IDENTIFYING CHALLENGES, TECHNOLOGY AND KNOWLEDGE GAPS ACROSS PLASTICS VALUE CHAIN WITH A FOCUS ON RECYCLING IN CIRCULAR ECONOMY

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ABSTRACT

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Keywords: Circular economy, plastic, plastic waste, plastic recycling, recycling, mechanical recycling, chemical recycling, stakeholder interview, questionnaire.

The circular economy of plastics is currently more relevant than ever. With the EU setting ambitious plastic waste recycling targets and businesses seizing the opportunities in circular economy the interest is high. However, the plastic value chain has a long history of fitting perfectly into a linear economy. Linear economy has not shown to be a sustainable model for plastics and has resulted in environmental harm in a form of marine and on land plastic waste and pollution through fossil based raw material use and incineration.

Circular economy is a newly resurfaced model and efforts to transition for circular economy of plastics are undergoing. However, various challenges hamper the transition. The transition requires changes across the whole value chain, which has been designed to fit linear economy.

This thesis was done with an objective to identify the challenges, technology and knowledge gaps related to plastic recycling in circular economy in the EU. The work is divided into two parts. First part is a broad literature review including regulatory and state-of-the-art technology review. Second part is an experimental part including stakeholder interviews across the plastics value chain and questionnaire for researchers in the field. Additionally, experimental part contains Modix trial runs of agricultural plastic waste as a pre-treatment step to respond to a known existing challenge.

The identified challenges and gaps were divided into four categories: 1) feedstock acquisition and its quality, 2) recycled plastic and its uptake, 3) technology, 4) policies. Challenges and gaps across the whole value chain were identified and the conclusion is that effort across all actors is needed to solve complex problems that are sometimes very application-dependant issues.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT School of Engineering Science

Kemiantekniikka

Mikko Myrä

Muovin kiertotalouteen liittyvien haasteiden, teknologian ja tietämyksen puutteiden tunnistaminen kierrätyksen näkökulmasta.

Kemiantekniikan diplomityö

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99 sivua, 33 kuvaa, 2 taulukkoa ja 2 liitettä

Tarkastajat: Teollisuusprofessori Jutta Nuortila Jokinen ja vanhempi tutkija ja projektipäällikkö Anna Tenhunen-Lunkka

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Muovien kiertotalous on tällä hetkellä erittäin ajankohtainen aihe. EU on asettanut kunniahimoisia tavoitteita muovijätteen kierrätykselle, ja yritykset alkavat näkemään kiertotalouden hyötyjä. Muovia on pitkään käytetty lineaarisen talousmallin mukaan, jolle tarvitaan muutos. Muovin lineaarinen talous on aiheuttanut muovin päätymistä ympäristöön, sekä ilmaston saastumista fossiilisten raaka-aineiden käytön ja jätteenpolton seurauksena. Kiertotalous on uudelleen otsikoihin nouseva malli, johon siirtymiseen panostetaan niin sääntelyillä, kuin myös tutkimuksella ja kehityksellä.

Tämän diplomityön tavoitteena on tunnistaa haasteet, sekä teknologian ja tietämyksen puutteet liittyen muovin kierrätykseen kiertotaloudessa. Työ koostuu kirjallisuus- ja kokeellisesta osasta. Kirjallisuusosa sisältää katsauksen nykyisistä sääntelyistä ja olemassa olevista teknologioista. Kokeellinen osa koostuu pääosin sidosryhmähaastatteluista ja kyselystä. Haastatteluissa haastateltiin toimijoita muovin arvoketjulta ja kysely oli kohdennettu tutkijoille. Haastatteluiden ja kyselyn lisäksi kokeellinen osa sisälsi maatalousmuovijätteen Modix-koeajoja, joiden tavoitteena oli vastata olemassa olevaan haasteeseen.

Tunnistetut haasteet ja puutteet jaettiin neljään kategoriaan: 1) raaka-aine ja sen laatu, 2) kierrätetty muovi ja sen käyttö, 3) teknologia, 4) politiikkatoimet. Tunnistettujen haasteiden ja puutteiden perusteella voidaan päätellä, että toimia tarvitaan koko arvoketjulta, jotta monimutkaisia ongelmia pystytään ratkaisemaan.

ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
BFR	Brominated Flame Retardants
CDW	Construction and demolition waste
CH_4	Methane
CMD	Catalytic Microwave Depolymerisation
CO	Carbon monoxide
CO_2	Carbon dioxide
DMT	Dimethyl Terephthalate
DRS	Deposit Return System
DSC	Differential Scanning Calorimetry
ELV	End of Life Vehicles
EPR	Extended Producer Responsibility
FTIR	Fourier-transform infrared spectroscopy
GHG	Greenhouse Gas
GHS	Globally Harmonized System
H_2	Hydrogen
HDPE	High-density polyethylene
HIPS	High Impact Polystyrene
HIS	Hyperspectral imaging spectroscopy
IR	Infrared
LCA	Life cycle assessment
LDPE	Low-density polyethylene (LDPE)
LLDPE	Linear low-density polyethylene

