for DMPs, the project team recognised multiple challenges and tasks to achieve their goals. The tasks included the necessity to standardise the structure and format of data for the passport, understand the motivation of its potential users to engage with such passports, and develop the data governance model that would ensure effective exchange, accuracy, and completeness data, etc. The analysis of different options resulted in choosing the hybrid data governance model, where the ownership and responsibility for the data are decentralised, but the data entry is based on centrally agreed standards (Platform CB'23, 2020).

Another approach to the digitalisation of construction data is the development of **digital building logbooks (DBLs)**. DBLs are recognised as important digital tools that could serve the circular economy goals in Europe by 'promoting measures to improve the durability and adaptability of built assets in line with the circular economy principles for buildings design' (European Commission, 2020a).

DBL is a repository of data about a building. The data collected about a building focus on different stages in its lifecycle: design, planning and construction; sales, leasing, operation and property management; repurpose or demolition. Among the datasets usually covered by a digital building, logbooks are building material inventory that provides information about the properties of materials used to construct the building. Data for a building material inventory could be provided by manufacturers, developers or installers of specific products or materials. Such inventory is relevant to recyclers who decide about the recovery potential and construction waste treatment methods (Volt et al., 2020). A study for the development of the EU framework for digital building logbooks identified 21 ongoing building logbook initiatives worldwide, with eleven of them being digital and ten – paper-based. Most of the analysed initiatives were launched by public authorities. Interestingly, publicly governed initiatives usually were mandatory. The majority of initiatives (67%) contained a building material inventory (Dourlens-Quaranta et al., 2020). Examples of the European DBL are provided in Figure 8-2.

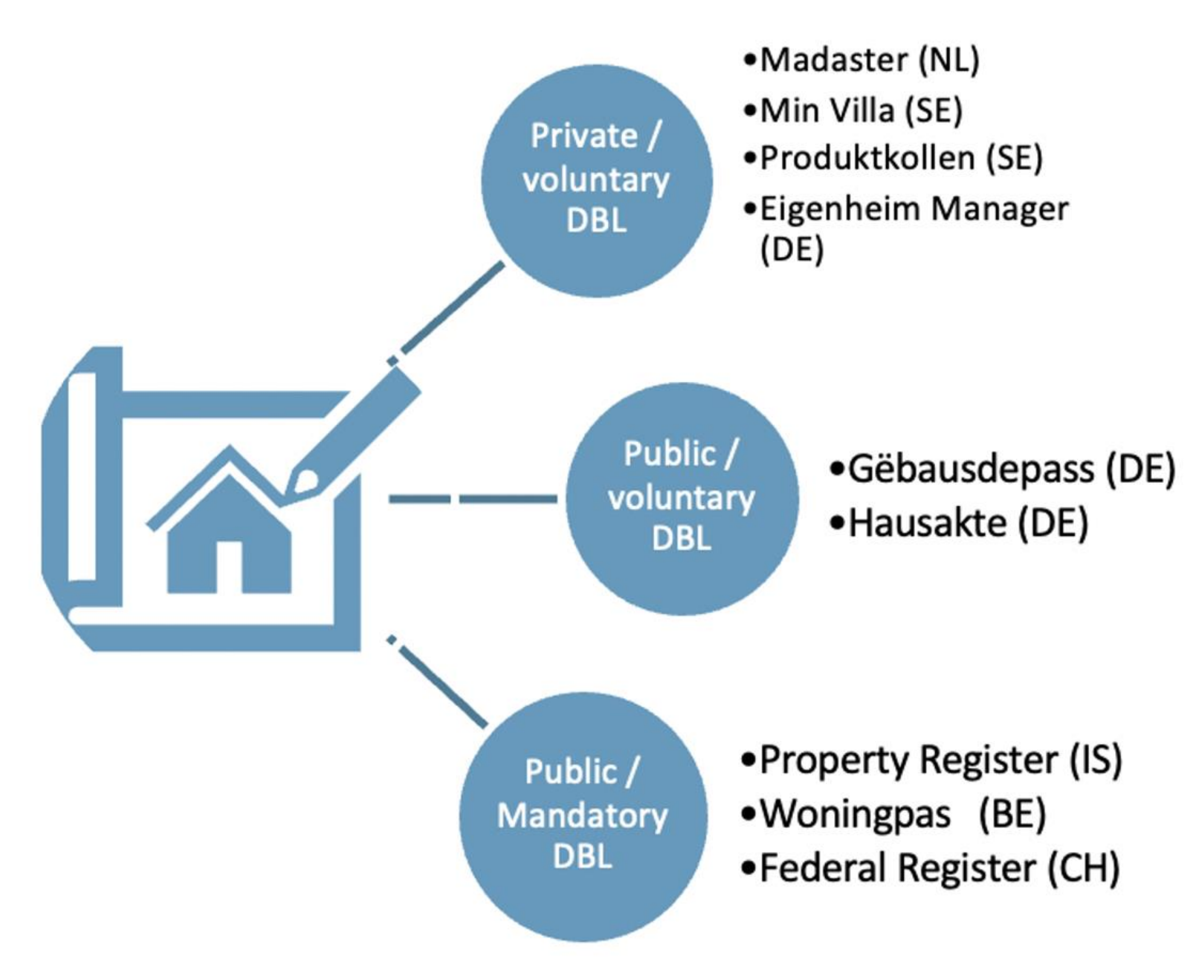

Figure 8-2: Examples of DBL initiatives in Europe - *Source : Dourlens-Quaranta et al., 2020*
NOTE: BE – Belgium; CH – Switzerland; DE – Germany; IS – Iceland; NL – The Netherlands; SE – Sweden

Figure 8-2 shows that examples from Germany and Sweden are prominent among DBL initiatives. Interestingly, one of the initiatives – Madaster, evolved to the international network, functioning in Germany, Norway and Switzerland. Madaster provides information about materials by automatically generating material passports for registered buildings and objects (Madaster, n. d.).

Although multiple stakeholders benefit from DBL data, there are still barriers to the implementation of such initiatives. They are mainly related to running and maintenance costs, difficulty and effort to update data, uncertainty in privacy management, access to information, administrative burden, and fragmentation of initiatives (Dourlens-Quaranta et al., 2020).

Examples of data fields in DBL and DMP initiatives are summarised in Table 8-4.

Table 8-4: Data fields in DBL/DMP initiatives

The EU framework for DBL study (Dourlens-Quaranta et al., 2020)	**BAMB project – DMP** (Heinrich & Lang, 2019)
Building descriptions and characteristics	Physical properties
Equipment, with description and design	Chemical properties
Ownership information	Biological properties
Building material inventory	Material health
Financial, legal and insurance documents	Unique product and system identifiers

Table 8-4: Data fields in DBL/DMP initiatives	
Design and plans of the building	Design and production
Designs and plans of the building interventions	Transportation and logistics
Energy performance certificate	Construction – identifying material and product location within building
Information on occupancy	Use and operate phase
Designs and plans of the main surroundings and land	Disassembly and reversibility
Consumption data of energy, gas, water and other resources	Reuse and recycling
Cost information	
Information on renovation potential	
Taxation information	
3D/BIM models of the building and its systems	
Other ratings, certifications	
Dynamic data	

Table 8-4 shows that DBL initiatives are wider in scope and provide a lot of building-related data, while DMP is material focused and provides extensive data on material properties. Data on material properties usually include sub-fields on the recyclability of material and the presence of SoCs.

The brief overview of initiatives in digital material (product) passports and digital building logbooks showed both opportunities and challenges in digitisation for managing product/material/substance data.

On the one hand, integrated information systems containing the data on properties, the safety of products and materials, and the presence of SoCs **enhance the recyclers' knowledge about the composition of waste streams**. Such information systems allow collecting and maintaining data that come from different sources and otherwise would not be easily accessed by recyclers. Moreover, **systematic data collection makes it possible to re-use them for different purposes as many times as needed**. Over time, with the constant addition of new information, the value of such databases increases.

On the other hand, a lot of **effort is needed to develop and maintain such datasets** since information arrives from different players in the supply chain, and it is constantly updated. The current DBL and DMP initiatives discussed in the case study solve similar **data governance** issues – standardisation, verification, responsibility and ownership. Therefore, substantial efforts are required to benefit from digital technologies in managing substances, especially SoCs in products and waste recycling.

9 Findings of the Expert Consultation

Twenty two semi-structured interviews (one hour long) were conducted in May – June 2021 with representatives from industry, academia, governmental agencies, industry associations and non-profit organisations. Most of them represented European countries (see the list of interviewees in Annex 4). MS Teams platform was used for conducting virtual interviews and making the recordings. All participants gave their consent to publishing their names in the list of interviewees and recording the conversation. The interview recordings were transcribed, and a thematic analysis was carried out to highlight the main topics that emerged.

The expert consultation was not specifically focused on the chemical recycling of plastic waste to allow capturing any other significant application domains to be explored in the future.

Two topics were typically discussed in each interview with a few exceptions where three or only one topic was covered. Each topic was covered in six or more different interviews to reach data saturation. The number of interviews that considered each topic is summarised in Table 9-1.

Table 9-1: Responses to the topics of interviews

Topic of discussion	Number of interviews
Topic 1: Chemical recycling technologies	6
Topic 2: Waste streams	9
Topic 3: Recovered substances, materials and waste residues	7
Topic 4: Chemical recycling and SVHCs	9
Topic 5: Chemical recycling policy developments, including UVCBs	7
Topic 6: Chemical recycling and tracking systems	8
NOTE: the sum of interviews dedicated to each topic does not coincide with the total number of interviews because one interview addressed from one to three topics	

Table 9-1 shows that the data saturation point (six interviews) was reached for all topics, while it was even higher for five topics.

During the analysis of interview data, a lot of intersections between the comments of experts were noticed in the interviews on Topics 4, 5 and 6. In all interviews on these topics, the issue of handling SoCs was visible; the experts discussed similar solutions, e.g., in all interviews, design for recyclability was mentioned. Considering these links and similarities in interpreting the questions, the analysis of these topics was presented in one section.

Furthermore, the topic of chemical recycling is very broad. Therefore, some issues addressed in the interviews are relevant only to specific chemical recycling technologies. Due to the complexity of chemical recycling and multiple themes addressed in the interviews, it was impossible to examine each chemical recycling technology on a case-by-case basis. So, topics that were considered important and urgent were discussed. Appropriate explanations are provided in the text.

In the following sections, the thematic analysis of each topic is presented. It should be noted that in some cases, to support their argument, the respondents provided very specific information that could disclose their identity. In such cases, the appropriate comment is given, and quotes are not provided. Each section contains a map of thematic categories that emerged in discussions and their interpretation illustrated by quotes of the respondents.

9.1 Topic 1: Chemical recycling technologies

Discussions on Topic 1 **aimed** to get insights into the current state-of-the-art chemical recycling technologies, including the predominant types, performance, advantages, and shortcomings. All interviewees focused on discussing specific chemical recycling technologies, their advantages and disadvantages. The summary of thematic categories is provided in Figure 9-1.

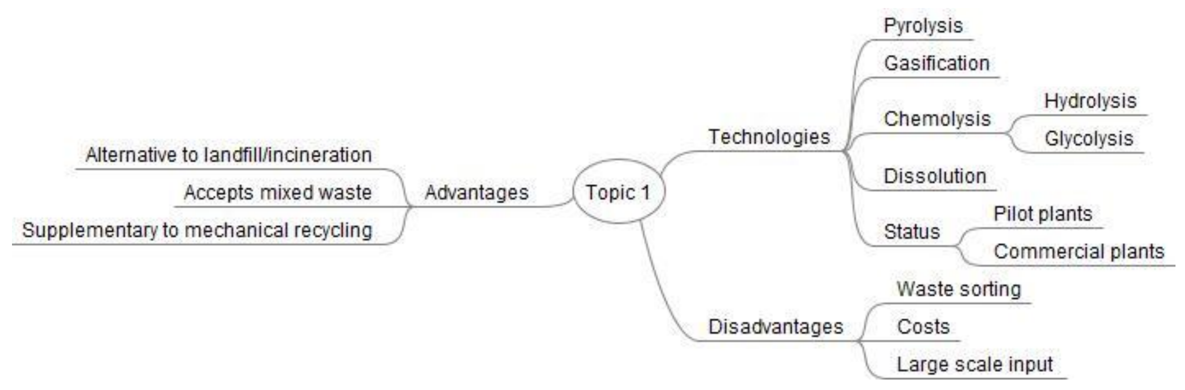

Figure 9-1: Thematic categories in Topic 1

As Figure 9-1 shows, most experts highlighted the **status in the development of chemical recycling** technologies. Most experts noted that chemical recycling is not widespread, with the predominance of pilot plants, e. g.: "we are in the first phase, there are pilot plants", "we would say it [chemical recycling – author note] is not a major technology, there are a lot of pilot plants, for instance, in Japan, plastic-to-fuel".

However, the respondents also provided examples of functioning **commercial plants**: "there is a large gasification – author note] plant in Canada, one commercial plant is under construction in the Netherlands", "there is one working gasification plant in Japan", "Plastic Energy owns two plants in Spain".

Pyrolysis, gasification and chemolysis were the most mentioned chemical recycling technologies in the interviews. However, some experts also mentioned dissolution (in other words, solvent-based purification), although it is not considered a chemical recycling technology. Experts expressed their concerns about dissolution. For instance:

- "Polymers are obtained by chemical depolymerisation, e.g., hydrolysis, glycolysis, etc. Thermal conversion is not directly converting it [feedstock – author note] to a monomer but into an intermediate, i.e., oil or gas, in case of pyrolysis and gasification."
- "There are four main processes – solvent-based, chemical depolymerisation, pyrolysis and gasification."
- "In the Chem Trust report, solvent purification is described as chemical recycling. I would say solvent purification is a separate [technology – author note]. What is the right definition?"

The main advantages noted by experts related to processing **mixed and contaminated waste** by some chemical recycling technologies and providing a **better alternative to landfilling or incinerating** waste. For instance:

- "An important factor is then to stop it [waste – author note] going to landfill."
- "The objective is to be able to treat waste, which is currently either landfilled or incinerated."

- “Gasification is most aggressive [technology – author note], you can work with a different feedstock, it can work well with contaminated waste streams.”
- “Pyrolysis is the core chemical recycling technology for mixed and contaminated plastic waste.”

Therefore, as the experts highglighted, chemical recycling can be treated as **supplementary to mechanical recycling** because it accepts waste that cannot be processed mechanically, e.g.:

- “If chemical recycling would be able to take care of waste that could not be treated with mechanical technologies, that would be one thing, but it is not really what we see now.”
- “When somebody asks me ‘why chemical recycling’ I always use the same explanation that chemical recycling applies to those products, plastics, polymers, which cannot be recycled mechanically.”

At the same time, experts recognised that not all chemical recycling technologies are capable to processed mixed and contaminated waste. According to experts, even those technologies that are claimed to be capable of handling mixed and contaminated waste have specific limitations. So, the disadvantage is that chemical recycling still requires **sorting**. For instance:

- “So, actually, pre-sorting is probably needed. The thermal [depolymerisation – author note] can handle mixed waste, but it should not be too mixed.”
- “When you ask a question if it [chemical recycling technology – author note] can it treat all types of plastic? The first answer you get is usually ‘yes’. And then you ask: “what about chlorinated and brominated plastic”? [You get the answer – author note] – ‘well, yes, but not exactly those, or you could treat those, but you would need a different process, or we try to separate them at the entrance because there is a likelihood for a secondary output or toxic emission.”
- “Mixed plastic waste seems to be a little bit problematic for depolymerisation; it requires a homogeneous waste stream.”
- “We also see many problematic waste streams. For instance, the PVC waste stream has a lot of problematic substances like lead and other heavy metals. And it is something that chemical recycling cannot handle.”

Other disadvantages covered the high **costs** of applying some chemical recycling technologies and the necessity to ensure **sufficient input quantities of waste**. E.g., “it is important to feed these plants with waste”, “for chemical recycling, the question is how to get appropriate quantities of waste to feed your plants”, “you have to compare the cost of chemical recycling with other options, so that other options would not offer a low cost that would kill the economics of your project”, for it [gasification – author note] it is a quite expensive preparation.

9.2 Topic 2: Waste streams

Topic 2 **aimed** to collect information and insights on the present and potential sources of waste that are or could be processed by chemical recycling technologies. The discussion focused on two topics – the purposes of the chemical recycling of particular streams of waste and their types (see Figure 9-2).

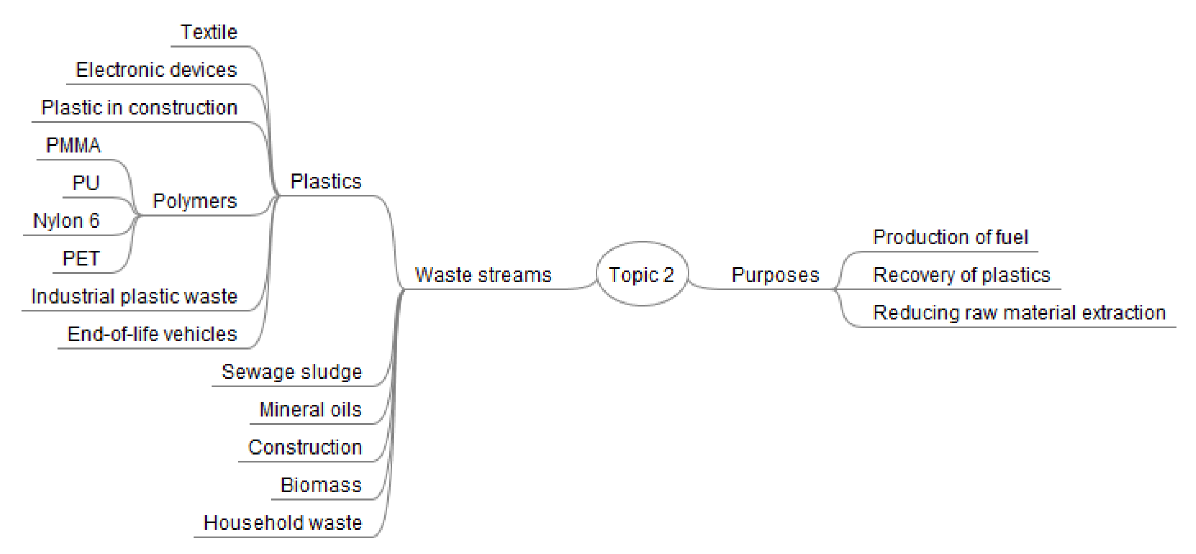

Figure 9-2: Thematic categories in Topic 2

Figure 9-2 shows that three purposes for using chemical recycling – **production of fuel**, **recovery of plastics** and **reduction of raw material extraction**, were highlighted by the respondents. Several experts mentioned "fuel", "transportation fuel" or provided examples of specific technology, e.g., "pyrolysis focuses on plastic oils, plastic-to-fuel [chemical recycling – author note]." Other experts emphasized the recovery of plastic – "directly convert polymer to monomer", "if we look at plastic-to-plastic, it is too early, but things are coming", "we have an idea of nylon 6 market". And finally, a comment on the recovery of materials from waste by chemical recycling to reduce raw material extraction was received: "[chemical recycling – author note] solves big problems and tries to reduce the virgin extraction".

The respondents provided a lot of different examples of waste that could be treated by chemical recycling technologies. However, many types of waste were related to **plastic goods or materials**. Some experts talked about plastics in general, e.g., mentioned "plastic waste", while others focused on polymers – "a technology to separate nylon 6 from products", "PMMA to MMA". One comment on using industrial plastic waste as feedstock to chemical recycling was received: "there are two distinct markets for getting feedstock; the one is in-process waste, industrial waste". Many respondents provided various examples when speaking about plastic products: "plastic window frames", "electronic devices", "textile and plastics", "end-of-life vehicles", etc. Examples of other waste streams to be treated by chemical recycling were fewer and covered biomass, sewage sludge, construction, household waste and mineral oils.

9.3 Topic 3: Recovered substances, materials and waste residues

In Topic 3, the interviews aimed to get information about the outputs of chemical recycling, including substances, by-products and residues and to understand their demand on the market and safety aspects. Discussions on this topic were challenging because examples and solutions provided by respondents were very specific, and quotations could disclose the identity of the interviewees. Therefore, specific examples and quotes are not provided here to preserve the anonymity of the respondents. Two major approaches to the topic emerged in the discussion, and they clearly related to the type of organisation represented by interviewees (Figure 9-3).

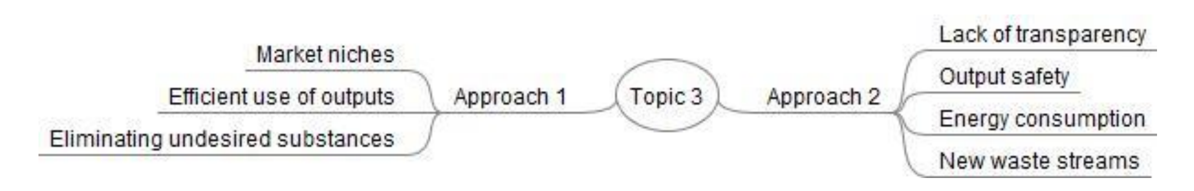

Figure 9-3: Thematic categories in Topic 3

Figure 9-3 shows that two approaches focused on different thematic threads. While Approach 1 was focused on establishing of chemical recycling on the market, Approach 2 raised questions about chemical recycling outputs. It should be noted that respondents referred to specific chemical recycling technologies, not to the whole field.

Stakeholders who demonstrated Approach 1 to dealing with outputs mainly focused on solutions how to make use of them. Interviewees mentioned that despite different types of **by-products** produced by chemical recycling, many of them could be usefully applied, e.g.:

"So, roughly 10% are of gases and 5% – coke, uh, which comes out of it [chemical recycling process – author note]. We can use most of the gases as fuel. The coke can be used in road transportation or similar. But, to be honest, you have to look at the composition of the coke because it can limit your ability to use it in different applications. A residue stream or a waste stream needs more processing."

Similarly, removing **undesired substances** is a practical issue pointed by some interviewees. These substances cover either contaminants or substances that may affect the treatment process or the yields, so the interviewees were interested in handling them:

- "If it [a substance – author note] is bonded to another polymer, then obviously you have got the challenge. If it does not fit well with pyrolysis process or even if it does go through the process, then the reduced yields may be an issue."

- "What do we have to do with waste residue? Incinerate it or landfill? It depends on the pre-treatment step."

Approach 1 was observed in the discussion of possible markets for both the feedstock for chemical recycling and the recyclates. However, here discussions provided too specific examples that can disclose the identity of the respondents.

The second approach raised three types of issues related to the outputs of chemical recycling: general lack of transparency about the content of the outputs, output safety, energy consumption and generation of new waste streams. The respondents noted a general **lack of transparency** about the processes of chemical recycling and their outputs:

- "I think there is the question of the definition of output. There is also a question of transparency, and discussions usually hit a question of confidential business and information about processes."
- "One thing about chemical recycling is the lack of transparency in the whole system. There is simple stuff around mass balance and stuff about what is in the waste and where the waste goes. But then there are all other chemicals. What is about chemical additives, solvents that you have used?"

Uncertainty about the **safety of outputs** causes doubts, e.g.:

- “What is still present in the fuel that has been created, and what happens when it is burnt? In some conversations with actual engineers, there were references to those types of fuels being produced through a chemical recycling pilot plans to be heavily loaded with sorts of compounds that would produce secondary emissions when that fuel is burned. I think this is one of the main questions that have been raising.”
- “So, we are dealing with contaminants, and we have to take it into account. If you have contaminants at the entry [to chemical recycling – author note], you will have contaminants somewhere at the outlet.”

The themes on **energy consumption** and the **generation of new waste streams** reflected general doubts about some chemical recycling technologies as contributors to the circular economy. For instance:

- “It [chemical recycling – author note] is a real chemical process that requires external energy. They need to generate energy within the process. And it is definitely not possible to recover 100% of the waste into chemicals.”
- “The whole [pyrolysis – author note] process uses huge amounts of energy and then creates a waste stream. Is it somehow sustainable?”

Obviously, Approach 2 was more concerned with factors of safety and sustainability of the outputs in some chemical recycling processes, while Approach 1 demonstrated a focus on business processes and investigated practical decisions of dealing with some chemical recycling processes and their outcomes. Importantly, Approach 2 evaluated chemical recycling in a broader context of the circular economy and sustainability, while Approach 1 was not focused on such broad evaluation.

9.4 Topics 4, 5, 6: Regulatory and technical developments

Topics 4, 5 and 6 were **aimed** to collect detailed information on diverse topics – SoCs in waste and their fate in chemical recycling (4), policy and legislative developments, including UVCBs (5), technical means to implement communication obligation in supply chain and handle SoCs. Various interviews addressed these topics, and many intersections between the topics were observed. For instance, in all three topics, the respondents highlighted design for recyclability as a necessity, increasing transparency and accountability to ensure that the outputs of chemical recycling are safe. Therefore, to bring together the same arguments, the topics were combined for the purposes of analysis. SoCs were mentioned in interviews on all three topics. A low level of knowledge was observed on UVCBs, however. Each of the three topics presented in this section was very broad, and it was noted by respondents (e.g., “obviously, chemical recycling technologies are diverse, so the SVHCs fate is not going to be the same in each one”). Due to interview time limits and the number of questions, it was not possible to systemically address all questions in terms of various chemical recycling technologies. So, it should be noted that not all issues are equally applicable to every chemical recycling technology. The respondents rather tried to highlight the issues that require discussion.

Four main themes emerged in the discussion. The experts highlighted main sources of origin, types of SoCs and elaborated on what could be done to eliminate them (see Figure 9-4). It should be noted that although the interviewees used the notion of “SVHCs”, their understanding of substances of concern was broader (e.g., see the example of substances disrupting chemical recycling processes below). Therefore, here the concept of SoCs is used; however, the original usage of the term is provided in the citations reflecting the arguments of the respondents.

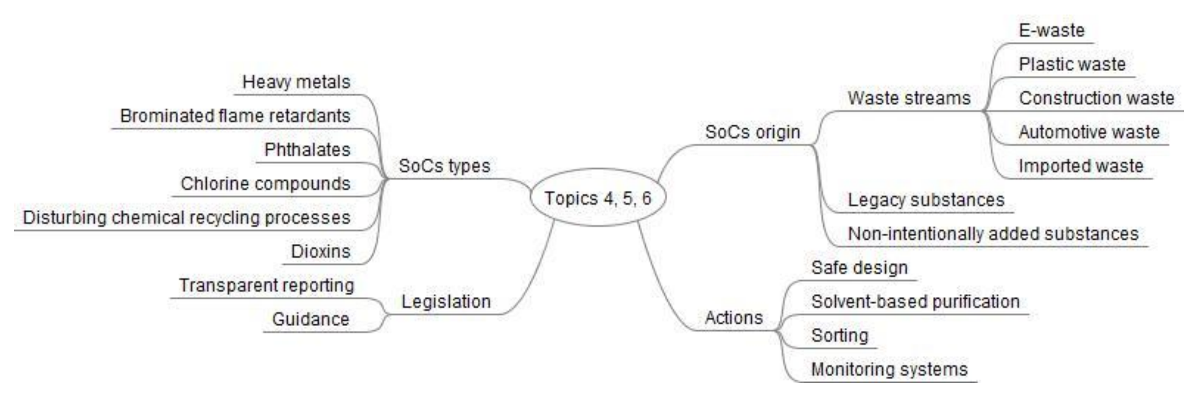

Figure 9-4: Thematic categories in Topics 4, 5 and 6

As Figure 9-4 shows, the respondents identified three sources of SoCs in chemical recycling – waste streams, legacy substances and non-intentionally added substances. The experts mentioned that specific **sources of waste** contain substances of concern, e.g., "we know that a large amount [of substances of concern – author note] comes from electrical and plastic waste", "you have to look at different markets, such as construction waste, or automotive waste". They drew attention to expanding list of SoCs (e.g., "obviously, SVHCs is a moving target, it is not a stable list of things") that leads to the presence of **legacy substances** (once used and then – restricted) in waste: "we must find the solution to manage substances that come from the past", "we have to distinguish between two types of possible input into the processes, what I would call the new plastics and the old legacy plastic that has been produced over the past 50 years". One mention of SoCs in the **imported waste** (and, possibly, imported goods that become waste in the EU) was received: "All the waste contains them [substances of concern – author note], they are transported across the border". And finally, one respondent commented about the lack of knowledge about non-intentionally inserted compounds:

> "We usually have a clear idea of what the main polymer is and, perhaps, about one or two main additives, but what about all of the rest, including what is commonly referred to as the non-intentionally added substances?"

The respondents mainly discussed **six types of SoCs** – heavy metals, phthalates, brominated flame retardants, chlorine compounds, dioxins and substances that disrupt the technological processes of chemical recycling, e.g.:

- "Flame retardants are a well-established example [of substances of concern – author note]."
- "I think the concern would be about brominated compounds, chlorinated compounds, heavy metals, whether it's lead or cadmium."
- "PVC is not used, but it is still there adding halogens, <…> causing corrosion; these products should not be added."
- "A few of them have become policy discussions, e.g., PVC and phthalates or brominated flame-retardants".
- "The possibility of forming dioxins is a concern of mine. It has not been officially peer reviewed but it would make sense that those could appear there".

The experts also provided insights into what **actions** should be taken to make chemical recycling more transparent and handle SoCs. Two sub-themes referred to additional steps or technical solutions in chemical recycling, such as sorting, introducing monitoring systems or using solvent-based purification to eliminate SoCs (e.g., "solvent-based purification is the only way forward to remove banned substances").

Some respondents spoke about **sorting** as a general step in chemical recycling (e.g., "it is difficult, of course, to deal with these substances, but if you have a chemical recycling process, you will always have a sorting facility"). Others considered **automated sorting** to be a promising solution, e. g.:

- "Two initiatives are quite promising. One is called "Holy Grail 2.0", it is for packaging. It prints invisible barcodes that allow high-speed separation in Tomra type sorting lines. <…> If you look at the Holy Grail 2.0, it is really something unique and successful. Still in its embryonic stage, but it holds a promise."
- "You may look at the incentives regarding the use of different automated solutions, as artificial intelligence. These prototypes are in early stage, for the sorting facilities."
- "Those technologies should be adapted to avoid unwanted side streams; sorting equipment to manage those will be the digital tools. I must admit an importance of digital tracking, technologies and systems for tracking and risk mitigation."

Two comments were received on the need for **traceability of chemicals** through their lifecycle and the use of **blockchain systems** for this purpose, e.g.:

- "Traceability is necessary to link the input and the product of chemical recycling. There is a need for certification by a third party. Currently, it is done on paper; there is a need to exchange information and rely on the certifier. The task of a regulator is to choose the certifier. With blockchain technology, there is a possibility to make links between these steps".
- "Blockchains are in Singapore, Hong Kong. There is no business development in the EU. We would like to implement a blockchain. With smart contracts, you can make everything transparent. At the same time, every transfer can be made anonymous."

However, one comment arguing that effective automatic sorting was not possible was received: "The idea that you could somehow use RFID or a marker and link it to a database that would be accessible to the recycler. It is a fantastic and magical idea but that will never happen. If you have a sorting center tons of material [are processed – author comment] per hour."

Notably, many respondents emphasized that the need for **design for recycling** as a measure for handling SoCs and ensuring that the output of chemical recycling is safe:

- "In general, it should start with design. Fair to say that design for recyclability is very important."
- "Eliminate SVHCs from the product design stage".
- "What needs to be done is introducing some kind of quote [of substances of concern – author note], a system to put pressure on the producers."
- "Design for recycling".
- "We need toxic free materials. The same as we change our behavior, we need to change the way we design products, the way we think about them. For instance, I think, using a toothpaste tube is not going to be the solution anymore. We are going to use these little tablets that you chew and they don't require packaging. You have to rethink it completely and customers have to change their consuming habits and expectations of products."

The experts discussed the regulatory practices and needs related to the management of SoCs and UVCBs. Many respondents emphasized the need for **accountability and transparent reporting** for ensuring that the composition of the recyclates is known, documented and communicated to other stakeholders in the supply chain:

- "So, I believe it has to be done on the legislation side – sorting and obviously reporting as well. And it is important to make information more public".

- “Communicating and tracking how well the product is monitored. A lot of things are sold by brand names – people do not know what chemicals are in them. There should be a tracking system and mandatory communication requirements. <…> The accountability – recovered or disposed of.”
- “An alternative that works and something that we have been doing for some time now is supply chain communication.”
- “We have to understand that things will not move in the positive direction if there is no transparency and clarity. Especially on risks and toxic chemicals; that kind of discussions, which show up alongside. If they are not fully transparent, we should accept that as a visible or hidden roadblocks.“
- “Depolymerization technologies require a lot of transparency. It is necessary to purify SVHCs or contamination. So, you need to know what is there [in the processed waste stream – author note] in order to do that and to take correct purification steps. When we talk about thermal pyrolysis and gasification, then we have the problem of additives. It might be a problem because they [thermal pyrolysis and gasification – author note] cannot handle a large amount of additives. Technology-wise, there are different problems. But it is something that we need to solve in order for chemical recycling to work. So, it requires different approaches and a lot of transparency.”

Several comments on implementing REACH were received. The comments addressed the need for **guidance**:

- “A company with a very strong background in chemistry and mechanical technology in general, are used to manage the UVCB substances. They have a good knowledge of REACH and can handle UVCB substances. The problem can arise when you have a very small company that works on it; then, they do not have enough knowledge in relation to REACH. “
- “Clearly, it is relevant to pyrolysis. So, UVCB within the process is a complex reaction product. I do not think we have enough information on that. It is going to be an issue.”
- “UVCBs should be classified, and you need to identify them; you need guidance.”

In general, the lack of detailed comments and explanations in the field of regulatory requirements, especially related to UVCBs, shows that these topics are very specific and require the targeted recruitment of experts with legal knowledge on the subject.

10 Conclusions and Recommendations

Analysis of literature and expert consultations provided insights for conclusions and recommendations of the study. Conclusions are presented together with relevant recommendations.

CONCLUSION 1. The lack of clarity in chemical recycling terminology leads to confusing conclusions on the potential role of chemical recycling in the circular economy. The review revealed that in the scholarly literature, the concept of 'recycling' is treated with a broader meaning than in regulatory documents of the European Union. Differently from the EU definition provided in the Waste Framework Directive (European Parliament, 2008), research papers treat chemical recycling as tertiary recycling and include fuel as a possible product of recycling (e.g., see Lee & Liew, 2020; Ragaert et al., 2017; Davidson et al., 2021, etc.). Production of fuel by means of chemical recycling received substantial attention in scholarly literature. Fuel products from chemical recycling are well-researched (see, e.g., Miandad et al., 2017; Miandad et al., 2019; Lopez et al., 2018; Budsaereechai et al., 2019). Some research addressed the environmental performance of fuel production in chemical recycling (e.g., see Qureshi et al., 2020) and conducted techno-economic assessment (see, e.g., Larrain et al., 2020; Fivga & Dimitriou, 2018). In the reports by civil organisations, chemical recycling is criticised for the production of fuel and associated environmental outcomes (e.g., see Patel et al., 2020; Rollinson & Oladejo, 2020; Schlegel, 2020). By and large, in grey literature, there is a lack of clarity on what technologies should be attributed to chemical recycling. For instance, dissolution is classified as chemical recycling technology in several grey literature reports (e.g., see Hann & Connock, 2020; Rollinson & Oladejo, 2020). However, it does not introduce chemical changes in the structure of a polymer, which is a definitive feature of chemical recycling technology (Vollmer et al., 2020). In turn, classifying dissolution as a chemical recycling technology may lead to false interpretations and generalisations, e.g., that all chemical recycling technologies can effectively eliminate SoCs. Such interpretation sets specific expectations for the performance of chemical recycling. Similar uncertainty about the status of dissolution was expressed in the consultation with experts.