MFI	Melt Flow Index
N_2	Nitrogen
NIR	Near infrared
OEM	Original Equipment Manufacturer
PA	Polyamides
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene terephthalate
PLA	Polylactide
POP	Persistent organic pollutants
PP	Polypropylene
PS	Polystyrene
PUR	Polyurethane
PVC	Polyvinyl chloride
R&D	Research and development
RDI	Research, Development, and Innovation
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RoHS	Restriction of Hazardous Substances Directive
rPET	Recycled polyethylene terephthalate.
SWIR	Short-wave infrared
TPA	Terephthalic acid
WEEE	Waste Electrical and Electronic Equipment
XRF	X-ray fluorescence

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Appendices

1 Introduction

Plastic recycling and circular economy are currently very important and topical to combat plastic pollution and climate change. The European Union (EU) has set ambitious targets (e.g., plastic recycling targets and mandatory recycled content in bottles), and is a frontrunner in transitioning to circular economy in key product value chains including plastics. The topic is currently more than ever relevant among researchers, businesses, and policy makers. Moreover, circularity of plastics is an important part of achieving carbon neutrality and decoupling from extensive fossil raw-material dependency as well as combat cumulative plastic waste in environment. The objective of this thesis is to identify current challenges, technology and knowledge gaps related to plastic recycling in circular economy.

The first part of the thesis is a literature review including brief description of current state of plastic waste and circular economy of plastic as well as regulatory and technological state-of-the-art review. Second part of the thesis is an experimental part, which includes findings from stakeholder interviews and questionnaire responses from researchers. Additionally, experimental part includes trial runs with Modix, to attempt to solve challenges of feeding agricultural plastic waste for pyrolysis. .

To the best knowledge of the author, previous research has not combined and analysed all of the methodologies used in this work to identify the challenges, knowledge and research gaps from regulatory environment, technological development and other matter such as feedstock and product quality. Additionally, as the plastic recycling space is quickly developing new and updated mapping is highly useful.

The plastic recycling field is widely researched and quickly developing. Novel technologies are emerging frequently, which makes it challenging for even experts to keep up with all the development. Previous research found in the literature about this topic has been conducted in a forms of literature reviews, interviews, and questionnaire. The most prominent challenge identified from the previous research on the topic is very diverse material properties of plastic enabling its use in countless of applications leading into complex waste management and its diversity.

The objective of this work is to identify the current challenges, technology and knowledge gaps across the plastics value chains in the EU. The main problem is the complexity of the said value chains and sometimes challenges consist of multiple, heavily application-dependent issues. The work will answer the following research questions: What are the challenges and gaps for transitioning to circular economy of plastics? What are the limitations of current and novel sorting and recycling technologies? What are the challenges in uptake of recycled plastic?

The findings come with certain limitations. Firstly, there was a limited number of interviews and questionnaire responses. To identify the patterns and the outliers, the number of interviews and responses could be higher. For this reason, further conclusions from this work should be drawn carefully by the reader. Additionally, the countries of interviewees and respondents are limited to draw a full picture of the challenges across plastics value chain in Europe.

2 Plastic in circular economy

In this section the difference between linear and circular economy will be discussed. Current view on circular economy of plastics will be explained, and key points will be discussed for understanding the circularity and its benefits.

2.1 Problems of plastic waste

Despite many negative impacts plastics are causing they are incredibly beneficial and one of the most used materials in the world. They are versatile and cost-efficient materials. Their strength, malleability, barrier properties and cheap price makes them excellent materials for many different applications such as in packaging, vehicles, buildings and electronics (Siltaloppi and Jähi, 2021). However too many plastics are designed for linear economy. Design for single-use, low-cost and ignoring the circularity coupled with insufficient waste management continue causing globally environmental, social, and economic harm (World Economic Forum et al., 2016). It is estimated that in total USD 80-120 billion of plastic packaging value is lost to the economy after a single brief use and additional expenses of USD 40 billion related to after use externalities and greenhouse gas emissions from its production annually (World Economic Forum et al., 2016).

It is estimated that 1.5-4% of all plastics produced each year end up in the ocean (European Commission, 2018). The amount of microplastics released into the environment in the EU is estimated to be between 75 000 and 300 000 tonnes annually (European Commission, 2018). The microplastic values above are ranging quite noticeably. This is explained by the difficulty of tracking the plastic waste. Actions to combat plastic pollution in oceans are developed. The Ocean Cleanup develops and scales technologies to remove plastic from oceans. The organization is currently working on scaling up their latest technology which has already successfully removed plastic from the great pacific garbage patch (The Ocean Cleanup, 2022).

Another worrying phenomenon regarding plastic waste is its management in developing countries. According to investigation by Guardian (2019) hundreds of thousands of tons of plastic waste from US are shipped every year to poorly regulated countries. There dirty, labour-intensive recycling is done by compromising public health and the environment. Too often the processing of plastic waste in developing countries means illegally burning plastic with consequences, such as toxic fumes being inhaled by citizens living nearby. (McCormick et al., 2019)

The problem with linear use of plastics is not only massive waste accumulation, but also greenhouse gas emissions during their life cycle. According to a study by Tenhunen-Lunna et. al. (2022) plastics contribute to climate change mainly during production 63%, polymer refining to products 22% and end-of-life management by incineration 15%, but also during their degradation in the environment as pollutants. The perspective of emissions was given in an report by CIEL (2019): emissions from 189 (500 MW) coal power plants are equal to around 850 million metric tons of greenhouse gases, which is equal to greenhouse gas emissions from plastic production in 2019. With current growth in plastic production and consumption by 2050 the emissions calculated as CO_2 equivalents will be over 56 gigatonnes (CIEL, 2019). According to findings by Tenhunen-Lunkka et al. (2022) if the EU Circular

Plastics related targets are met, the 2025 model estimates approximately 13% less greenhouse gas emissions than those estimated in 2018. With low recycling rates there is still significant potential to reduce CO_2 emissions by reducing the amount of incinerated plastic and production of primary raw material (Tenhunen-Lunkka et al., 2022).