RECOMMENDATION 1.1 Harmonisation of chemical recycling terminology is necessary for a sound and consistent discussion about the potential of chemical recycling in the circular economy. Papers, reports and regulatory documents should always specify the chemical reprocessing technologies that are included in their scope. This would allow distinguishing the technologies that meet the definition of 'recycling' provided by the Waste Framework Directive from those that do not meet the definition.

CONCLUSION 2. Chemical recycling technologies differ in their potential to contribute to the circularity of plastics. In accordance with the circular economy policies (European Commission, 2018; European Commission, 2018a; European Commission, 2020), circularity could be assessed by the ability of chemical recycling processes to restore/revitalise or renew sources of energy or materials and produce as little waste as possible. The established chemical recycling technologies – pyrolysis, gasification and chemolysis, vary in their ability to ensure the circularity of plastics. However, it should be noted that this conclusion is based on the qualitative evaluation of chemical recycling technologies provided in research papers. The analysis has shown that the robust quantitative assessment of chemical recycling technologies is still absent, although Lifecycle Assessment (LCA) and Techno-economic Assessment (TEA) show the potential for quantitative evaluations in terms of its environmental and economic performance (see section 5.3 for a detailed discussion).

According to the literature, **pyrolysis** and **gasification** only partly contribute to achieving the circular economy goals for several reasons. Both technologies generate by-products (e.g., char, tar etc.) that could be re-used to a certain extent, while some by-products (e.g., flue gas) require cleaning (Al-Salem et al., 2017; Lopez et al., 2018; Miandad et al., 2016). It means that both approaches to **treating plastic waste generate non-reusable residues that need to be disposed of**. Furthermore, pyrolysis and gasification mostly produce intermediates (e.g., gases, oils, waxes) that should be further processed to become either **chemicals, fuels or energy** (Sharuddin et al., 2016; Miandad et al., 2016; Al-Salem et al., 2017; Solis & Silveira, 2020; Ragaert et al., 2017). Production of fuel is well-researched and quoted in scholarly papers. **However, it does not create a circular closed-loop system for plastics**. It is also not covered by the concept of 'recycling' in the EU. Emerging technologies, identified by the literature search, are mainly based on pyrolysis and gasification and aim to enhance the efficiency and cost of the processes.

Despite the circularity limitations, **pyrolysis and gasification have the potential to serve efficient waste management technologies and substitute incineration and/or landfill**. Pyrolysis and gasification can treat heterogeneous streams of plastic waste, with gasification as the least demanding in terms of the composition of the feedstock (Lopez et al., 2018; Solis & Silveira, 2020). The most challenging stream of plastic waste – post-consumer waste is mixed and contaminated. Therefore, the rates of incineration (42.6%) of such waste are still higher than its recycling (32.5%), with landfilling (24.9%) very close to recycling levels (PlasticsEurope, 2020). Therefore, chemical recycling could be treated complementary method to mechanical recycling to address waste streams that otherwise would be landfilled or incinerated (e.g., see Davidson et al., 2021; Jeswani et al., 2021). Additionally, some lifecycle assessment studies indicated that sending rejected waste from mechanical recycling to pyrolysis is a more environmentally favourable option than incineration (Qureshi et al., 2020; Jeswani et al., 2021). Opinions about the preferability of chemical recycling over landfilling and incineration were also voiced in expert interviews.

Differently from pyrolysis and gasification, chemolysis is reported to produce monomers (Lee & Liew, 2020) of a virgin-grade quality (Vollmer et al., 2020; Ragaert et al., 2017). The literature search did not identify discussions on by-products or residues of chemolysis, although Vollmer et al. (2020) indicated that additives should be removed to obtain a high-quality output. However, no further elaborations on the topic were found. It means that, potentially, **chemolysis is capable of contributing to the circularity of plastics**.

Despite the high level of technological maturity of some chemolysis technologies (e.g., glycolysis or hydrolysis), the establishment on the market is problematic (Simon et al., 2018). However, **commercialisation of chemolysis is limited by several factors**: it can process only homogenous streams of plastic waste, mostly limited to condensation polymers, such as PET (Lee & Liew, 2020; Solis & Silveira, 2020; Simon et al., 2018); the price of recycled plastics is higher than the market price of virgin plastics (Vollmer et al., 2020) and for chemolysis to become economically viable, large quantities of waste are needed (Ragaert et al., 2017).

RECOMMENDATION 2.1 The potential of specific chemical recycling technologies to contribute to the circularity of plastics should be evaluated case-by-case to avoid mistaken generalisations of advantages/disadvantages of one technology to the whole field of chemical recycling.

CONCLUSION 3. Analysis of research literature has shown fragmented knowledge about the fate of substances of concern in various chemical recycling processes. Available studies mainly focused on various types of pyrolysis of e-waste and the fate of brominated flame retardants (Charitopoulou et al., 2020; Das et al., 2021; Ma et al., 2016); however, no studies were identified for other established chemical recycling technologies. It is important to note that **various pyrolysis technologies demonstrated different abilities to cope with substances of concern**. Das et al. (2021) and Ma et al. (2016) reported the presence of different bromine substances in the outputs of pyrolysis, such as liquid oils, waxes, as well as by-products, e.g., char. The presence of these substances varied depending on the pyrolysis method and the type of processed plastic (Ma et al., 2016). Other negative impacts, such as catalyst deactivation or poisoning during the process of removal of brominated flame retardants in catalyst pyrolysis (Ma et al., 2016). However, these findings do not provide a solid ground for making conclusions about the fate of substances of concern in all established chemical recycling processes. Furthermore, it is not clear if the technologies analysed in the scholarly literature have been applied in industrial settings. The lack of public data about the details of some technological processes in the industry was also mentioned in research papers (e.g., Barnard et al., 2021). Most experimental studies included in this report were conducted in laboratory settings.

RECOMMENDATION 3.1 The behaviour and fate of substances of concern in gasification and chemolysis should be investigated. Studies of substances of concern in commercial or pilot chemical recycling plants are necessary to make sound conclusions about the behaviour and fate of these substances.

CONCLUSION 4. Literature on regulatory issues in chemical recycling is absent. The general lack of knowledge about the regulatory concerns in chemical recycling was also obvious in the expert consultation. However, based on the data that substances of concern are not necessarily eliminated by chemical processing, it could be assumed that **several issues raised in mechanical recycling could be relevant to specific chemical recycling technologies as well**. These issues include:

- **The EU directives focused on the largest sources of plastic waste, such as packaging, construction materials and end-of-life vehicles, does not sufficiently encourage the recycling of plastic waste**. Such a situation is due to several reasons: a) the lack of proper connection of the Directives measures to the up-to-date EU strategic policy documents on plastics and circular economy, b) vague definitions of important recycling concepts and measures, and c) indicators of target attainment based on the weight that does not promote the recycling of lightweight plastic materials (Eunomia et al., 2020; European Commission, 2021). However, important steps have been taken to review the directives and overcome their weaknesses.
- **The absence of information about the presence of SoCs in plastic waste streams occurs due to the communication gap in the plastic supply chain and the long-term circulation of legacy SoCs in consumer goods**. According to REACH, manufacturers of substances should inform consumers and other stakeholders in the plastics supply chain about the presence of SoCs through safety datasheets, while producers and importers of articles should notify the ECHA about the presence of SVHCs if their concentration in an article exceeds 0.1% w/w. However, this information usually does not reach waste managers (de Römph & Van Calster, 2018; Alaranta & Turunen, 2021). After restricting the use of substances of concern, they still function in consumer goods that were produced before the restriction and can become waste in 20 to 50 years (e.g., in the case of automotive or construction plastic waste) (Wagner & Schlummer, 2020).
- **Regulatory uncertainties in the transition of the recyclers from waste manager to substance manufacturer status**. This uncertainty occurs because of a) differences in assessing hazards in waste management regulation, where waste is assessed as (non)hazardous as a whole, and chemicals regulation, where such assessment is based on intrinsic properties of a substance (Friege et al., 2019) and b) the lack of clear end-of-waste criteria and procedures for quality and safety assurance of the recyclates (Alaranta & Turunen, 2021).

It is important to note that in cases of mechanical and chemical recycling, recyclers are both waste managers and manufacturers of new substances/producers of articles who must comply with waste management and chemicals legislations. The feedstock for recycling is waste, and this is governed by waste legislation. However, the output of recycling falls under the regulation of chemical substances and articles, product safety and other sectorial legislation.

However, **it is not possible to make parallels with mechanical recycling in judging the opportunities and challenges faced by chemical recyclers in complying with REACH and other chemicals legislation**. All chemical recycling technologies cause chemical changes to the processed substances, which is not the case in mechanical recycling. Some chemical recycling technologies (e.g., pyrolysis) are specific for producing intermediate substances (e.g., pyrolysis oil, waxes etc.) that are used for manufacturing chemicals or fuel and multi-constituent substances of partly unknown composition (i.e., UVCB). However, these features can be irrelevant for other types of chemical processing (e.g., chemolysis). Technological processes of chemical recycling applied in commercial plants can also have differences that influence the final output of the process.

RECOMMENDATION 4. The regulatory issues in chemical recycling should be studied on a case-by-case basis, separately for each type of chemical recycling technology.

CONCLUSION 5. Digital technologies contribute to improving the traceability of substances of concern in recycling. Some chemical recycling technologies are either sensitive to specific constituents in plastic waste or can process only some sorts of plastic waste. For instance, pyrolysis has a low tolerance to PVC, catalytic cracking to chloride and nitrogen components, while chemolysis technologies can be applied only to condensation polymers (Solis & Silveira, 2020; Ragaert et al., 2017). Moreover, pre-treatment is often necessary to eliminate SoCs (Charitopoulou et al., 2020; Evangelopoulos et al., 2019). So, to perform efficiently, different chemical recycling technologies have to rely on sound knowledge about the composition of plastic waste they process (de Römph & Van Calster, 2018; Friege et al., 2019) and to apply sorting and pre-treatment (Schwarz et al., 2021). The literature analysis has shown that many databases with information about chemical substances contained in articles exist, including the newly launched SCIP database maintained by ECHA that provides information on SVHCs (Friege et al., 2021). These datasets are useful in locating information about substances of concern. The importance of sorting incoming waste was emphasized in expert consultation. Screening technologies in recycling facilities help to identify substances of concern (Norin et al., 2021; Stenmarck et al., 2017). However, these solutions have their limitations – databases lack historical information about legacy substances of concern, information is dispersed across various datasets with different access and search options. Screening technologies vary in their ability to detect SoCs, especially in low concentration, more accurate technologies are expensive (Norin et al., 2020). Inaccurate sorting of waste may result in the unnecessary rejection of plastic waste that could be potentially recycled (Wagner & Schlummer, 2020).

CONCLUSION 6. Blockchain technology offers a solution for monitoring substances of concern in plastic waste; however, its implementation requires substantial inter-organisational and organisational efforts. The literature analysis has shown that the main advantages of blockchain are decentralised management, verifiability of information, ability to track any event or transaction at different lifecycle stages of plastic materials and goods from manufacturing to end-of-life. Combined with tags (e.g., QR codes, RFID, digital watermarks, etc.), blockchains ensure access to necessary information about individual goods in a stream of waste to the recycler. However, the benefits of blockchains for recyclers come at the cost of large-scale digital transformation of the whole supply chain. The success of such initiatives depends on commitment, investments and collaboration between multiple players and requires a substantial amount of time to make blockchain solutions functional (Saberi et al., 2019; Taylor et al., 2020). So, blockchain is not a solution that will provide immediate benefits for recyclers. Other developments, such as the application of artificial intelligence for the analysis and evaluation of plastic waste, can be useful for recyclers as well. The relatively limited information on digitalisation in recycling obtained in the expert consultation proves the novelty of digital solutions in recycling. Different existing digital tools – databases, screening and sorting technologies, digital and printed tags can be combined for satisfying the practical needs of recyclers.

11 References

Ab Latif Wani, A. A., & Usmani, J. A. (2015). Lead toxicity: a review. *Interdisciplinary Toxicology*, *8*(2), 55.

Aishwarya, K. N., & Sindhu, N. (2016). Microwave assisted pyrolysis of plastic waste. *Procedia Technology*, *25*, 990-997.

Al Rayaan, M. B. (2021). Recent advancements of thermochemical conversion of plastic waste to biofuel-A review. *Cleaner Engineering and Technology*, 100062.

Al-Salem, S. M., Antelava, A., Constantinou, A., Manos, G., & Dutta, A. (2017). A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). *Journal of Environmental Management*, *197*, 177-198.

Alaranta, J., & Turunen, T. (2021). How to Reach a Safe Circular Economy?—Perspectives on Reconciling the Waste, Product and Chemicals Regulation. *Journal of Environmental Law*, *33*(1), 113-136

Almeida, D., & Marques, M. D. F. (2016). Thermal and catalytic pyrolysis of plastic waste. *Polímeros*, *26*(1), 44-51.

Alvarez-de-los-Mozos, E., & Renteria, A. (2017). Collaborative robots in e-waste management. *Procedia Manufacturing*, *11*, 55-62.

Antelava, A., Damilos, S., Hafeez, S., Manos, G., Al-Salem, S. M., Sharma, B. K., ... & Constantinou, A. (2019). Plastic Solid Waste (PSW) in the context of Life Cycle Assessment (LCA) and sustainable management. *Environmental Management*, *64*(2), 230-244.

Arshad, H., Sulaiman, S. A., Hussain, Z., Naz, Y., & Basrawi, F. (2017). Microwave-assisted pyrolysis of plastic waste for production of fuels: a review. In *MATEC Web of conferences* (Vol. 131, p. 02005). EDP Sciences.

BAMB (2020). *Buildings as material banks*. Retrieved on June 1, 2021, from https://www.bamb2020.eu/.

Barbarias, I., Lopez, G., Artetxe, M., Arregi, A., Bilbao, J., & Olazar, M. (2018). Valorisation of different waste plastics by pyrolysis and in-line catalytic steam reforming for hydrogen production. *Energy Conversion and Management*, *156*, 575-584.

Barbarias, I., Lopez, G., Artetxe, M., Arregi, A., Santamaria, L., Bilbao, J., & Olazar, M. (2016). Pyrolysis and in-line catalytic steam reforming of polystyrene through a two-step reaction system. *Journal of Analytical and Applied Pyrolysis*, *122*, 502-510.

Barnard, E., Arias, J. J. R., & Thielemans, W. (2021). Chemolytic depolymerisation of PET: a review. *Green Chemistry*.

BASF (2021). *Envisioning plastics circularity*. Retrieved on June1, 2021, from https://www.basf.com/ca/en/who-we-are/sustainability/Sustainability-in-Canada/reciChain.html.

BASF (n.d). *From plastic waste to virgin-grade products.* Retrieved on June 1, 2021, from https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy/mass-balance-approach/chemcycling.html.

Beekman, M., Bakker, J.C., Bodar, C.W.M., van Leeuwen, L.C., Waaijers-van der Loop, S.L., Zijp, M.C & Verhoeven, J.K. (2020). *Coping with substances of concern in a circular economy*. https://www.rivm.nl/sites/default/files/2020-05/2020-0049.pdf. Accessed on: 02/06/2021.

Beneroso, D., Monti, T., Kostas, E. T., & Robinson, J. (2017). Microwave pyrolysis of biomass for bio-oil production: Scalable processing concepts. *Chemical Engineering Journal*, *316*, 481-498.

Berg, H., Sebestyén, J., Bendix, P., Le Blevennec, K. & Vrancken, K. (2020). *Digital waste management*. https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-reports/digital-waste-management. Accessed 01/06/2021.

Bernard, A. & Buonsante, V. (2017*). Keeping it clean: How to protect the Circular Economy from hazardous substances.* https://mk0eeborgicuypctuf7e.kinstacdn.com/wp-content/uploads/2019/05/Keeping-it-clean_How-to-protect-the-circular-economy-from-hazardous-substances-2017-3.pdf. Accessed on: 02/06/2021.

Bilsen, V., Kretz, D., Padilla, P., Van Acoleyen, M., Van Ostaeyen, J., Izdebska, O., Hansen, M.E., Bergmans, J. & Szuppinger, P. (2018). *Development and implementation of initiatives fostering investment and innovation in construction and demolition waste recycling infrastructure*. https://op.europa.eu/lt/publication-detail/-/publication/3637d9db-1c3e-11e8-ac73-01aa75ed71a1/language-en. Accessed on: 07/07/2021.

Biron, M. (2018). *Thermoplastics and thermoplastic composites*. William Andrew.

Borrelle, S. B., Ringma, J., Law, K. L., Monnahan, C. C., Lebreton, L., McGivern, A., ... & Rochman, C. M. (2020). Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science*, *369*(6510), 1515-1518.

Bougas, K., Corden, C., Federici, G., Crookes, M. & Fisk, P. (2020). *Scientific and technical support for the development of criteria to identify and group polymers for Registration/Evaluation under REACH and their impact assessment*. https://op.europa.eu/en/publication-detail/-/publication/1cc811ff-d5fc-11ea-adf7-01aa75ed71a1. Accessed on: 07/07/2021.

Bouwmeester, H., Hollman, P. C., & Peters, R. J. (2015). Potential health impact of environmentally released micro-and nano plastics in the human food production chain: experiences from nanotoxicology. *Environmental Science & Technology*, *49*(15), 8932-8947.

Brekke, A., Lyng, K. A., Olofsson, J., & Szulecka, J. (2019). Life cycle assessment: A governance tool for transition towards a circular bioeconomy?. In *From Waste to Value* (pp. 272-292). Routledge.

Briassoulis, D., Pikasi, A., & Hiskakis, M. (2019). End-of-waste life: Inventory of alternative end-of-use recirculation routes of bio-based plastics in the European Union context. *Critical Reviews in Environmental Science and Technology*, *49*(20), 1835-1892

Budsaereechai, S., Hunt, A. J., & Ngernyen, Y. (2019). Catalytic pyrolysis of plastic waste for the production of liquid fuels for engines. *RSC Advances*, *9*(10), 5844-5857.

Cefic (2019). *Cefic's mid-century report 'Molecule Managers'*. https://cefic.org/thought-leadership/mid-century-vision/. Accessed on: 26/03/2021.

Cefic (2020). *Introducing chemical recycling: Plastic waste becoming a resource*. https://cefic.org/app/uploads/2020/03/Cefic-Position-Paper-on-Chemical-Recycling.pdf. Accessed on: 07/05/2021.

CEN-CLC BTWG 11 (2018). *Identification of Potential Needs of Standardisation for 'Sustainable Chemicals' from Primary and Secondary Raw Materials Related to the Circular Economy Action Plan*. https://ftp.cencenelec.eu/EN/News/Brief/2019/SustainableChemicals/FinalReport_BTWG11.pdf. Accessed on: 02/06/2021.

Charitopoulou, M. A., Kalogiannis, K. G., Lappas, A. A., & Achilias, D. S. (2020). Novel trends in the thermo-chemical recycling of plastics from WEEE containing brominated flame retardants. *Environmental Science and Pollution Research*, 1-24.

ChemSafetyPRO (2020). *REACH Annex XVII: REACH Restricted Substance List 2021.* Retrieved on June 1, 2021, from https://www.chemsafetypro.com/Topics/EU/REACH_annex_xvii_REACH_restricted_substance_list.html.

ChemSafetyPro (2021, January 19). REACH SVHC Finder. Retrieved on May 10, 2021, from https://www.chemsafetypro.com/Topics/EU/REACH_SVHC_Finder.html.

Chen, T., Yu, J., Ma, C., Bikane, K., & Sun, L. (2020). Catalytic performance and debromination of Fe–Ni bimetallic MCM-41 catalyst for the two-stage pyrolysis of waste computer casing plastic. *Chemosphere*, *248*, 125964.

Court of Justice of the European Union (2009). Judgment of the Court (Grand Chamber) of 7 July 2009 (Reference for a preliminary ruling from the High Court of Justice (Queen's Bench Division) (United Kingdom) — The Queen, on the application of S.P.C.M. SA, C.H. Erbslöh KG, Lake Chemicals and Minerals Ltd, Hercules Inc. v Secretary of State for the Environment, Food and Rural Affairs (Case C-558/07). *Official Journal of the European Union*, C 205/6.

Court of Justice of the European Union (2017). *Judgment of the Court (First Chamber) of 25 October 2017. Polyelectrolyte Producers Group GEIE (PPG) and SNF SAS v European Chemicals Agency. Appeal — Regulation (EC) No 1907/2006 (REACH) — Article 57 — Substances of very high concern — Identification — Article 2(8)(b) — Exemption — Article 3(15) — Definition of 'intermediate' — Acrylamide. Case C-650/15 P.* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A62015CJ0650. Accessed on: 07/07/2021.

CreaCycle (n. d.). *CreaCycle GmbH – innovative plastic recycling technologies*. Retrieved on May 7, 2021, from https://www.creacycle.de/en/.

Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorsselaer, K., Velis, C. & Wagner, M. (2019) *A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions*. (M. De Smet & M. Linder, Eds.). European Commission, Brussels, Belgium.

Dahlbo, H., Poliakova, V., Mylläri, V., Sahimaa, O., & Anderson, R. (2018). Recycling potential of post-consumer plastic packaging waste in Finland. *Waste Management*, *71*, 52-61.

Dai, L., Zhou, N., Li, H., Wang, Y., Liu, Y., Cobb, K., ... & Ruan, R. (2021). Catalytic fast pyrolysis of low density polyethylene into naphtha with high selectivity by dual-catalyst tandem catalysis. *Science of The Total Environment*, *771*, 144995.

Das, P., Gabriel, J. C. P., Tay, C. Y., & Lee, J. M. (2020). Value-added products from thermochemical treatments of contaminated e-waste plastics. *Chemosphere*, 129409.

Datta, J., & Kopczyńska, P. (2016). From polymer waste to potential main industrial products: Actual state of recycling and recovering. *Critical Reviews in Environmental Science and Technology*, *46*(10), 905-946.

Davidson, M. G., Furlong, R. A., & McManus, M. C. (2021). Developments in the life cycle assessment of chemical recycling of plastic waste–A review. *Journal of Cleaner Production*, 126163.

de Römph, T. J., & Van Calster, G. (2018). REACH in a circular economy: The obstacles for plastics recyclers and regulators. *Review of European, Comparative & International Environmental Law*, *27*(3), 267-277.

Debacker, W. & Manshoven, S. (2016). *D1 Synthesis of the state-ofthe-art. Key barriers and opportunities for Materials Passports and Reversible Building Design in the current system.* https://www.bamb2020.eu/wp-content/uploads/2016/03/D1_Synthesis-report-on-State-of-the-art_20161129_FINAL.pdf. Accessed on: 02/06/2021.

Dogu, O., Pelucchi, M., Van de Vijver, R., Van Steenberge, P. H., D'hooge, D. R., Cuoci, A., ... & Van Geem, K. M. (2021). The chemistry of chemical recycling of solid plastic waste via pyrolysis and gasification: State-of-the-art, challenges, and future directions. *Progress in Energy and Combustion Science*, *84*, 100901.

Dourlens-Quaranta, S., Carbonari, G., De Groote, M., Borragán, G., De Regel, S., Toth, Z., Volt, J., Glicker, J., Lodigiani, A., Marco Calderoni, M., Loureiro, T., Sterling, R., Vandevelde, B., Spirinckx, C., Kondratenko, I., Rajagopalan, N. & Rapf, O. (2020). *Study on the Development of a European Union Framework for Digital Building Logbooks FINAL REPORT*. https://op.europa.eu/en/publication-detail/-/publication/40f40235-509e-11eb-b59f-01aa75ed71a1/language-en/format-PDF/source-search. Accessed on: 02/06/2021.

ECHA (2010). *Guidance on intermediates*. https://echa.europa.eu/documents/10162/23036412/intermediates_en.pdf/0386199a-bdc5-4bbc-9548-0d27ac222641. Accessed on: 02/06/2021.

ECHA (2012). *Guidance for monomers and polymers.* https://echa.europa.eu/documents/10162/23036412/polymers_en.pdf/9a74545f-05be-4e10-8555-4d7cf051bbed. Accessed on: 02/06/2021.

ECHA (2015). *Generic exemptions from authorisation requirements*. https://echa.europa.eu/documents/10162/13640/generic_exemptions_authorisation_en.pdf. Accessed on: 08/07/2021.

ECHA (2016). *Practical guide for SME managers and REACH coordinators How to fulfil your information requirements at tonnages 1-10 and 10-100 tonnes per year.* https://echa.europa.eu/documents/10162/13655/pg_sme_managers_reach_coordinators_en.pdf/1253d9f9-d1f0-4ca8-9e7a-c81e337e3a7d. Accessed on: 02/06/2021.

ECHA (2017). *Registration*. https://echa.europa.eu/documents/10162/23036412/nutshell_guidance_registration_en.pdf/9fda505f-972d-4bbb-b22c-bd71b6941571. Accessed on: 02/06/2021.

ECHA (2017a). *Guidance for identification and naming of substances under REACH and CLP*. https://echa.europa.eu/documents/10162/23036412/substance_id_en.pdf/ee696bad-49f6-4fec-b8b7-2c3706113c7d. Accessed on: 02/06/2021.

ECHA (2017b). *Applications for authorisation under REACH*. https://echa.europa.eu/documents/10162/13637/factsheet_applications_authorisation_en.pdf/8c2fd11c-290b-4caa-b900-272dc8a8fb27. Accessed on: 02/06/2021.

ECHA (2017c). *Guidance on Scientific Research and Development (SR&D) and Product and Process Orientated Research and Development (PPORD)*. https://echa.europa.eu/documents/10162/23036412/ppord_en.pdf/22a12900-ad27-454c-aedd-82972ef2f675. Accessed on: 02/06/2021.

ECHA (2018). *Annex to the Background Document to the Opinion on the Annex XV dossier proposing restrictions on Lead compounds-PVC.* https://echa.europa.eu/documents/10162/f278e9fd-c5ba-50fa-528d-3923821e0b32. Accessed on: 01/06/2021.

ECHA (2019). *Report on the pilot project on cooperation with customs in enforcement of REACH restrictions and CLP labelling*. https://echa.europa.eu/documents/10162/13555/customs2_project_report_en.pdf/5a2c3795-7ed9-5900-fe28-540228abc7c1. Accessed on: 07/07/2021.

ECHA (2021). *Guidance on the preparation of an application for authorisation*. https://echa.europa.eu/documents/10162/13643/authorisation_application_en.pdf. Accessed on: 08/07/2021.

ECHA (n.d.). *Authorisation*. Retrieved on June 2, 2021, from https://echa.europa.eu/substances-of-very-high-concern-identification-explained.

ECHA (n.d.a). *Restriction*. Retrieved on June 2, 2021, from https://echa.europa.eu/regulations/reach/restriction.

ECHA (n.d.b). *Mapping exercise – Plastic additives initiative*. Retrieved on June 2, 2021, from https://echa.europa.eu/mapping-exercise-plastic-additives-initiative#table.

ECHA (n.d.c). *What is not a substance?* Retrieved on June 2, 2021, from https://echa.europa.eu/support/substance-identification/what-is-not-a-substance.

ECHA (n.d.d). *Authorisation process.* Retrieved on July 7, 2021, from https://echa.europa.eu/authorisation-process.

Enerkem (n.d.). *Waste Hierarchy*. Retrieved on July 7, 2021, from https://enerkem.com/feedstock/waste-hierarchy/.

Eriksen, M. K., Damgaard, A., Boldrin, A., & Astrup, T. F. (2019). Quality assessment and circularity potential of recovery systems for household plastic waste. *Journal of Industrial Ecology*, *23*(1), 156-168.

Eunomia Research & Consulting Ltd, COWI, Adelphi, Ecofys (Navigant), Milieu (2020). *Effectiveness of the Essential Requirements for Packaging and Packaging Waste and Proposals for Reinforcement*. https://op.europa.eu/en/publication-detail/-/publication/05a3dace-8378-11ea-bf12-01aa75ed71a1. Accessed on: 07/07/2021.

European Commission (2011). COMMISSION REGULATION (EU) No 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food. *Official Journal of the European Union,* 12, 1-89. https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:012:0001:0089:EN:PDF. Accessed on: 02/06/2021.

European Commission (2013). COMMISSION RECOMMENDATION of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations. *Official Journal of the European Union,* 124, 1-210. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013H0179&from=EN. Accessed on: 02/06/2021.

European Commission (2018). Commission notice on technical guidance on the classification of waste. *Official Journal of the European Union*, 124, 1-134. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018XC0409(01)&from=EN. Accessed on: 02/06/2021.

European Commission (2018a). *Communication on the implementation of the circular economy package: options to address the interface between chemical, product and waste legislation*. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0032&from=EN. Accessed on: 26/03/2020.

European Commission (2018b). *Commission Staff Working Document accompanying the document 'Communication on the implementation of the circular economy package: options to address the interface between chemical, product and waste legislation*. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018SC0020&from=EN. Accessed on: 26/03/2021.

European Commission (2018c). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A European Strategy for Plastics in a Circular Economy. https://eur-lex.europa.eu/resource.html?uri=cellar:2df5d1d2-fac7-11e7-b8f5-01aa75ed71a1.0001.02/DOC_1&format=PDF. Accessed on: 08/07/2021.

European Commission (2018d). *Directive of the European Parliament and of the Council on the reduction of the impact of certain plastic products on the environment*. https://eur-lex.europa.eu/resource.html?uri=cellar:fc5c74e0-6255-11e8-ab9c-01aa75ed71a1.0002.02/DOC_1&format=PDF. Accessed on: 25/03/2021.

European Commission (2020). *Circular Economy Action Plan*. https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf. Accessed on: 26/03/2021.

European Commission (2020a). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS A new Circular Economy Action Plan For a cleaner and more competitive Europe. https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF. Accessed on: 02/06/2021.

European Commission (2021). COMMISSION STAFF WORKING DOCUMENT EVALUATION of Directive (EC) 2000/53 of 18 September 2000 on end-of-life vehicles SWD/2021/0060 final. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021SC0060&from=en. Accessed on: 07/07/2021.

European Commission (n.d.). *What does a circular economy mean?* Retrieved on June 4, 2021, from https://ec.europa.eu/info/research-and-innovation/research-area/environment/circular-economy/circular-economy-strategy_en.

European Commission (n.d.a). *Persistant Organic Pollutants (POPs).* Retrieved on June 2, 2021, from https://ec.europa.eu/environment/chemicals/international_conventions/index_en.htm.

European Commission (n.d.b). *Waste Framework Directive*. Retrieved on July 7, 2021, from https://ec.europa.eu/environment/topics/waste-and-recycling/waste-framework-directive_en.

European Commission (n.d.c). *End-of-Life Vehicles*. Retrieved on July 7, 2021, from https://ec.europa.eu/environment/topics/waste-and-recycling/end-life-vehicles_en.

European Environment Agency (2019, October 28). *The plastic waste trade in the circular economy.* Retrieved on March 16, 2021, from https://www.eea.europa.eu/publications/the-plastic-waste-trade-in/the-plastic-waste-trade-in.

European Parliament (2006). REGULATION (EC) No 1013/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 June 2006 on shipments of waste. *Official Journal of the European Union,* 190, 1-98. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32006R1013&from=EN. Accessed on: 02/06/2021.

European Parliament (2006a). REGULATION (EC) No 1907/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC. *Official Journal of the European Union,* 396, 1-849. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02006R1907-20140410&from=EN. Accessed on: 02/06/2021.

European Parliament (2008). DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives. *Official Journal of the European Union*, 312, 3-30. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN. Accessed on: 02/06/2021.

European Parliament (2009). Directive 2009/48/EC of the European Parliament and of the Council of 18 June 2009 on the safety of toys (Text with EEA relevance). *Official Journal of the European Union*, 170, 1-37. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0048&from=EN. Accessed on: 08/07/2021.

European Parliament (2010). DIRECTIVE 2010/75/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 24 November 2010 on industrial emissions (integrated pollution prevention and control). *Official Journal of the European Union*, 334, 17-119. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02010L0075-20110106&from=EN. Accessed on: 02/06/2021.

European Parliament (2011). Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment Text with EEA relevance. *Official Journal of the European Union*, 174, 88-110. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011L0065&from=en. Accessed on: 08/07/2021.

European Parliament (2011a). Commission Regulation (EU) No 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food Text with EEA relevance. *Official Journal of the European Union*, 12, 1-89. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32011R0010&from=EN. Accessed on: 08/07/2021.

European Parliament (2018). Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance). *Official Journal of the European Union*, 312, 3-30. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02008L0098-20180705&from=EN. Accessed on: 07/07/2021.

European Parliament (2018a). European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste. *Official Journal of the European Union*, 365, 10-23. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01994L0062-20180704&from=EN. Accessed on: 07/07/2021.

European Parliament (2019). REGULATION (EU) 2019/1021 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 20 June 2019 on persistent organic pollutants. *Official Journal of the European Union,* 169, 45-77. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02019R1021-20210222. Accessed on: 02/06/2021.

European Parliament (2019a). Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment (Text with EEA relevance). *Official Journal of the European Union,* 155, 1-19*.* https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019L0904#:~:text=(1)%20'plastic'%20means,which%20can%20function%20as%20a. Accessed on: 08/07/2021.

European Parliament (2020). Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles - Commission Statements. *Official Journal of the European Union*, 269, 34-43. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000L0053-20200306&from=EN. Accessed on: 07/07/2021.

European Parliament (2021). Consolidated text: Regulation (EC) No 1935/2004 of the European Parliament and of the Council of 27 October 2004 on materials and articles intended to come into contact with food and repealing Directives 80/590/EEC and 89/109/EEC. *Official Journal of the European Union*, 338, 4-17. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02004R1935-20210327&from=EN. Accessed on: 08/07/2021.

Eurostat (n. d.). *Guidance on the interpretation of the term backfilling*. https://ec.europa.eu/eurostat/documents/342366/4953052/Guidance-on-Backfilling.pdf/c18d330c-97f2-4f8c-badd-ba446491b47e. Accessed on: 26/07/2021.

Eurostat (2020). *Waste statistics*. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation. Accessed on 02/06/2021.