Ultimately achieving circularity for plastics is complex problem. Today there are thousands of different types of plastics. 70 % of total plastic production are so called commodity plastics which are PET, HDPE, PVC, LDPE, PP, PS (Figure 1) (Tenhunen and Pöhler, 2020). There are numerous applications for plastics (Figure 2) of which packaging is the main application in Europe (40,5 %) alongside buildings and construction (20,4 %), automotive sector (8,8 %), waste from electronics and electrical equipment (WEEE) (6,2 %), household, leisure and sports (4,3 %), agriculture (3,2 %) (PlasticsEurope, 2021).

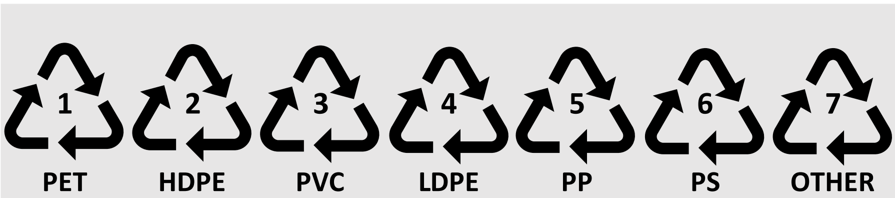

Figure 1. Recycle codes for most common plastics (Modified from Seaman, 2020).

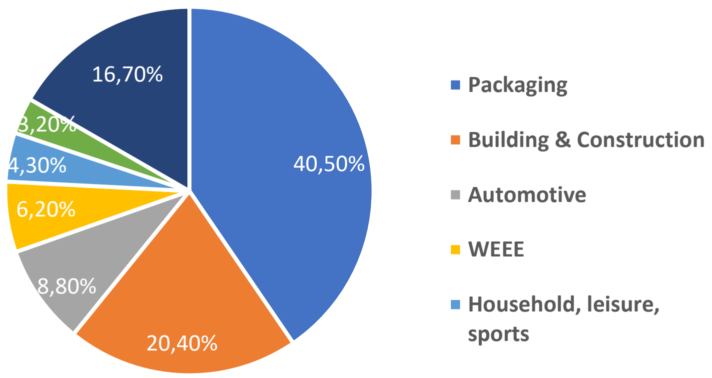

Figure 2. EU27+3 converters plastic demand by segments in 2020 (PlasticsEurope, 2021).

By bringing lifecycle and circular thinking into product design (i.e., design for recycling) substantial future waste, pollution and toxins could be avoided. An example of a problematic product designs are multilayer materials (e.g., high-performance food packaging) that are made of multiple complex layers of different plastics. The multilayer packaging structure consists of mostly PE due to its cheap price, but other plastics such as PET for toughness and ethylene-vinyl alcohol (EVOH) for blocking oxygen are layered on top. The separation and thus recycling of these layers is often difficult or impossible. (Ragaert et al., 2017)

Moreover, the addition of harmful or toxic additives makes recycling even more challenging. Precise control and separation for waste flow into recycling plant is needed to ensure safety and good product quality that some additives may compromise. These products are often waste from construction and demolition, automotive or WEEE. There is no one technology or exact solution for transition to solve all challenges related to transition to circular economy of plastics, rather there is a need for joint actions across the whole value chain including manufacturers, consumers, recyclers, and policies. (Tenhunen and Pöhler, 2020)

2.2 Linear and circular economy of plastics

Circular economy is emerging among not only researchers but also politicians, designers and CEOs are making effort to implement transition to circular economy (Ellen MacArthur Foundation, 2014). Linear economy approach has numerous of problems and it is important to identify them to understand the benefits of circular approach. The life cycle of material: take, make, use and dispose is an approach of a linear economy, as an example, that is a typical life cycle of plastics products. Linear approach is where finite resources, which in the case of plastics for the most part is crude oil, is used as raw material, manufactured into products, and after the use ultimately ending up as a waste.

According to the report published by PlasticsEurope (2021) in the year 2020, 34,6 % of plastics collected in EU was sent to recycling facilities inside or outside of the EU. Meaning that the remaining 65,4 % of collected plastics was landfilled or incinerated for energy recovery and thus lost from circulation. In circular way of thinking, 65,4 % of valuable polymeric material was lost which could have been utilized by functional circular economy.