Evangelopoulos, P., Arato, S., Persson, H., Kantarelis, E., & Yang, W. (2019). Reduction of brominated flame retardants (BFRs) in plastics from waste electrical and electronic equipment (WEEE) by solvent extraction and the influence on their thermal decomposition. *Waste Management*, *94*, 165-171.

Evangelopoulos, P., Persson, H., Kantarelis, E., & Yang, W. (2020). Performance analysis and fate of bromine in a single screw reactor for pyrolysis of waste electrical and electronic equipment (WEEE). *Process Safety and Environmental Protection*, *143*, 313-321.

Faraca, G., & Astrup, T. (2019). Plastic waste from recycling centres: Characterisation and evaluation of plastic recyclability. *Waste Management*, *95*, 388-398.

Fekhar, B., Gombor, L., & Miskolczi, N. (2019). Pyrolysis of chlorine contaminated municipal plastic waste: In-situ upgrading of pyrolysis oils by Ni/ZSM-5, Ni/SAPO-11, red mud and Ca (OH) 2 containing catalysts. *Journal of the Energy Institute*, *92*(5), 1270-1283.

Fivga, A., & Dimitriou, I. (2018). Pyrolysis of plastic waste for production of heavy fuel substitute: A techno-economic assessment. *Energy*, *149*, 865-874.

Friege, H., Kummer, B., Steinhäuser, K. G., Wuttke, J., & Zeschmar-Lahl, B. (2019). How should we deal with the interfaces between chemicals, product and waste legislation?. *Environmental Sciences Europe*, *31*(1), 1-18.

Friege, H., Zeschmar-Lahl, B., Kummer, B., & Wagner, J. (2021). The new European database for chemicals of concern: How useful is SCIP for waste management?. *Sustainable Chemistry and Pharmacy*, *21*, 100430.

Garrido, M. A., Font, R., & Conesa, J. A. (2016). Pollutant emissions during the pyrolysis and combustion of flexible polyurethane foam. *Waste Management*, *52*, 138-146.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Science Advances*, *3*(7), e1700782.

Giacovelli, C. (2018). *Single-use plastics: a road for sustainability*. https://wedocs.unep.org/handle/20.500.11822/25496. Accessed on: 25/03/2021.

Gligoric, N., Krco, S., Hakola, L., Vehmas, K., De, S., Moessner, K., ... & Van Kranenburg, R. (2019). Smarttags: IoT product passport for circular economy based on printed sensors and unique item-level identifiers. *Sensors*, *19*(3), 586.

Guest, G., Bunce, A., & Johnson, L. (2006). How many interviews are enough? An experiment with data saturation and variability. *Field Methods*, *18*(1), 59-82.

Hahladakis, J. N., & Iacovidou, E. (2018). Closing the loop on plastic packaging materials: What is quality and how does it affect their circularity?. *Science of the Total Environment*, *630*, 1394-1400.

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.

Hann, S. & Connock, T. (2020). *Chemical Recycling: State of Play.* https://chemtrust.org/wp-content/uploads/Chemical-Recycling-Eunomia.pdf. Accessed on: 02/06/2021.

HBM4EU (2021). *HBM4EU Priority Substances*. https://www.hbm4eu.eu/the-substances/lead/. Accessed on 01/06/2021.

He, Z., Li, G., Chen, J., Huang, Y., An, T., & Zhang, C. (2015). Pollution characteristics and health risk assessment of volatile organic compounds emitted from different plastic solid waste recycling workshops. *Environment International*, *77*, 85-94.

Heinrich, M. & Lang, W. (2019). *Materials passports – best practice*. https://www.bamb2020.eu/wp-content/uploads/2019/02/BAMB_MaterialsPassports_BestPractice.pdf. Accessed on: 02/06/2021.

Hennebert, P., & Filella, M. (2018). WEEE plastic sorting for bromine essential to enforce EU regulation. *Waste Management*, *71*, 390-399.

Hestin, M., Mitsios, A., Ait Said, S., Fouret, F., Berwald, A. & Senlis, V. (2017). *Blueprint for plastic packaging waste: quality sorting and recycling*. https://www2.deloitte.com/content/dam/Deloitte/my/Documents/risk/my-risk-blueprint-plastics-packaging-waste-2017.pdf. Accessed on: 25/03/2021.

Ho, H. J., Iizuka, A., & Shibata, E. (2020). Chemical recycling and use of various types of concrete waste: A review. *Journal of Cleaner Production*, 124785.

Hong, M., & Chen, E. Y. X. (2017). Chemically recyclable polymers: a circular economy approach to sustainability. *Green Chemistry*, *19*(16), 3692-3706.

Hoosain, M. S., Paul, B. S., Raza, S. M., & Ramakrishna, S. (2021). Material Passports and Circular Economy. In *An Introduction to Circular Economy* (pp. 131-158). Springer, Singapore.

Horodytska, O., Valdés, F. J., & Fullana, A. (2018). Plastic flexible films waste management–A state of art review. *Waste Management*, *77*, 413-425.

Huijbregts, M. A., Steinmann, Z. J., Elshout, P. M., Stam, G., Verones, F., Vieira, M., ... & van Zelm, R. (2017). ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *The International Journal of Life Cycle Assessment*, *22*(2), 138-147.

International Organization for Standardization (2006). *Environmental management — Life cycle assessment — Principles and framework (ISO 14040:2006).* https://www.iso.org/standard/37456.html. Accessed on: 02/06/2021.

International Organization for Standardization (2006a). *Environmental management — Life cycle assessment —Requirements and guidelines (ISO 14044:2006)*. https://www.iso.org/standard/38498.html. Accessed on: 07/06/2021.

International Organization for Standardization (2006b). *Environmental labels and declarations — Type III environmental declarations — Principles and procedures (ISO 14025:2006). https://www.iso.org/standard/38131.html.* Accessed on: 08/07/2021.

International Organization for Standardization (2008). *Plastics – guidelines for the recovery and recycling of plastic waste (ISO 15270:2008)*. https://www.iso.org/standard/45089.html. Accessed on: 07/05/2021.

International Organization for Standardization (2013). *Plastics – Vocabulary (ISO 472:2013).* https://www.iso.org/standard/44102.html. Accessed on: 04/06/2021.

International Organization for Standardization (2020). *Blockchain and distributed ledger technologies — Vocabulary (ISO 22739:2020(en)).* https://www.iso.org/obp/ui/#iso:std:iso:22739:ed-1:v1:en. Accessed on: 04/06/2021.

IUPAC (2021). *Pyrolysis.* In Compendium of Chemical Terminology, 2nd ed. (the "Gold Book"). Compiled by A. D. McNaught and A. Wilkinson. Blackwell Scientific Publications, Oxford (1997). Online version (2019-) created by S. J. Chalk. ISBN 0-9678550-9-8. https://goldbook.iupac.org/terms/view/P04961. Accessed on: 07/07/2021.

Janssen, M. P. M., & van Broekhuizen, F. A. (2017). *Waste handling and REACH: Recycling of materials containing SVHCs: daily practice challenges.* https://www.rivm.nl/bibliotheek/rapporten/2016-0159.pdf. Accessed on: 02/06/2021.

Janssen, M. P. M., Spijker, J., Lijzen, J. P. A., & Wesselink, L. G. (2016). *Plastics that contain hazardous substances: recycle or incinerate?* https://www.rivm.nl/bibliotheek/rapporten/2016-0025.pdf. Accessed on: 02/06/2021.

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.

Ji, M., Chen, L., Que, J., Zheng, L., Chen, Z., & Wu, Z. (2020). Effects of transition metal oxides on pyrolysis properties of PVC. *Process Safety and Environmental Protection*, *140*, 211-220.

Joint Research Centre (2018). *Best Available Techniques (BAT) Reference Document for Waste treatment Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control); EUR 29362 EN; Publications Office of the European Union, Luxembourg.* https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/JRC113018_WT_Bref.pdf. Accessed on: 01/06/2021.

Joint Research Centre (2019). *Best Available Techniques (BAT) Reference Document for Waste Incineration. Publications Office of the European Union: Luxembourg.* https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC118637_WI_Bref_2019_published_0.pdf. Accessed on: 01/06/2021.

KEMI (2015). *Tillsyn 5/16. Tillsyn av plastvaror 2015*. Swedish Chemicals Agency. https://www.kemi.se/en/publications/enforcement-reports/2016/tillsyn-5-16-tillsyn-av-plastvaror-2015. Accessed on: 02/06/2021.

Kousaiti, A., Hahladakis, J.N., Savvilotidou, V., Pivnenko, K., Tyrovola, K., Xekoukoulotakis, N., Astrup, T.F. and Gidarakos, E. (2020). Assessment of tetrabromobisphenol-A (TBBPA) content in plastic waste recovered from WEEE. *Journal of Hazardous Materials*, *390*, 121641.

Kristoffersen, E., Blomsma, F., Mikalef, P., & Li, J. (2020). The smart circular economy: A digital-enabled circular strategies framework for manufacturing companies. *Journal of Business Research*, *120*, 241-261.

Lahtela, V., Hyvärinen, M., & Kärki, T. (2019). Composition of plastic fractions in waste streams: Toward more efficient recycling and utilization. *Polymers*, *11*(1), 69.

Larrain, M., Van Passel, S., Thomassen, G., Kresovic, U., Alderweireldt, N., Moerman, E., & Billen, P. (2020). Economic performance of pyrolysis of mixed plastic waste: Open-loop versus closed-loop recycling. *Journal of Cleaner Production*, *270*, 122442.

Lau, W. W., Shiran, Y., Bailey, R. M., Cook, E., Stuchtey, M. R., Koskella, J., Velis, C.A., Godfrey, L., Boucher, J., Murphy, M.B. and Thompson, R.C. (2020). Evaluating scenarios toward zero plastic pollution. *Science*, *369*(6510), 1455-1461.

Lazarevic, D. (2018). The legitimacy of life cycle assessment in the waste management sector. *The International Journal of Life Cycle Assessment*, *23*(7), 1415-1428.

Lebreton, L., & Andrady, A. (2019). Future scenarios of global plastic waste generation and disposal. *Palgrave Communications*, *5*(1), 1-11.

Lee, A., & Liew, M. S. (2020). Tertiary recycling of plastics waste: an analysis of feedstock, chemical and biological degradation methods. *Journal of Material Cycles and Waste Management*, 1-12.

Leslie, H. A., Leonards, P. E. G., Brandsma, S. H., De Boer, J., & Jonkers, N. (2016). Propelling plastics into the circular economy—weeding out the toxics first. *Environment International*, *94*, 230-234.

Li, X., Wu, P., Shen, G. Q., Wang, X., & Teng, Y. (2017). Mapping the knowledge domains of Building Information Modeling (BIM): A bibliometric approach. *Automation in Construction*, *84*, 195-206.

Linares, V., Bellés, M., & Domingo, J. L. (2015). Human exposure to PBDE and critical evaluation of health hazards. *Archives of Toxicology*, *89*(3), 335-356.

Liu, P., Farzana, R., Rajarao, R., & Sahajwalla, V. (2017). Lightweight expanded aggregates from the mixture of waste automotive plastics and clay. *Construction and Building Materials*, *145*, 283-291.

Lopez, G., Artetxe, M., Amutio, M., Alvarez, J., Bilbao, J., & Olazar, M. (2018). Recent advances in the gasification of waste plastics. A critical overview. *Renewable and Sustainable Energy Reviews*, *82*, 576-596.

Lopez, G., Artetxe, M., Amutio, M., Bilbao, J., & Olazar, M. (2017). Thermochemical routes for the valorization of waste polyolefinic plastics to produce fuels and chemicals. A review. *Renewable and Sustainable Energy Reviews*, *73*, 346-368.

Luo, Y., & Deng, K. (2021, February). Sustainable Fashion Innovation Design for Marine Litter. In *Journal of Physics: Conference Series* (Vol. 1790, No. 1, p. 012098). IOP Publishing.

Lyche, J. L., Rosseland, C., Berge, G., & Polder, A. (2015). Human health risk associated with brominated flame-retardants (BFRs). *Environment International*, *74*, 170-180.

Ma, C., Yu, J., Wang, B., Song, Z., Xiang, J., Hu, S., Su, S. and Sun, L., (2016). Chemical recycling of brominated flame retarded plastics from e-waste for clean fuels production: A review. *Renewable and Sustainable Energy Reviews*, *61*, 433-450.

Madaster (n.d.). *Madaster – the digital library of materials*. https://madaster.com/. Accessed on 02/06/2021.

Meys, R., Frick, F., Westhues, S., Sternberg, A., Klankermayer, J., & Bardow, A. (2020). Towards a circular economy for plastic packaging wastes–the environmental potential of chemical recycling. *Resources, Conservation and Recycling*, *162*, 105010.

Miandad, R., Barakat, M. A., Aburiazaiza, A. S., Rehan, M., & Nizami, A. S. (2016). Catalytic pyrolysis of plastic waste: A review. *Process Safety and Environmental Protection*, *102*, 822-838.

Miandad, R., Barakat, M. A., Aburiazaiza, A. S., Rehan, M., Ismail, I. M. I., & Nizami, A. S. (2017). Effect of plastic waste types on pyrolysis liquid oil. *International Biodeterioration & Biodegradation*, *119*, 239-252.

Miandad, R., Rehan, M., Barakat, M. A., Aburiazaiza, A. S., Khan, H., Ismail, I. M., ... & Nizami, A. S. (2019). Catalytic pyrolysis of plastic waste: moving toward pyrolysis based biorefineries. *Frontiers in energy research*, *7*, 27.

Miandad, R., Rehan, M., Nizami, A. S., Barakat, M. A. E. F., & Ismail, I. M. (2016a). The energy and value-added products from pyrolysis of waste plastics. *Recycling of Solid Waste for Biofuels and Bio-chemicals*, 333-355.

Minkov, N., Schneider, L., Lehmann, A., & Finkbeiner, M. (2015). Type III environmental declaration programmes and harmonization of product category rules: status quo and practical challenges. *Journal of Cleaner Production*, *94*, 235-246.

Möllnitz, S. et al. (2021). Processability of Different Polymer Fractions Recovered from Mixed Wastes and Determination of Material Properties for Recycling. *Polymers*, *13*(3), 457.

Mrowiec, B. (2018). Plastics in the circular economy (CE). *Environmental Protection and Natural Resources; The Journal of Institute of Environmental Protection-National Research Institute.*, *29*(4), 16-19.

Munir, D., Irfan, M. F., & Usman, M. R. (2018). Hydrocracking of virgin and waste plastics: A detailed review. *Renewable and Sustainable Energy Reviews*, *90*, 490-515.

Munir, M. T., Mardon, I., Al-Zuhair, S., Shawabkeh, A., & Saqib, N. U. (2019). Plasma gasification of municipal solid waste for waste-to-value processing. *Renewable and Sustainable Energy Reviews*, *116*, 109461.

Nisar, J.; Ali, G.; Shah, A.; Iqbal, M.; Khan, R. A.; Sirajuddin, F.; Anwar, F.; Ullah, R.; Akhter, M. S. (2019). Fuel production from waste polystyrene via pyrolysis: Kinetics and products distribution. *Waste Manage, 88,* 236−247.

Norin, H., Oskarsson, H., Brodin, M., Halling, M. & Sallermo, R. (2020). *Review of techniques for detection, quantification and removal*. Report 6938. https://www.naturvardsverket.se/Documents/publ-filer/6900/978-91-620-6938-4.pdf?pid=27480. Accessed on: 26/03/2021.

Ökopol, Sofia & RPA (2020). *Information flows on substances of concern in products from supply chains to waste operators.* https://op.europa.eu/en/publication-detail/-/publication/59d9b462-a9f6-11ea-bb7a-01aa75ed71a1/language-en. Accessed on: 01/06/2021.

Oleszek, S., Kumagai, S., Grabda, M., Shiota, K., Yoshioka, T., & Takaoka, M. (2021). Mitigation of bromine-containing products during pyrolysis of polycarbonate-based tetrabromobisphenol A in the presence of copper (I) oxide. *Journal of Hazardous Materials*, *409*, 124972.

Pagoropoulos, A., Pigosso, D. C., & McAloone, T. C. (2017). The emergent role of digital technologies in the Circular Economy: A review. *Procedia CIRP*, *64*, 19-24.

Paladino, O. and Moranda, A. (2021). Human Health Risk Assessment of a pilot-plant for catalytic pyrolysis of mixed waste plastics for fuel production. *Journal of Hazardous Materials*, *405*, p.124222.

Patel, D., Moon, D., Tangri, N., Wilson, M. (2020). *All Talk and No Recycling: An Investigation of the U.S. "Chemical Recycling" Industry.* Global Alliance for Incinerator Alternatives. https://www.no-burn.org/chemical-recycling-us/. Accessed on: 26/03/2021.

Pilát, P., & Patsch, M. (2020). Possibilities of Energy Utilization of Waste from the Automotive Industry at Present. In *MATEC Web of Conferences* (Vol. 328). EDP Sciences.

PlasticsEurope (2016). *Plastics – the Facts 2016.* https://www.plasticseurope.org/application/files/4315/1310/4805/plastic-the-fact-2016.pdf. Accessed on: 25/03/2021.

PlasticsEurope (2017). *Plastics – the Facts 2017.* https://www.plasticseurope.org/application/files/5715/1717/4180/Plastics_the_facts_2017_FINAL_for_website_one_page.pdf. Accessed on: 25/03/2021.

PlasticsEurope (2018). *Plastics – the Facts 2018.* https://www.plasticseurope.org/application/files/6315/4510/9658/Plastics_the_facts_2018_AF_web.pdf. Accessed on: 25/03/2021.

PlasticsEurope (2019). *Plastics – the Facts 2019.* https://www.plasticseurope.org/application/files/9715/7129/9584/FINAL_web_version_Plastics_the_facts2019_14102019.pdf. Accessed on: 25/03/2021.

PlasticsEurope (2019a). *The Circular Economy for Plastics. A European Overview.* https://www.plasticseurope.org/en/resources/publications/1899-circular-economy-plastics-european-overview. Accessed on: 08/07/2021.

PlasticsEurope (2020). *Plastics – the Facts 2020.* https://www.plasticseurope.org/en/resources/publications/4312-plastics-facts-2020. Accessed on: 25/03/2021.

Platform CB'23 (2020). *Passports for the Construction Sector Working agreements for circular construction.* https://platformcb23.nl/images/downloads/Platform_CB23_Guide_Passports_for_the_construction_sector_2.0.pdf. Accessed on: 02/06/2021.

Quantis (2020). *Chemical recycling: greenhouse gas emission reduction potential of an emerging waste management route*. https://cefic.org/app/uploads/2020/12/CEFIC_Quantis_report_final.pdf. Accessed on: 26/03/2021.

Qureshi, M. S., Oasmaa, A., Pihkola, H., Deviatkin, I., Tenhunen, A., Mannila, J., Minkkinen, H., Pohjakallio, M. & Laine-Ylijoki, J. (2020). Pyrolysis of plastic waste: opportunities and challenges. *Journal of Analytical and Applied Pyrolysis*, *152*, 104804.

Ragaert, K., Delva, L., & Van Geem, K. (2017). Mechanical and chemical recycling of solid plastic waste. *Waste Management*, *69*, 24-58.

Ragaert, K., Hubo, S., Delva, L., Veelaert, L., & Du Bois, E. (2018). Upcycling of contaminated post-industrial polypropylene waste: A design from recycling case study. *Polymer Engineering & Science*, *58*(4), 528-534.

Ragaert, K., Huysveld, S., Vyncke, G., Hubo, S., Veelaert, L., Dewulf, J., & Du Bois, E. (2020). Design from recycling: A complex mixed plastic waste case study. *Resources, Conservation and Recycling*, *155*, 104646.

Rašković, M., Ragossnig, A. M., Kondracki, K., & Ragossnig-Angst, M. (2020). Clean construction and demolition waste material cycles through optimised pre-demolition waste audit documentation: A review on building material assessment tools. *Waste Management & Research*, *38*(9), 923-941.

Recycling Technologies (n.d.). *Technology.* https://recyclingtechnologies.co.uk/technology/. Accessed on 01/06/2021.

Rex, P., Masilamani, I. P., & Miranda, L. R. (2020). Microwave pyrolysis of polystyrene and polypropylene mixtures using different activated carbon from biomass. *Journal of the Energy Institute*, *93*(5), 1819-1832.

Riedewald, F., Patel, Y., Wilson, E., Santos, S., & Sousa-Gallagher, M. (2021). Economic assessment of a 40,000 t/y mixed plastic waste pyrolysis plant using direct heat treatment with molten metal: A case study of a plant located in Belgium. *Waste Management*, *120*, 698-707.

Rollinson, A. & Oladejo, J. (2020). *Chemical Recycling: Status, Sustainability, and Environmental Impacts.* Global Alliance for Incinerator Alternatives. https://www.breakfreefromplastic.org/bffp_reports/chemical-recycling-status-sustainability-and-environmental-impacts/. Accessed on: 08/07/2021.

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research*, *57*(7), 2117-2135.

Santaweesuk, C. & Janyalertadun, A., 2017. The production of fuel oil by conventional slow pyrolysis using plastic waste from a municipal landfill. *International Journal of Environmental Science and Development, 8*(3), p.168.

Sarc, R., Curtis, A., Kandlbauer, L., Khodier, K., Lorber, K. E., & Pomberger, R. (2019). Digitalisation and intelligent robotics in value chain of circular economy oriented waste management–A review. *Waste Management*, *95*, 476-492.

Schlegel, I. (2020). *Deception by numbers*. Greenpeace. https://www.greenpeace.org/usa/wp-content/uploads/2020/09/GP_Deception-by-the-Numbers-3.pdf. Accessed on: 26/03/2021.

Schmidt, A. (2016). *Gaining benefits from discarded textiles: LCA of different treatment pathways*. Nordic Council of Ministers. https://norden.diva-portal.org/smash/get/diva2:957517/FULLTEXT02.pdf. Accessed on: 02/06/2021.

Schwabl, D., Bauer, M., & Lehner, M. (2021). Advancing Plastic Recycling by Wet-Mechanical Processing of Mixed Waste Fractions. *Processes*, *9*(3), 493.

Schwarz, A. E., Ligthart, T. N., Bizarro, D. G., De Wild, P., Vreugdenhil, B., & van Harmelen, T. (2021). Plastic recycling in a circular economy; determining environmental performance through an LCA matrix model approach. *Waste Management*, *121*, 331-342.

Sethi, B. (2016). Methods of recycling. In *Recycling of polymers: methods, characterization and applications*. Edited by Raju Francis. John Wiley & Sons.

Sharkey, M., Abdallah, M. A. E., Drage, D. S., Harrad, S., & Berresheim, H. (2018). Portable X-ray fluorescence for the detection of POP-BFRs in waste plastics. *Science of The Total Environment*, *639*, 49-57.

Sharuddin, S. D. A., Abnisa, F., Daud, W. M. A. W., & Aroua, M. K. (2016). A review on pyrolysis of plastic wastes. *Energy Conversion and Management*, *115*, 308-326

Shehu, S. (2017). Separation of plastic waste from mixed waste: Existing and emerging sorting technologies performance and possibilities of increased recycling rate with Finland as case study.

Shen, Y., Chen, X., Ge, X., & Chen, M. (2018). Chemical pyrolysis of E-waste plastics: char characterization. *Journal of Environmental Management*, *214*, 94-103.

Shuaib, N. A., & Mativenga, P. T. (2016). Energy demand in mechanical recycling of glass fibre reinforced thermoset plastic composites. *Journal of Cleaner Production*, *120*, 198-206.

Simón, D., Borreguero, A. M., De Lucas, A., & Rodríguez, J. F. (2018). Recycling of polyurethanes from laboratory to industry, a journey towards the sustainability. *Waste Management*, *76*, 147-171.

Simon, J.M., Rosa, F., Allen, C., Wilson, M., Moon, D. (2018). *Changing trends in plastic waste trade Plastic Waste shipments report.* Zero Waste Europe. https://zerowasteeurope.eu/wp-content/uploads/2019/11/zero_waste_europe_report_changing_trends_in_plastic_waste_en.pdf. Accessed on: 18/03/2021.

Soler, A., Conesa, J. A., & Ortuño, N. (2017). Emissions of brominated compounds and polycyclic aromatic hydrocarbons during pyrolysis of E-waste debrominated in subcritical water. *Chemosphere*, *186*, 167-176.

Solis, M., & Silveira, S. (2020). Technologies for chemical recycling of household plastics–A technical review and TRL assessment. *Waste Management*, *105*, 128-138.

Stenmarck, Å., Belleza, E. L., Fråne, A., & Busch, N. (2017). *Hazardous substances in plastics:–ways to increase recycling*. https://norden.diva-portal.org/smash/get/diva2:1070548/FULLTEXT01.pdf. Accessed on: 02/06/2021.

Sun, B., Hu, Y., Cheng, H., & Tao, S. (2016). Kinetics of brominated flame retardant (BFR) releases from granules of waste plastics. *Environmental Science & Technology*, *50*(24), 13419-13427.

Tabrizi, S., Rollinson, A.N., Hoffmann, M. & Favoino, E. (2020). *Understanding the environmental impacts of chemical recycling: ten concerns with existing life cycle assessments*. https://zerowasteeurope.eu/library/understanding-the-environmental-impacts-of-chemical-recycling-ten-concerns-with-existing-life-cycle-assessments/. Accessed on: 13/05/2021.

Taylor, P., Steenmans, K., & Steenmans, I. (2020). Blockchain Technology for Sustainable Waste Management. *Frontiers in Political Science*, *2*, 15.

Thomassen, G., Van Dael, M., Van Passel, S., & You, F. (2019). How to assess the potential of emerging green technologies? Towards a prospective environmental and techno-economic assessment framework. *Green Chemistry*, *21*(18), 4868-4886.

Torres, D., Jiang, Y., Sanchez-Monsalve, D. A., & Leeke, G. A. (2020). Hydrochloric acid removal from the thermogravimetric pyrolysis of PVC. *Journal of Analytical and Applied Pyrolysis*, *149*, 104831.

United Nations Environmental Programme (2019). *Stockholm convention on persistent environmental pollutants*. http://www.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx. Accessed on: 08/07/2021.

Van Dael, M., Kuppens, T., Lizin, S., & Van Passel, S. (2015). Techno-economic assessment methodology for ultrasonic production of biofuels. In *Production of biofuels and chemicals with ultrasound* (pp. 317-345). Springer, Dordrecht.

Veksha, A., Giannis, A., Oh, W. D., Chang, V. W. C., & Lisak, G. (2018). Upgrading of non-condensable pyrolysis gas from mixed plastics through catalytic decomposition and dechlorination. *Fuel Processing Technology*, *170*, 13-20.

Volk, R., Stallkamp, C., Steins, J. J., Yogish, S. P., Müller, R. C., Stapf, D., & Schultmann, F. (2021). Techno-economic assessment and comparison of different plastic recycling pathways: A German case study. *Journal of Industrial Ecology*.

Vollmer, I., Jenks, M.J., Roelands, M.C., White, R.J., van Harmelen, T., de Wild, P., van Der Laan, G.P., Meirer, F., Keurentjes, J.T. and Weckhuysen, B.M. (2020). Beyond mechanical recycling: Giving new life to plastic waste. *Angewandte Chemie International Edition*, *59*(36), 15402-15423.

Volt, J., Toth, Z., Glicker, J., De Groote, M., Borragán, G., & De Regel, S., Dourlens-Quaranta, S. & Carbonari, G. (2020). *Definition of the digital building logbook. Report 1 of the study on the development of a European Union framework for buildings' digital logbook.* https://op.europa.eu/en/publication-detail/-/publication/cacf9ee6-06ba-11eb-a511-01aa75ed71a1/language-en/format-PDF/source-search. Accessed on: 08/07/2021.

Vox, G., Loisi, R. V., Blanco, I., Mugnozza, G. S., & Schettini, E. (2016). Mapping of agriculture plastic waste. *Agriculture and Agricultural Science Procedia*, *8*, 583-591.

Wagner, S., & Schlummer, M. (2020). Legacy additives in a circular economy of plastics: Current dilemma, policy analysis, and emerging countermeasures. *Resources, Conservation and Recycling*, *158*, 104800.

Wajima, T., Hlaing, Z. Z., Saito, A., & Nakagome, H. (2015). Removal of bromine from pyrolysis oil with NaOH in a reflux condenser system. *Journal of Multidisciplinary Engineering Science and Technology*, *2*(5), 1201-1204.

Wassenaar, P. N. H., Janssen, N., de Poorter, L. R. M., & Bodar, C. W. M. (2017). *Substances of very high concern and the transition to a circular economy: An initial inventory*. https://www.rivm.nl/bibliotheek/rapporten/2017-0071.pdf. Accessed on: 02/06/2021.

Weiland, F., Lundin, L., Celebi, M., van der Vlist, K., & Moradian, F. (2021). Aspects of chemical recycling of complex plastic waste via the gasification route. *Waste Management*, *126*, 65-77.

Westerholm, N. (2020). *State of Play for Circular Built Environment in Europe.* https://www.oneplanetnetwork.org/sites/default/files/europe_final_201030.pdf. Accessed on: 02/06/2021.

Wu, X., Li, J., Yao, L., & Xu, Z. (2020). Auto-sorting commonly recovered plastics from waste household appliances and electronics using near-infrared spectroscopy. *Journal of Cleaner Production*, *246*, 118732.

Wuppertal Institute et al. (2019). *Market analysis for plastic waste recovery by regional blockchain networks*. https://ecircular.climate-kic.org/wp-content/uploads/sites/2/2019/02/Market-Analysis-for-Plastic-waste-recovery-by-regional-blockchain-networks.pdf. Accessed on: 01/06/2021.

Zampori, L., & Pant, R. (2019). Suggestions for updating the Product Environmental Footprint (PEF) method. *Publications Office of the European Union: Luxembourg*. https://core.ac.uk/download/pdf/188760726.pdf. Accessed on: 02/06/2021.

Zarean, M. et al. (2016). A systematic review on the adverse health effects of di-2-ethylhexyl phthalate. *Environmental Science and Pollution Research*, *23*(24), 24642-24693.

Zhang, Q., Zhang, X., Mu, X., Wang, Z., Tian, R., Wang, X., & Liu, X. (2021). Recyclable waste image recognition based on deep learning. *Resources, Conservation and Recycling*, *171*, 105636.

Zhou, X., Broadbelt, L. J., & Vinu, R. (2016). Mechanistic understanding of thermochemical conversion of polymers and lignocellulosic biomass. *Advances in Chemical Engineering*, *49*, 95-198.

Annex 1 Interview Questions for Study on 'Chemical Recycling from Waste in the Circular Economy'

May 2021

Thank you for agreeing to participate in an interview and share your knowledge about this topic. This interview is part of the study 'Chemical Recycling from Waste in the Circular Economy', commissioned by the European Chemicals Agency and performed by the consultant RPA Europe. The purpose of the study is to investigate the current state of knowledge regarding the chemical recycling of waste. The specific objectives of the study are a collection of information through review of literature, consultation of experts and the development of case studies.

A report will be prepared for publication around August/September, covering the following areas: sources, main materials, substances and processes of chemical recycling; current performance of chemical recycling technologies; opportunities and challenges; benefits on the context of the circular economy; readiness level of different technologies and regulatory oversight. The interview will help the consultants enrich information found in the scientific literature with relevant examples, case studies and expert knowledge. In the analysis of interview findings, answers of all interviewees will be anonymised, so it will not be possible to identify an individual expert or link answers with any personal information. Interview materials will be kept safe and available only to the consultants involved in the interview data analysis. We will destroy all interview materials after the study has been completed.

At the start of the interview, you will be asked if you agree:

- to have your name and affiliation listed in an annexe to the report with everyone interviewed in this study;
- to allow us to make a recording of the interview for data analysis purposes

Thank you for sharing your knowledge and expertise with us!

Introductory questions

Could you briefly present your professional/research experience related to the topics in question? Highlight relevant experiences, such as your daily work, participation in projects, working groups, discussions, etc. Would you rate your knowledge in the area as high, medium?

In your opinion, what is the potential for applying chemical recycling in waste management? What features of chemical recycling make it useful for managing waste? What features of chemical recycling limit its application for managing waste? How does chemical recycling compare in its usefulness to other methods that are used for managing the same streams of waste?

Thematic topics with questions

You have been allocated one or two specific topics of the six thematic topics for elaboration during the interview. The six topics and their related questions are:

Topic 1: Chemical recycling technologies: types, performances, advantages and disadvantages

- **In your view, what are the main established chemical recycling technologies?** Focus on technologies that have been applied commercially or at least in pilot/demonstration plants. Could you refer to any examples of companies, consortia, pilot plants or projects where these technologies are applied? Why do you consider these technologies as established?
- **How are the technologies/processes you have mentioned applied in waste management?** What are the main features that makes the technology/ies useful for managing waste? Are there features that limit the application for managing waste?
- **Can you rank the established top-three chemical recycling technologies?** Which, in your view is the most suited technology for chemical recycling? What feature(s) make it better than other technologies?
- **In your opinion, what are the emerging chemical recycling technologies that have high potential in the near future?** List as many examples as possible. Why do you think these technologies have potential for future application? What are their possible benefits/limitations for managing waste? How do these technologies compare to the established waste management methods (e.g., waste-to-energy, incineration etc.)? How do these technologies compare to the established chemical recycling technologies we have discussed earlier?

Topic 2: Waste streams: past, present and future of waste sources, types and quantities

- **In your view, what are the main established chemical recycling technologies?** Focus on technologies that have been applied commercially or at least in pilot/demonstration plants. Could you refer to any examples of companies, consortia, pilot plants or projects where these technologies are applied? Why do you consider these technologies as established?
- **What types of waste are typically treated by chemical recycling technologies?** Where do these waste streams originate from? What components/fractions do they typically contain? Do these waste streams need any particular waste treatment process (e.g., sorting) before chemical recycling can be applied? Why is chemical recycling suitable to treat these waste streams? What factors encourage/limit the application of a chemical recycling technology to these waste streams? Could you refer us to any studies that analyse the applicability and efficiency of chemical recycling for these types of waste?
- **What other types of waste could be treated by chemical recycling technologies in the near future?** Consider typical and emerging waste streams. In your opinion, why is should chemical recycling be considered an appropriate option to manage this waste? Could you refer us to studies or projects that explore chemical recycling of the streams of waste you have discussed?

Topic 3: Recovered substances, materials and waste residues, side streams and by-products: identification, safety aspects and markets

- **In your view, what are the main established chemical recycling technologies?** Focus on technologies that have been applied commercially or at least in pilot/demonstration plants. Could you refer to any examples of companies, consortia, pilot plants or projects where these technologies are applied? Why do you consider these technologies as established?
- **What are the outputs of the chemical recycling technologies you have mentioned?** Think of all outputs, including the recycled materials, residues, and by-products. What are the typical applications of these outputs? Could all outputs be reused in some way? Are the outputs valuable in a circular economy? What happens to those outputs that cannot be reused?