The circular economy is an intentionally restorative industrial economy with aim to enable effective material flows, energy, labour, and information. Reduction of energy use per unit of output and acceleration of the shift to renewable energy is also highly important. Treating everything in the economy including waste as a valuable resource is in central focus of circular economy. (Ellen MacArthur Foundation, 2013)

In circular economy, products are designed and optimized to stay in circulation. Meaning that materials and products are preserved as long as possible and as high value as possible. This way material, energy, and labour bound in the product is used more efficiently (Ellen MacArthur Foundation, 2013). Circular economy strategies include, for example sharing, leasing, reusing, repairing, refurbishing, and recycling to maximize materials and products life cycle (EuroParl, 2015). Widely used 9R framework (Figure 3) illustrates strategies that promote circular economy in which the first ones (e.g., rethink and reduce) are considered more circular than the last ones (e.g., recycle and recover). Noticeably recycling is placed on the bottom of the table, which highlights the fact that there are many strategies and options beforehand for utilizing and keeping the product in cycles before it must be completely recycled. However, when talking about plastic waste, recycling is the most focused strategy currently to tackle large amount of plastic and let go from fossil based raw material use.

By extending the materials lifetime, resources, energy, and labour bound in the material are kept for longer (Ellen MacArthur Foundation, 2014). Only after no further uses are possible for products recycling is a great and viable option. However, with current recycling technologies materials such as plastics often experience downgrade in their properties. Downcycling is a term used to describe downgrade in material properties after recycling. Downcycling happens for example in mechanical recycling of plastics where plastic waste is processed yielding lower quality polymers after certain amount of recycling times (Sinai, 2017). The lower quality recycled polymers do not function as such in their original application, for example, when the material from recycled plastic bottles is not suitable for new bottles it is used in clothing, fleece, or lumber. Additionally, recycling process typically requires more energy alongside production of new products making it hard to compete with virgin plastics.

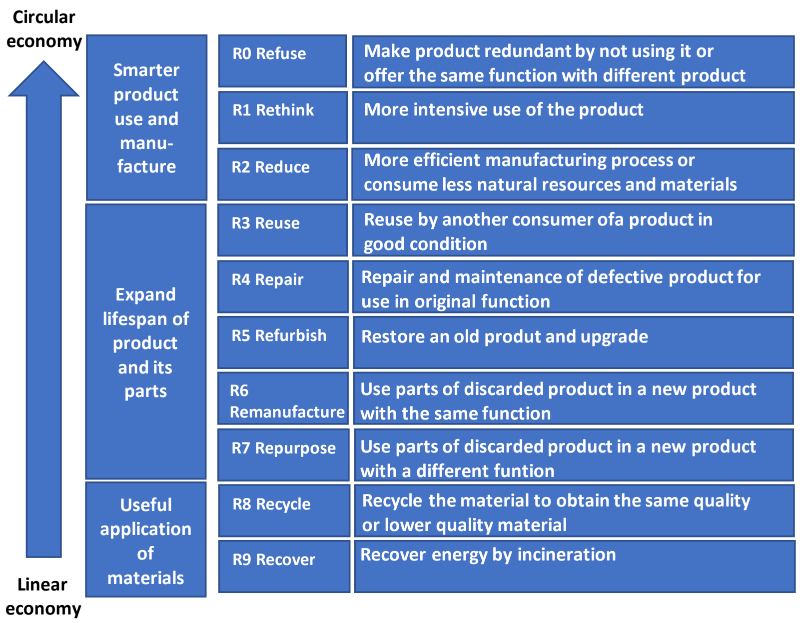

Figure 3. The 9R Framework (Modified from Kirchherr et al., 2017).

3 Review of strategies and regulations in the European Union

European Union has shown to be a front runner for promoting transition to circular economy and in 2019 launched The European Green Deal. European Union has set ambitious goals through Green Deal and other regulations. Couple of the many goals that has been set are carbon neutrality by 2050 and strategies for circular economy of plastics such as recyclability of all plastic packaging by 2030. In this section the European strategy for circular economy for plastics will be reviewed including the European Green Deal, Circular Economy Action Plan, Directive (EU) 2019/904 on reducing the impact of certain plastic products on the environment, Directive 94/62/EC on packaging and packaging waste , Regulation (EU) 2022/1616 on recycled plastic materials and articles intended to come into contact with foods, Directive 2008/98/EC on waste, Ecodesign for sustainable products and other Regulations affecting other than packaging sectors including chemical regulations.

3.1 Current state and goals set by key regulations of European Union

Europe is committed to tackle climate and environmental-related challenges. The European Green Deal is one of the European Commission's priorities for years 2019-2024. The European Green Deal plan is set to transform the EU into a modern, resource-efficient, and competitive economy. It has two ultimate goals: no net emissions of greenhouse gases by 2050 and economic growth decoupled from resource use ensuring that no person and no place is left behind. The plastics sector is one among many other sectors addressed in the European Green Deal. (EC/2019/640)

A new Circular Economy Action Plan was adopted by the Commission in 2020 as one of the main building blocks of the European Green Deal. The action plan is focused on resource-intensive sectors which includes plastics. The Action Plan sets a framework for sustainable product policy. It promotes designing sustainable products, empowering consumers and public buyers, and circularity in production processes. (EC/2020/98)

According to the Action Plan mandatory requirements for recycled plastic content in key products such as packaging, construction materials and vehicles will be proposed to increase uptake of recycled plastic (EC/2020/98). The requirements for some beverage bottles are already set in single-use plastics directive, e.g., in 2025 PET bottles should contain minimum of 25 % recycled plastic and as of 2030 recycled content should be 30 % in all bottles (EU/2019/904).