- **Which of the outputs of the chemical recycling technologies are the most demanded or could potentially be demanded on the market?** Focus on all outputs that can be reused. What qualities of the outputs make them wanted on the market? What qualities of these outputs limit their demand on the market? How do these outputs compare to virgin materials available on the market? What other factors (if any) could boost or diminish the demand for these outputs on the market?

Topic 4: Chemical recycling and Substances of Very High Concern (SVHC): sources, identities, treatment, fate and emissions

- **Which Substances of Very High Concern (SVHC) in waste would enter chemical recycling facilities?** Provide examples of the most significant SVHC to your knowledge. In what components/fractions of waste are they usually found? From where do these SVHC containing waste usually originate from (industrial or consumer applications)? What chemical recycling technologies can be used/are used to process these SVHC containing waste streams?
- **What happens to SVHC contained in the waste materials that are chemically recycled?** According to your knowledge, does this apply to all chemical recycling technologies? Does all SVHCs undergo the same fate in chemical recycling technologies or do certain SVHC have different fates in different technologies? What is the ultimate fate of chemically recycled SVHC?
- **Are there other sources of SVHC in chemical recycling, in addition to waste streams containing SVHC?** What is (if any) the role of chemical recycling technologies in generating SVHCs (e.g., through the use of SVHC in chemical recycling processes, by emitting SVHCs or generating SVHC in the chemical recycling processes, etc.)? If chemical recycling technologies generate SVHC, how should the outputs of these recycling processes be treated?
- **At what stages of chemical recycling are emissions of SVHC most likely to happen?** What kind of physical/chemical transformations can lead to generation and emissions of SVHC? What human health and environment hazards are posed by these emissions? Can you refer us to any case studies analysing the behaviour and fate of SVHC in real-life chemical recycling facilities?
- **What are the best available technologies (BATs) that can be used for avoiding emissions of SVHC in chemical recycling facilities?** Please provide examples and briefly describe the stages of chemical recycling treatment they are used at, and the purposes they are used for. To your knowledge, what factors influence the effectiveness of treatment of SVHC? Why do you think these BATs are more effective than others? Can you refer us to any case studies or actual chemical recycling facilities that apply these technologies?

Topic 5: Chemical recycling and policy developments: UVCBs substances classification and mixture rule, authorisation requirements for mixtures containing SVHC constituents

- **What are examples of chemical recycling technologies that results in substances of Unknown or Variable composition, Complex reaction products or Biological materials (UVCBs)?** Which technologies generate UVCBs as outputs? To your knowledge, what are the common instances of UVCBs? What are factors that lead to generation of UVCBs when a specific chemical recycling technology is applied?
- **How do chemical recycling facility operators manage the presence of UVCBs in their recycling outputs?** What decisions and actions should be taken by operators to manage UVCBs in recycling outputs? What challenges are faced by operators in taking appropriate actions? Could you refer us to any examples of best practices in dealing with UVCBs by chemical recycling facility operators (e.g., hazard classification/risk

management measure approaches)? Have you faced issues when SVHC have been present in UVCBs? What have you done in that case?

- **What is the role of existing regulatory measures in dealing with UVCBs in chemical recycling?** How do current regulatory measures support operators of chemical recycling facilities to manage UVCBs in recycling outputs? Please provide examples. Are their gaps in the existing regulatory measures that pose challenges to managing UVCBs in the recycling outputs? Please provide examples.
- **What can be done to improve regulations to cope with UVCBs in chemical recycling more effectively?** Could you give us any examples of regulatory solutions? Could you refer us to any projects/public discussions/working groups working on such solutions?

Topic 6: Chemical recycling and tracking systems: mandatory communication requirements, sector by sector or waste stream-by-waste stream approach, block-chain technologies

- **What are the main impacts of substances of very high concern (SVHC) on chemical recycling of waste?** Could you provide examples of specific SVHCs that have specific impacts on chemical recycling? Could you explain how the presence of SVHCs resulted in these impacts? Are the impacts you have just mentioned specific to certain types of chemical recycling/types of SVHCs/types of waste?
- **How can chemical recycling facility operators mitigate the negative impacts related to the presence of SVHCs in the waste streams?** What decisions and actions should be taken by the operators to eliminate or otherwise control SVHCs negative impacts? What are the challenges faced by the operators in taking the necessary actions? Could you refer us to any examples of best practices in dealing with SVHCs developed by chemical recycling facility operators?
- **What is the role of existing technical (e.g. digital tools) and regulatory solutions in dealing with SVHCs in chemical recycling?** How can currently existing technical measures/regulatory solutions help operators of chemical recycling facilities to mitigate SVHC-related impacts? Please provide examples and explain their benefits. What are the deficiencies in the existing technical/regulatory solutions that pose challenges to managing impacts of SVHC in chemical recycling? Please provide examples and explain their harm.
- **What can be done to develop/improve the technical measures to eliminate or otherwise control negative impacts of SVHCs on chemical recycling?** Please think about examples of potentially effective technical solutions. Do they refer to specific SVHC or their groups? Are any of the measures you mentioned applied in practice? Could you give any examples? Could you refer us to any projects/public discussions/working groups on the topic?
- **What can be done to develop/improve regulations to eliminate or otherwise control impacts of SVHCs on chemical recycling?** Please think about examples of potentially effective regulatory measures/improvements to the current legislation. Has the possibility of such regulatory developments/improvements been publicly discussed? Could you refer us to any documents, publications or presentations covering these discussions?

Closing question

Is there any other important information we have not discussed that would help us to answer the research questions? Could you recommend any relevant experts, reports, case studies on the topics we have discussed? You are welcome to share anything that you find relevant by email: zinaida.manzuch@rpa-europe.eu

Thank you for talking to us!
The RPA study team

Annex 2 Highest Ranked Keywords and Phrases

Table 11-1: Highest ranked keywords and phrases by research topic		
TF_IDF	**TextRank (with GenSim)**	**RAKE algorithm**
Topic 1: Chemical recycling technologies		
waste	waste	Environmental benefits
process	product	high calorific
product	plastic	brominated flame retardants
polymer	polym	flexible pu foams
plastic	recycl	rigid pu foams
recycling	process	pilot plant scale
glycol	chemical	ground tire rubber
action	catalyst	fluidized bed reactor
ratio	material	municipal solid waste
Chemical	acidicrubber	flexible polyether polyol
ethane	foam	flexible polyurethane foams
LCA	Polyurethane	chemical recycling process
Polyurethane	environ	efficient
foam	temperature	clean fuels production
reaction	energy	european plastics production
pyrolysis	oil	gas formation reaction
used	produce	
temperature	technology	
catalyst	lifecycle	
recover		
Topic 2: Waste streams		
plastic	plastics	loop supply chain
waste	recycl	flexible pu foams
recycling	waste	rigid pu foams
environment	product	solid plastic waste
material	process	pilot plant scale
ethane	materi	life cycle assessment
glycol	polym	flexible polyurethane foams
foam	environ	polypropylene
scenario	management	high hydroxyl number
polyurethane	manag	chemical recycling processes
environmental	chemic	pet automobile waste
chemical	foam	plastic production
recover	polyurethane	chemical recycling process
biodegrad	packag	consumer plastic waste
pyrolysis	container	density polyethylene
consumer	degrade	
degradation		
pvc		
Topic 3: Recovered substances, materials & waste residues, side streams & by-products		
polyurethane	polyurethane	life cycle assessment
action	polym	pilot plant scale
product	product	flexible pu foams
foam	process	/ composites part
waste	wastes	rigid pu foams
process	recycl	/ polymer degradation
polyol	polyol	flexible polyurethane foams
reaction	char	flexible polyether polyol
polymer	chemical	polym degrad stab

Table 11-1: Highest ranked keywords and phrases by research topic

TF_IDF	TextRank (with GenSim)	RAKE algorithm
recycling glycolys ethyl ratio recover obtain temperature plastic catalyst methanol chemical	catalyst high materials sustainably flexible foams recycled degrad glycol yield	gasification efficiency influence catalytic cracking pilot plant carbon dioxide liquid oil yield
Topic 4: Chemical recycling and substances of very high concern		
plastic bfrs cycle material packaging recycling recycle ratio recycled high materials pops sample polymer waste product process	recycl material food packag plastic plasticizer limited recyclability flame retardants samples products contamination contaminant polym migrate additives metals differ process environment	Organic pollutants mineral oil hydrocarbons food packaging materials polyolefins ray fluorescence thermal desorption plastic packaging supply chain density polyethylene packaging waste mass spectrometry hazardous substance inorganic elements waste stream virgin material brominated flame retardants
Topic 5: Chemical recycling and policy developments		
plastic manufacturer polymer regulation Pollution product process waste recycling substance	microplastic polymer processes plastics impacts recycl production waste pollut	plastic waste decabde chemical recycling phthalates mechanical recycling bromine hazardous waste chemical composition hazardous substance
Topic 6: Chemical recycling: monitoring and tracking systems		
plastic detect image spectra data form track high source move	plastic water environ track science detect pollut image satellites spectral	spectral signature remote sensing smart tags artificial intelligence circular economy digitalization

Table 11-1: Highest ranked keywords and phrases by research topic		
TF_IDF	**TextRank (with GenSim)**	**RAKE algorithm**
pollution using information ict	source inform tag	

Annex 3 Results of the Expert Poll

Figure A1-1 shows the distribution of the respondents according to the types of organisations they represented.

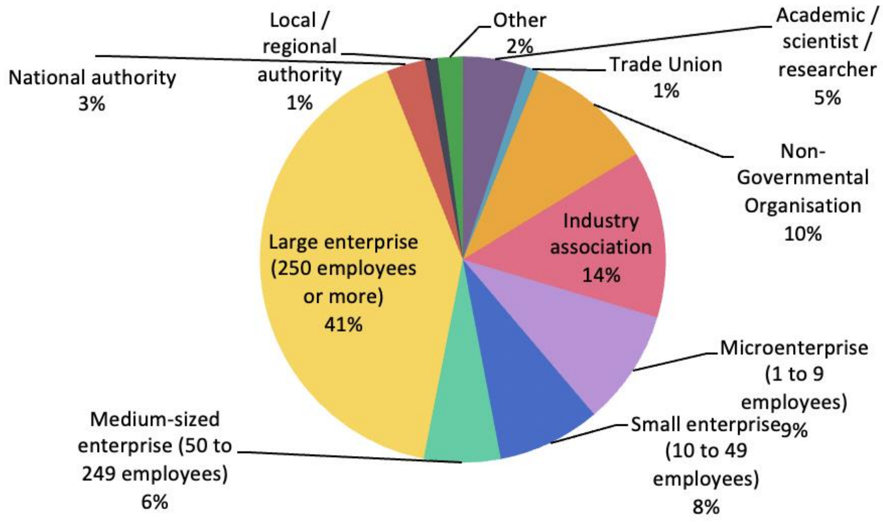

Figure A3-1: Respondents by the type of represented organisation

According to Figure A1-1, most respondents represented large enterprises (41%), industry associations (14%), and non-governmental organisations (10%). Other businesses (medium to small and micro enterprises) were also visible (13%). Much less responses were obtained from national and regional authorities (4%) and academia (5%).

The respondents represented 18 countries: mostly European (106), but also North American (5) and Australia (1). The summary of this data is provided in Figure A1-2

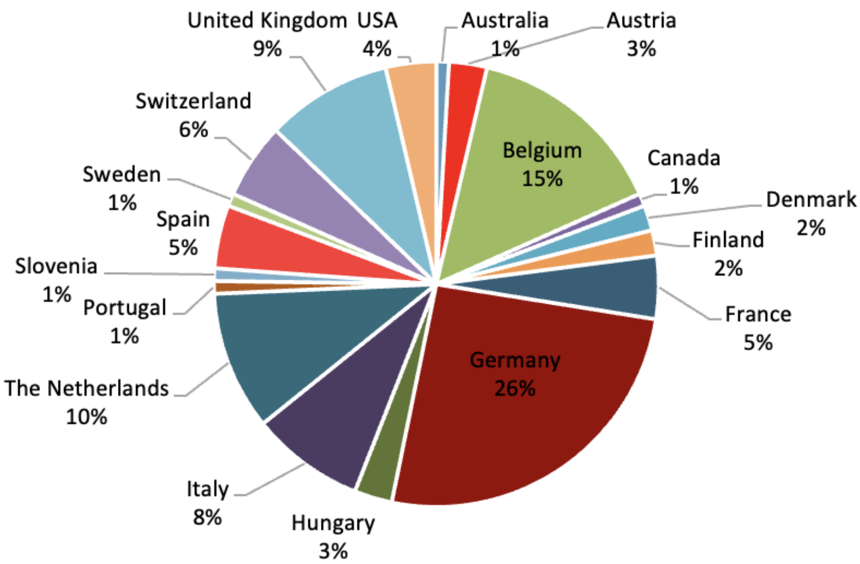

Figure A3-2: Respondents by country (N=109)*
*NOTE: * three respondents indicated the continent (Europe)*

Figure A1-2 shows that the respondents from several European countries – Germany (26%), Belgium (15%), The Netherlands (10%), UK (9%) and Italy (8%), were predominant.

In the poll the respondents were asked to indicate, if they could share any information on six research topics. Table A1-1 provides the summary of answers.

Table A3-2: Expertise of the respondents by research topic

Topics	I have information on this topic that I can share in an interview		No information available		Total no. of answers
	No. of answers	*Answers (%)*	*No. of answers*	*Answers (%)*	
1. Chemical recycling technologies and processes	88	90.7%	9	9.3%	97
2. Waste streams	80	87%	12	13%	92
3. Recovered substances, materials and waste residues, side streams and by-products	75	78.9%	20	21.1%	95
4. Chemical recycling and substances of very high concern	54	57.4%	40	42.6%	94
5. Chemical recycling and policy developments	55	58.5%	39	41.5%	94
6. Chemical recycling and tracking systems	44	46.8%	50	53.2%	94
Total no. of answers	396		170		566
Total answers (%)	70%		30%		100%

Table A1-1 shows that the majority of respondents can share information on topics 1-3 (80% to 91% respondents) and slightly less – on topics 4-6 (47% to 57%).

Annex 4 Interviewed Experts

Table A5-3: The list of interviewees	
Last name, first name	**Organisation (Country)**
Azoulay, David	Center for International Environmental Law (CIEL) (Switzerland)
Blumenstein, Uwe	BASF SE (Germany)
Cinaralp, Fazilet	ETRMA (Belgium)
Comotto, Mattia	CIRFS / IVC (Germany)
Creswell, Roger	European Solvent Recycler Group ESRG (Germany)
Hoffmann, Marieke	Deutsche Umwelthilfe (Germany)
Jaumotte, Raphael	PETCORE (France)
Kihl, Anders & Stiernström, Sara	Ragn-SellsfV∂retagen AB (Sweden)
Loro, Francesco	ARPAV (Italy)
Maschmeyer, Thomas	Licella/The University of Sydney (Australia)
Millet, Herve	PLASTICS EUROPE (France)
Morgano, Marco Tomasi	ARCUS Greencycling Technologies GmbH (Germany)
Munier, Jasper	Clariter S.A. (Netherlands)
Noordegraaf, Jan	PolystyreneLoop BV (Netherlands)
Rateau, Fanny	ECOS - Environmental Coalition on Standards (Belgium)
Smith, David	Mitsubishi Chemical Methacrylates (United Kingdom)
Thornton, Chris	ESPP (European Sustainable Phosphorus Platform) (France)
Vogel, Julia	German Federal Environment Agency (Germany)
Warhurst, Michael	CHEM Trust (United Kingdom)

Annex 5 Survey Results

A5.1 Introduction

Representatives from companies currently developing, testing, or using chemical recycling technologies were asked to complete a questionnaire aiming to collect information about the state-of-the-art of chemical recycling as well as any regulatory challenge with chemical legislation and REACH in particular. Out of the 19 responses received, the majority were from large enterprises (250 employees or more) and the fifth was from microenterprises (1 to 9 employees). There were only few respondents from medium-sized and small enterprises.

Almost half of participants were from companies that are currently using or testing pyrolysis technology, one forth was from companies that use chemolysis, few that apply gasification and several companies that are currently using or testing other technologies, such as hydrothermal liquefaction or acidulation. The large majority of companies were at the pilot testing phase (TRL 5-7), several were fully operational (TRL 8-9), and only one technology was under development.

A5.2 Survey questionnaire

Information on the survey

This questionnaire is part of the study "Chemical Recycling from Waste in the Circular Economy" commissioned by the European Chemicals Agency and carried out by RPA Europe S.R.L. and Risk & Policy Analysts Ltd. The aim is to investigate the current state of knowledge on chemical recycling.

> This survey is aimed at companies currently developing, testing or using chemical recycling technologies. The purpose is to collect information about the state-of-the-art of chemical recycling as well as any regulatory challenge with chemical legislation and REACH in particular. It consists of three parts:
>
> 1) Demographic information
>
> 2) State-of-the-art of chemical recycling technologies
>
> 3) Regulatory and technical aspects of substances of unknown or variable composition, complex reaction products or biological materials (UVCBs) and substances of very high concern (SVHCs) in chemical recycling

IMPORTANT! Chemical recycling is intensively used for reprocessing of plastic waste, so the questionnaire focuses on this type of waste. However, the questionnaire allows providing information about the chemical recycling of other waste too.

Please submit the completed questionnaire no later than 30 July 2021.

N.B. You do not need to answer all the questions at the same time, as you can save your progress and complete the survey later. To return to the survey, you must provide a valid email address via the toolbar. A continuation link is sent to the provided email. When you use the Save and Continue feature, all survey progress up to that point is saved (including on the active page).

About you

Please provide the following details about yourself.

Your personal data (name, organisation name, email address) will not be published or shared and are collected for the only purpose of this survey. The Data Controller only keeps your personal data for the time necessary to fulfil the purpose of collection or further processing, namely for a maximum of one year after the closure of the file to which the present targeted consultation belongs.

If you would like to exercise your rights under Regulation (EU) 2018/1725, or if you have comments, questions or concerns, or if you would like to submit a complaint regarding the collection and use of your personal data, please feel free to contact the Data Controller at: info@rpa-europe.eu

1) Please provide the following details:*

Your name:
Organisation name:
e-mail address:
Country of operation:

2) What is the size of your organisation?

☐ Microenterprise (1 to 9 employees)
☐ Small enterprise (10 to 49 employees)
☐ Medium-sized enterprise (50 to 249 employees)
☐ Large enterprise (250 employees or more)

PART II: State-of-the-art of chemical recycling technologies

3) What chemical recycling technology is being used, tested or developed in your company? If relevant, specify chemical recycling technologies under 'Other'.

☐ Pyrolysis
☐ Gasification
☐ Chemolysis (also known as chemical depolymerisation or solvolysis)
☐ Other (please specify):

4) Please select the technology readiness level.

☐ Fully operational (TRL 8-9)
☐ Pilot testing (TRL 5-7)
☐ Under development (TRL 1-4)

5) What waste streams are processed by your chemical recycling technology? Check as many options as relevant.

☐ Municipal solid waste
☐ Industrial (manufacturing) waste
☐ Building and construction waste
☐ Waste electric and electronic equipment

☐ Agricultural waste	☐ Automotive waste
☐ Plastic packaging waste	☐ Other streams of waste (please, specify):

6) What types of waste are recycled through your chemical recycling technology? Check as many options as relevant.

☐ Mono plastic waste [containing one polymer]
☐ Mixed plastic waste [containing a blend of polymers]
☐ Multi-layered plastic waste [containing a main layer of plastic combined with several layers of plastic and/or other materials]
☐ Contaminated plastic waste [containing organic and inorganic impurities]
☐ Sorted plastic waste [containing one or more polymers suitable for chemical reprocessing]
☐ Other types of waste (please, specify):

7) What is the end-use of the output of the chemical recycling process in your company? Please indicate the chemical products category. Multiple choices are possible.

☐ Adhesives, sealants	☐ Fertilisers	☐ Lubricants, greases, release products	☐ Textile dyes, and impregnating products
☐ Adsorbents	☐ Fuels	☐ Metal working fluids	☐ Washing and cleaning products
☐ Air care products	☐ Metal surface treatment products	☐ Papers and board treatment products	☐ Water softeners
☐ Anti-Freeze and de-icing products	☐ Non-metal-surface treatment products	☐ Plant protection products	☐ Water treatment chemicals
☐ Base metals and alloys	☐ Heat transfer fluids	☐ Perfumes, fragrances	☐ Welding and soldering products, flux products
☐ Biocidal products	☐ Hydraulic fluids	☐ Pharmaceuticals	☐ Cosmetics, personal care products
☐ Coatings and paints, thinners, paint removers	☐ Ink and toners	☐ Photo-chemicals	☐ Extraction agents
☐ Fillers, putties, plasters, modelling clay	☐ Processing aids such as pH-regulators, flocculants, precipitants, neutralization agents	☐ Polishes and wax blends	☐ Oil and gas exploration or production products
☐ Finger paints	☐ Laboratory chemicals	☐ Polymer preparations and compounds	☐ Electrolytes for batteries
☐ Explosives	☐ Leather treatment products	☐ Semiconductors	☐ Other:

8) Is the output of the chemical recycling process a chemical substance that is used as an intermediate (according to the REACH definition)?

☐ Yes
☐ No
Comments:

9) What is the fate of residues of the chemical recycling process? Multiple choices are possible.

☐ Our chemical recycling technology does not produce residues
☐ The residues are landfilled (specify the type of residue):
☐ The residues are incinerated (specify the type of residue):
☐ Other (please, specify):
Comments:

10) What are the advantages of the main output of your chemical recycling technology compared to virgin counterparts? Multiple choices are possible.

☐ Competitive or lower price
☐ Quality that is comparable or higher
☐ Better environmental footprint
☐ Other (please, specify):

Comments:

PART III. Regulatory and technical aspects of substances of Very High Concern (SVHC) and substances of Unknown or Variable composition, Complex reaction products or Biological materials (UVCBs) in chemical recycling

11) Are the outputs of your chemical recycling technology substances of Unknown or Variable composition, Complex reaction products or Biological materials (UVCBs)?

☐ Yes
☐ No
☐ Don't know

12) Does the waste processed by your chemical recycling technology contain substances of very high concern? If yes, please specify their identities and technical functions if known.

☐ Yes. Please specify:

☐ No
☐ Don't know
Comments:

13) Does your chemical recycling process use substances of very high concern? If yes, please specify their identities and technical functions.

☐ Yes. Please specify:

☐ No
☐ Don't know
Comments:

14) Does your chemical recycling process generate substances of very high concern?

☐ Yes. Please specify:

☐ No
☐ Don't know
Comments:

15) Do substances of very high concern have negative impacts on your chemical recycling process? Multiple choices are possible.

☐ Yes, they contaminate the output.
☐ Yes, they reduce the effectiveness of the chemical recycling process.
☐ Yes, they increase the operational cost of the process.
☐ Yes, they may be released by the chemical recycling process.
☐ No, they are destroyed during the chemical recycling process.
☐ Other (please, specify):

16) If present, how do you mitigate the risks posed by substances of very high concern in your chemical recycling process? Multiple choices are possible.

☐ We sort the input material.
☐ We pre-treat the input material.
☐ We have emission abatement technologies to prevent/reduce the emissions of SVHCs.
☐ Our chemical recycling technology destroys SVHCs contained in the input material.
☐ Other (please, specify):

Comments:

17) What are the main uncertainties you have when dealing with obligations posed by the chemical legislation and in particular by REACH?

☐ We do not know if we have to register the chemical substances resulting from chemical recycling
☐ We do not know if we can benefit of the exemption for recovered substances that have already been registered by someone else
☐ We do not know how to inquire with ECHA whether a registration has already been submitted for that substance
☐ We do not know how to prepare a Product and process orientated research and development (PPORD) dossier
☐ We do not know whether we can benefit of the exemptions for substances used in Scientific research and development (SR&D)
☐ Other. Please specify:

Comments:

18) How do you deal with these uncertainties?

☐ We approach ECHA for clarification
☐ We attend workshops, webinars and events organised by ECHA
☐ We approach the national Helpdesk
☐ We approach our industry/trade association
☐ We contract consultants:
☐ Other. Please specify:

19) What type of support would help you in dealing with regulatory uncertainties?

☐ Guidance material specific to chemical recycling
☐ A workshop focusing on chemical recycling and REACH
☐ Other. Please specify:

20) Please provide any other comment or information you would like to share with us.

Thank You!

Thank you for taking our survey. Your response is very important to us.

A5.3 Survey results

Pyrolysis

When asked what waste streams were processed by their chemical recycling technology, those working with pyrolysis indicated that all types of waste streams could be used: municipal solid waste, industrial (manufacturing) waste, plastic packaging waste, building and construction waste, agricultural waste, WEEE, and automotive waste. It was also noted that the process recycled all types of plastic waste, including mono, mixed, multi-layered, contaminated, sorted, and other (e.g., hard to recycle waste streams like UHMWPE). The most common end-use of the output of pyrolysis were polymer preparations and compounds, fuels, and crude oil/naphtha. Other products were also mentioned, such as adhesives, sealants, semiconductors, lubricants, coatings, paints, thinners, ink, toners, etc. In addition, several companies emphasised that they were producing feedstock and monomers for plastic production. Some of the companies were producing intermediates and some were producing end-products. When asked about the fate of residues from pyrolysis process, few respondents mentioned the use of residues as building materials or in cement kilns. However, most of participants noted that the residue was incinerated and/or landfilled. All participants thought that better environmental footprint and quality comparable or higher to virgin counterparts were the main advantages of the process. Several suggested the circularity of the process.

Participants were asked if the outputs of their chemical recycling technology were substances of unknown or variable composition, complex reaction products or biological materials (UVCBs). Some respondents indicated that this was the case, several said ‘no’, and few did not have the answer. Although most respondents noted that the waste processed by their chemical recycling technology did not contain substances of very high concern (SVHCs), few respondents said it probably did (e.g., phthalates as plasticisers or brominates flame retardants). One of the respondents commented:

> “Phthalates and halogenated flame retardants (which could be introduced from impurities in the mixed packaging plastic waste), and PAHs (from waste tires) are destroyed/converted or removed in the process.”

None of the pyrolysis technology used SVHCs in their processes, and majority of participants indicated that the process did not produce SVHCs. Nevertheless, few respondents mentioned the formation of SVHCs, such as PCDDs, PCDFs, and PAHs; however, their formation was either in negligible quantities or destroyed by subsequent reaction or cleaning processes. Although many representatives thought that SVHCs did not have any negative impacts on their chemical recycling processes as they were usually destroyed, few indicated that they might limit the downstream processing potential, reduce the effectiveness of the process, contaminate the output, or increase the operational cost. Respondents were also asked how they mitigate risks posed by SVHCs in their recycling processes. Majority indicated that they sort and pre-treat the input material, and that their technology destroys SVHCs that remains in the input material. There were also few mentions of emission abatement technologies to prevent/reduce the emissions of SVHCs.

When asked about uncertainties they had when dealing with obligations posed by the chemical legislation and in particular REACH, several respondents indicated that they did not know if they could benefit from the exemption for recovered substances that have already been registered by someone else, did not know how to inquire with ECHA whether a registration has already been submitted for that substance, did not know how to prepare a product and process oriented research and development (PPORD) dossier and whether they could benefit from the exemptions for substances used in scientific research and development (SR&D). One of respondents commented:

> "Variability in feeds results in broad range and variability of products which is difficult to specify for REACH registration."

When dealing with uncertainties, they approached industry and trade associations, ECHA for clarification, the national Helpdesk, or contract consultants. The majority of participants noted that they would benefit from guidance material specific to chemical recycling and workshops focusing on chemical recycling and REACH. One of the respondents also mentioned the comprehensive dossier, which would create clarity and allow for stable and reliable legal compliance. There were also some additional comments on regulation:

> "Product of chemical recycling is a feedstock to the petrochemical industry and should be treated as currently naphtha w.r.t REACH registrations."

> "Due to the waste origin of chemical recycling products, it is very difficult to fit the product from different waste streams into only one Substance. A number of UVCBs should be established as it is for substances of fossil origin <…> Registration process is long and extremely expensive for technology developers. Joint registrations with the support and under the guidance of ECHA can be an enabler."

> "We see the main uncertainties twofold: 1) The waste shipment regulation (WSR) affecting plastics: For waste as a raw material for chemical recycling you need a 24/7 supply of high quantities. The WSR adopting the BASEL convention on EU27 assumes almost the same level of waste, sorting, and recycling infrastructure as in low developed countries. This poses a big burden on approval of plastic waste transports between and through Member States. This should be mitigated by allowing long time approvals of high quantities between established certified partners of the waste value chain, supported by an EU wide digital tool allowing authorities sufficient control of those transports avoiding illegal practices. 2) Accepting a suitable mass balance approach for chemical recycling is a pre-requisite."

<u>Chemolysis</u>

When asked what types of waste were processed by their chemical recycling technology, those working with chemolysis indicated the following waste streams: municipal solid waste, industrial waste, plastic packaging waste, WEEE, and other (e.g., carpets, textiles, highly modified polyester). It was also noted that the process recycled mono plastic waste, multi-layered plastic waste, contaminated plastic waste, and sorted plastic waste. The most common end-use of the output of pyrolysis were polymer preparations and compounds. Other products included plasticisers, adhesives, sealants, coatings, paints, thinners, paint removers, and biocidal products. Some of the companies were producing intermediates and some were producing end-products. One of the respondents commented:

> "The strategy is more and more to get sorted plastics, that have passed the end of waste criteria to be treated in a material processing plant and give substances that will be registered in REACH. In that way, it is not a waste recycling plant, but produces a substance that has to be REACH registered."

When asked about the fate of residues from pyrolysis, most of participants noted that the residues were incinerated and/or landfilled. One participant noted:

> "All the processes generate residues. They accumulate the additives used in plastics. But those are largely unknown and poorly identified. The situation is even worse for post-consumer wastes that may have been produced long time ago. Postproduction waste should at least satisfy current regulations and it would be easier to know the additives used, but the degradation products from those additives are largely unknown."

All participants thought that better environmental footprint and quality comparable or higher to virgin counterparts were the main advantages of the process.

One respondent indicated that the outputs of their chemical recycling technology were UVCBs, however few said that this was not the case. All respondents indicated that the waste processed by their technology did not contain SVHCs, their process did not use SVHCs, and did not generate such substances. SVHCs did not have any negative impact on their chemolysis processes, as they were either removed during purification steps, destroyed during the process, or did not include any waste containing SVHCs. When asked how they mitigate risks posed by SVHCs in their recycling processes, participants indicated that they sort and pre-treat the input material, or that their technology destroys SVHCs that remain in the input material. They also mentioned emissions abatement technologies to prevent/reduce the emissions of SVHCs.

When asked about uncertainties they had when dealing with obligations posed by the chemical legislation and in particular REACH, one respondent commented:

> "Current regulations are clear, but the exemption 2.7 has been made from mechanical recycling, and it is not clear if that would apply to chemical recycling. The strategy is to have sorted plastics to feed the depolymerization (chemical recycling) plant. In that case, the plant process materials that have passed the end-of-waste criteria, so the exemption 2.7 cannot apply to the product of the depolymerization plant, and the product has to be REACH registered. The exemption cannot be carried away for ever... So, in that case the exemption is useless, but another exemption process could be useful."

When dealing with uncertainties, they would approach industry and trade associations or ECHA, or contract consultants. The majority of participants noted that they would benefit from guidance material specific to chemical recycling and workshops focusing on chemical recycling and REACH.

Gasification

When asked what waste streams were processed by their chemical recycling technology, those working with gasification indicated municipal solid waste, industrial waste, plastic packaging waste, agricultural waste, and other (e.g., sewage sludge, carpets, textile). It was also noted that the process recycled mixed, multi-layered, contaminated, sorted, and other type of plastic waste. The end-use of the output of gasification were fuels, fertilisers, polymer preparations and compounds, and bulk chemicals. All companies that use gasification were producing intermediates. When asked about the fate of residues from gasification, participants noted that the residues were landfilled. All participants thought that better environmental footprint and quality comparable or higher to virgin counterparts were the main advantages of the process.

All respondent indicated that the outputs of their chemical recycling technology were not UVCBs. All respondents indicated that the waste processed by their technology did not contain SVHCs, their process did not use SVHCs, and did not generate such substances. SVHCs did not have any negative impact on gasification process, as they were destroyed during the process. When asked how they mitigate risks posed by SVHCs in their recycling processes, participants indicated that they sort the input material, or that their technology destroys SVHCs.

Respondents did not have any uncertainties when dealing with obligations posed by the chemical legislation and in particular REACH. If there were any uncertainties, they would approach ECHA for clarification or attend workshops, webinars and events organised by ECHA. The majority of participants noted that they would benefit from guidance material specific to chemical recycling and workshops focusing on chemical recycling and REACH.

Other technologies

Respondents from companies using other technologies indicated that they processed municipal solid waste, plastic packaging waste, building and construction waste, agricultural waste, and other (e.g., sewage sludge ash). These processes recycled various types of plastic waste: hydrothermal liquefaction – mono, mixed, multi-layered, contaminated, and sorted plastic waste, acidulation – phosphate containing ashes. The end-use of the output of hydrothermal liquefaction were polymer preparations and compounds, feedstock for polymers and chemicals, lubricants, greases, and photo-chemicals, whereas acidulation produced fertilisers and flame retardants. All companies were producing intermediates. When asked about the fate of residues, participants noted that residues from hydrothermal liquefaction are incinerated while residues from acidulation are reused as coagulants. All participants thought that better environmental footprint, quality comparable or higher to virgin counterparts, and competitive or lower price (in the case of hydrothermal liquefaction) were the main advantages of their processes.

One respondent indicated that the outputs of their chemical recycling technology were UVCBs, however few said that this was not the case. All respondents indicated that the waste processed by their technology did not contain SVHCs, their process did not use SVHCs, and did not generate such substances. However, one respondent emphasised that with variable waste, there could not be 100% certainty. SVHCs did not have any negative impact on their chemical recycling processes. When asked how they mitigate risks posed by SVHCs in their recycling processes, participants indicated that they sort or pre-treat the input material, or that their technology destroys SVHCs. They also mentioned emission abatement technologies to prevent/reduce the emissions of SVHCs.

When asked about uncertainties they had when dealing with obligations posed by the chemical legislation and in particular REACH, respondents commented:

> "The whole REACH process is complicated and expensive, but we know how it works."
>
> "The amount and particularity of different pieces of chemicals legislation in the EU and globally creates a need to spend a lot of resources in keeping all operations compliant on all occasions."

When dealing with uncertainties, they approach industry and trade associations, ECHA for clarification, the national Helpdesk, contract consultants, or attend workshops, webinars and events organised by ECHA. Participants noted that they would benefit from guidance material specific to chemical recycling and a workshop focusing on chemical recycling and REACH. One respondent noted:

> "In addition to relevant guidance and seminars, a possible solution to ensure correct understanding could be an interactive application that would guide companies to provide relevant information and then get case specific guidance as feedback. Also, Q&As related to chemical recycling and common problems would be beneficial."

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