Sectors such as electronics, vehicles, construction and building, and packaging are handled separately from plastics in Circular Economy Action Plan. However, all these sectors are using plastics in products and packaging being the main application for plastics (PlasticsEurope, 2021). This fact also explains the high interest in regulating plastic packaging sector by introducing recycling targets and mandates for plastic packaging before others. In European Green Deal it is stated that by, 2030 all packaging should be reusable or recyclable in an economically viable way (EC/2019/640). Linking into directive on packaging and packaging waste, where it is stated that by 2025 50 w-% of plastic packaging material should be recycled and for 2030 the target is 55 w-% (EU/2018/852).

In EU recycling rate of plastics is lagging compared to other materials. Recycling rates of packaging by material type in 2019 are 82 % for paper and cardboard, 77,4 % for metallic, 75,4 for glass, 40,6 % for plastic, and only wooden packaging has lower recycling rate than plastic of 31 % (Figure 4) (eurostat, 2022). There are environmental and economic benefits for the EU to improve the recycling of plastics. However, there must be a joint effort from industry, plastics manufacturers as well as public and private waste management companies.

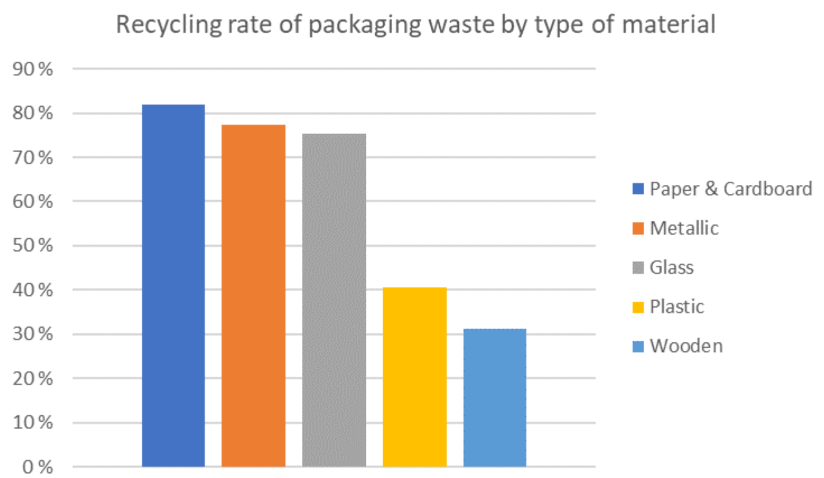

Figure 4. Recycling rate of packaging waste by type of material. (eurostat, 2022)

The European Commission (2018) set four key actions to improve recycling and recyclability of plastics. Firstly, improvements in design and support innovations to make plastics more recyclable. This means, for example, to stop using multilayer packaging that are hard to separate and various additives that complicate the recycling process. Secondly, expanding and improving the collection. This will help with initially better separated waste flows to recycling facilities resulting in better quality product. Thirdly, expanding and modernising the sorting and recycling capacity. Current capacity is not enough to achieve EU's recycling goals for plastics, so it is required to distribute current best practises and adding more recycling facilities. Lastly, creation of viable markets for recycled and renewable plastics. Too many industries lack trust for recycled plastics, whether because of potential steady feedstock issues, quality issues, or monetary gain. (European Commission, 2018)

To promote the use of recycled plastic Circular Plastics Alliance was created and supported by European Commission. The main goal of the alliance is to increase the use of recycled plastic in products to at least 10 million tonnes by 2025. In 2021 this number was 5,8 Mt (PlasticsEurope, 2022). The alliance involves private and public stakeholders in the plastics value chain to promote the use of recycled plastics. According to the declaration of the alliance they are committed to various actions regarding the circular economy of plastics and uptake of recycled plastics such as design of plastic products, collection and sorting, use of recycled content, R&D, and investments, and monitoring the progress. The design of plastic products will be developed, updated, or revised for recycling guidelines to deliver the volumes and quality needed for market needs. Work will be done on improvements in collection and sorting of plastic waste with all relevant actors across Europe. Regarding uptake of recycled plastics, the legal, economic, and technical requirements will be identified. R&D and investment needs will be defined including chemical recycling. For monitoring the progress, a transparent and trusted voluntary system will be set up. (European Commission, 2019)

3.2 Directive on reducing the impacts of certain plastic products on the environment (EU) 2019/904

The directive on reducing the impacts of certain plastic products on the environment was set in 2019. There are two main objectives of the directive. First, to prevent and reduce the impact of single-use plastic (SUP) products on the environment. This is promoted by inhibiting their placement on the market when more sustainable alternatives are available. Second, delivering a significant element on EU's plastics strategy to move towards a circular economy. (EU/2019/904)

Key points of the directive on reducing the impacts of certain plastic products on the environment are market restrictions of certain single-use-plastic products such as cutlery, plates and straws. In addition to banning certain products on the market EU Member states are required to take actions to reduce the consumption of some products such as covers, lids, containers of prepared food. Furthermore, the commission has laid down implementing act on calculating, verifying, and reporting the reduction in the consumption of certain SUP products for Member States (EU/2022/162). (EU/2019/904)

SUP Directive has also set separate collection and design requirements for SUP bottles. The collection target of 90 % for SUP plastic bottles by 2029. Additionally, to earlier mentioned recycled plastic content targets caps and lids made of plastic should remain attached to the containers. Compulsory harmonized markings are required on certain products (Figure 5). (EU/2019/904)

Figure 5. Harmonized markings for certain single-use plastic products. A) sanitary towels and wet wipes. B) tampons and tampon applicators. C) beverage cups. D) tobacco filters. (EU/2020/2151)

The directive includes an extended producer responsibility (EPR) for certain products. The principle of the polluter pays has been incorporated. This affects producers making it mandatory to cover the costs of waste collection and of cleaning up litter, data gathering, awareness-rising. (EU/2019/904)

3.3 Directive on packaging and packaging waste 94/62/EC

The EU rules on packaging and packaging waste are set in the Directive 94/62/EC with the lates version being in force from 2018. There are four main objectives of the Packaging Directive. First, to harmonise national measures on packaging and the management of packaging waste. Second, to have a positive impact on the environment by preventing and reducing its impacts caused by packaging and packaging waste. Third, prevent production of packaging waste. Fourth, contribute to the transition to the circular economy by promoting strategies such as reuse and recycle. (EU/2018/852)

Key measures for EU countries according to the Directive are the following: take measures such as national programmes, incentives through EPR schemes and other economic instruments to rule out the generation of packaging waste and reduce impacts of packaging on environment. The actions by EU countries may include for example deposit-return schemes, targets, economic incentives, and reusable packaging targets. Recycling targets set by the Directive discussed earlier in terms of plastic packaging are 50 % by 2025 and 55 % by 2030. (EU/2018/852)

Some essential requirements are specified in the Packaging Directive. First, to limit the weight and volume of packaging, while still meet the requirements on the level of safety, hygiene and acceptability for the products and consumers. Second, to reduce hazardous substances and materials in the packaging. Third, to design reusable or recoverable packaging. (EU/2018/852)

3.4 Regulation on recycled plastic materials and articles intended to come into contact with food (EU) 2022/1616

The Regulation (EU) 2022/1616 on recycled plastic materials and articles intended to come into contact with food was set in force in 2022. The objectives of the regulation are to lay down rules for the sale of products or articles that are intended or expected to come into contact with food manufactured from recycled plastic. The regulation additionally sets rules for development and operation of plastic recycling technologies. Lastly, the regulation sets rules for the use of plastic materials and articles which have been or are intended to be recycled. (EU/2022/1616)

Key points stated in the regulation are specifications for suitable recycling technologies. The technologies must ensure microbiological safety, endanger human health or affect the food or its colour, aroma, taste and texture. Additionally, appropriate labelling, advertising and presentation should be used to prevent from misleading the consumers. (EU/2022/1616)

Collection of plastic waste must be ensured to be originated from municipal waste or specific food retail or business and collected with certified collection system. Plastic waste must be collected separately or with a recycling scheme in which participants ensure no contaminations of the plastic. (EU/2022/1616)

Only two types of suitable recycling processes are listed. Post-consumer mechanical PET recycling is one of them. Amount of non-food post-consumer PET waste is limited to maximum of 5 % in plastic input. The output material cannot be used in microwave or conventional ovens, but additional output specifications can be applied for individual processes. Another technology is recycling from product loops which are in a closed and controlled chain. Only plastic input allowed is plastic intended for food contact originated from closed loop cycles which are manufacturing, distribution or catering stage and contamination cannot be an issue. Microbiological decontamination by high temperature and basic surface cleaning must be provided for the plastic input. Recyclate must be used for same purpose as originally intended. (EU/2022/1616)

Novel technologies can be developed independently. However, development of novel technologies has several requirements. It is required by the technology developers to inform national authority and the Commission and providing information of the work with scientific proof and studies conducted. Update during installation is required including summarising the complete process and publishing a report twice a year of average contamination levels. Approval from European Food Safety Authority is required and other specific rules for recyclers. (EU/2022/1616)

3.5 Waste Framework Directive and other sectors

The Waste Framework Directive has set various general rules of waste management including definitions of waste, recycling and recovery related basic concepts and definitions. Waste Framework Directive prevents waste management actions to harm human health and the environment. It provides waste hierarchy to prioritize waste prevention. The Directive also establishes the polluter pays principle and the EPR, and its general minimum requirements. (EC/2008/98)

While the Directive does not focus specifically on plastic it includes sectors such as construction and demolition (CDW), waste from electrical and electronic equipment (WEEE) and end-of-life vehicles (ELV) that use plastic in products. These sectors may include plastic with hazardous substances and thus may be classified as hazardous waste. The Waste Framework Directive provides additional labelling, record keeping, monitoring and control obligations from the waste production to the final disposal or recovery also known as “cradle to grave”. However, additional regulations and directives such as Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), Restriction of Hazardous Substances (RoHS) and persistent organic pollutants (POP) take place to protect human health and the environment from the risks of chemicals (EC/1907/2006; EU/2011/65; EU/2019/1021). The main purpose of these is to ensure protection of human health and the environment. The main target is a restriction of products containing hazardous substances that exceed the limit values defined in the regulations. Thus, restricting them from being placed on market and therefore phasing them out from circulation. (EC/2008/98)

Directives such as 2012/19/EU on waste electrical and electronic equipment (WEEE) and 2000/53/EC on end-of-life vehicles, set out measures to prevent and limit waste from said products and components. Their objective is also to promote circular strategies and support resource efficiency. However, no plastic fraction specific issues are discussed in these directives. (EC/2000/53; EU/2012/19)

3.6 Eco-design

The Ecodesign for Sustainable Products has been proposed in 2022. The new Ecodesign for Sustainable Products will build on current Ecodesign Directive 2009/125/EC, which cover energy-related products. The framework will be setting requirements for specific products, and significantly improve their circularity, energy performance and other environmental sustainability aspects. The following requirements are included (European Commission, 2022):

- Product durability, reusability, upgradability, and reparability
- Presence of substances that inhibit circularity
- Energy and resource efficiency
- Recycled content
- Remanufacturing and recycling
- Carbon and environmental footprints
- Information requirement, including Product Passport

3.7 Summary of regulatory review

A wide range of regulatory environment was reviewed in this section. From the review it is clear that the EU is heavily prioritising the plastic problem and sets ambitious targets in the near future. The regulatory environment is still under development and not everything is yet to be specified. Packaging sectors seems to be currently the prioritized sector. Other sectors such as WEEE, ELV and CDW sectors are also generally mentioned and regulated with objectives to increase circularity. However, no such immediate targets or actions as for plastic packaging sector were noticed from the review, that target specifically plastic fractions from these sectors. Currently work is being done to foster the regulatory environment with proposals such as the Ecodesign for Sustainable Products and end-of-waste criteria which development began in 2022 (Directorate-General for Environment, 2022). These regulations have a significant potential to improve the waste management and circularity of plastics.

4 State-of-the-art review

In this section state-of-the-art for plastic waste recycling will be reviewed, including examples of good practices and challenges. The section will include feedstock, collection pre-treatment, mechanical recycling, chemical recycling and solvent based depolymerization, as well as problems with extensive incineration and landfill.

4.1 Feedstock and collection

Post-consumer plastic waste consists of everyday plastic products. The products are mainly plastic bottles and packaging. This waste stream can include all kinds of plastics but mainly PE, PP and PET. Post-consumer plastic waste stream often contains foreign materials and contaminants such as additives, paper, glass, and even hazardous substances due to improper sorting by consumers or businesses. Therefore, post-consumer plastic waste stream is very heterogenous, even though it often is collected separately. (Lange, 2021)

Collection of post-consumer plastic waste is typically done in the EU by curbside pickup or from permanent drop-off collection points, deposit-return points, or special collections. Plastic waste can be included in single-stream recycling where multiple types of recyclable materials such as plastic, glass, paper, and aluminium are placed in a single bag or container. This mixed collection method has lower collection costs, but major drawbacks are lower quality recycled material due to contamination and higher sorting costs. Another way is separate collection. When all recyclable materials are collected separately. Hence, the waste stream to recyclers is more homogenous. The more homogenous stream is the easier it is to sort, and it is less contaminated from other material, and thus better-quality material is produced through recycling. (BCC Publishing, 2022)

Amount of waste of electrical and electronic equipment (WEEE) is growing rapidly. In 2019 global e-waste generated was estimated to be 53,6 Mt and expected to grow to 74,7 Mt by the year 2030. E-waste generated by the EU in 2019 was 12 Mt. In the EU, e-waste management infrastructure is considered well-developed covering collection, recovery of recyclable components and residual disposal in environmentally sound manner. However, only 5,1 Mt of e-waste was documented to be collected and properly recycled in EU. (Forti et al., 2020)

The WEEE is complicated waste stream due to wide range of different equipment and appliances as well as composition such as ferrous metals, non-ferrous metals, plastics, glass, and hazardous substances. Plastics share in WEEE is estimated to be 10-51 % and mainly consisting of plastics such as ABS, HIPS, PC and PP (Weißenbacher et al., 2015). As a result of complex waste stream, identification and plastic separation is an expensive, time-consuming, and complicated process, and therefore a large share of plastics remains unrecycled. Generally, in Europe WEEE-streams are collected and treated separately from other streams thus avoiding mixing into other streams. However, as WEEE-streams contain valuable metals the traditional processes are optimized for metal recovery and not for plastic resulting in high incineration rate of plastic residue from WEEE. (Kaartinen et al., 2020)

Similarly, to WEEE-stream, end of life vehicle (ELV) waste stream has a composition containing various materials and hazardous substances but mainly ferrous metals, non-ferrous metals, and plastics. For the same reason as in the case of WEEE treatment of ELV is optimized for valuable metal recovery. The share of plastics varies depending on the model of the vehicle but generally is 13-21 %. (Kaartinen et al., 2020)

Construction and demolition waste comes from construction, renovation and demolition of buildings and infrastructure. The waste stream is complex, containing various materials such as plastic, concrete, bricks, gypsum, wood, glass etc. including hazardous substances. Collection of CDW is reported to vary within countries in the EU. This makes treatment of CDW hard as there is no harmony across EU countries in definition of CDW, collection or on-site separation. (Kaartinen et al., 2020)

It is estimated that one fifth of all plastics are used in construction. Typical uses of plastics are insulation materials, moisture, and damp proofing materials. Mainly PVC is used accounting for 50-55% of polymers used in building. PS is also a typical polymer present in building with a share of around 14-19%. Other polymers are also present but typically in amount of less than 10%. (Häkkinen et al., 2019)

4.1.1 Extended producer responsibility

Extended producer responsibility (EPR) is an environmental policy approach making producers responsible of product's end-of-life management (Kosior and Mitchell, 2020). As EPR shifts the cost of waste management from local governments to the producing industry, it creates incentive for easier recyclability of products. By making the industry take back their products that have reached end-of-life state encourages them to design them for recyclability or reusability. Thus, minimizing the production cost for the industry by reusing recovered material in new products. (Kosior and Crescenzi, 2020)

Benefits of EPR schemes:

- Increased collection and recycling rates.
- Reduced waste management spending for consumers.
- Reduced overall cost of waste management.
- Environmentally friendly designs. (Kosior and Crescenzi, 2020)

Successful example of EPR scheme is deposit return system (DRS) for plastic bottles. It works by including monetary value on a bottle, which customer pays when buying a beverage. The money is then returned to the customer when the empty bottle is returned to the local retailer. Positive impacts of DRS are discussed in PET bottle to bottle example.

Good example of efficient collection: PET bottle to bottle

PET bottle recycling system is the most developed of any PET product. Average collection rate of PET bottles in European countries which have implemented deposit return system (DRS) is estimated at 96% and for those who do not have DRS at only 48%, making the average collection rate of around 60% (Eunomia, 2022). Remaining 40% of PET bottles placed on the market are leakage from circulation and ending up in landfills, incineration, or environment (Figure 6).

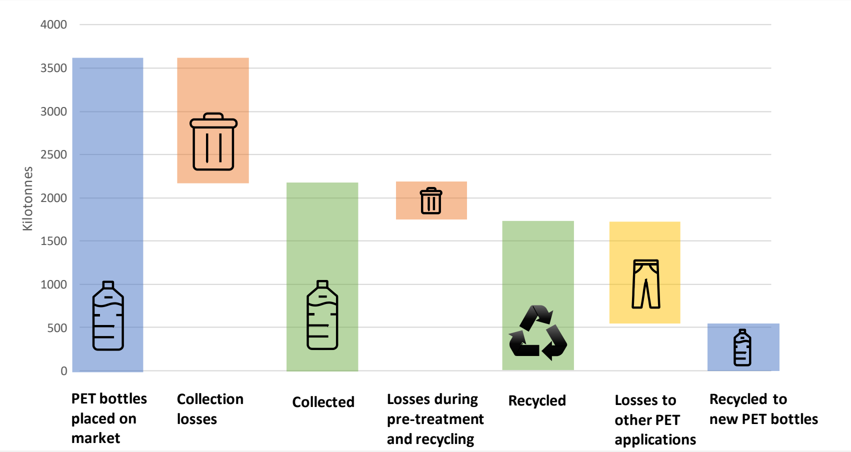

Figure 6. Current state of PET bottle recycling. (Modified from Eunomia and Zero Waste Europe, 2022)

Typically recycling rates are reported as equivalent to the collection rates, however material losses also happen during recycling process. Additional leakages come from pre-treatment and recycling in a form of lost caps, lids, and labels, and during sorting, washing, flake and extrusion losses. These losses are estimated to be around 15% of collected PET bottles. Around 50% of PET bottles placed on the market end up in recycling. However, majority (69%) of it is downcycled for other applications such as trays or textiles and thus lost from circular bottle system. (Eunomia and Zero Waste Europe, 2022)

High success and positive impact of DRS on PET bottle collection will likely attract the rest of European countries to implement the system. More adoption of DRS will improve the quality of collected bottles and reduce contamination caused by separately collected bottle streams. Continued widespread of DRS could result in less material losses due higher collection rates and better quality. (Eunomia and Zero Waste Europe, 2022)

4.2 Pre-treatment

As plastic waste streams are complex, pre-treatment is always required before both mechanical and chemical recycling. Complexity of the waste streams comes from mixture of plastics, contaminants, additives and a bulky nature of plastic waste. As a rule of thumb, the better the quality of feedstock the better product quality will be produced by recycling facilities, which makes pre-treatment equally important as recycling process. There are currently various methods applied for pre-treatment including traditional methods such as sorting and washing as well as more advanced treatments. However, current methods are not sufficient to thoroughly clean and remove the impurities from plastic waste stream (Kol et al., 2021).

Depending on source of plastic waste (e.g., food packaging or construction) the waste stream will contain drastically different contaminants. So, procedures such as sorting, screening, washing, and shredding may be performed for a waste stream in different orders, not at all or multiple times (Ragaert et al., 2017).

Good example of pre-treatment: Modular mixer (Modix-extruder)

Traditional extrusion process of bulky plastic waste requires multiple steps before extrusion such as shredding and pelletizing caused by its limitations of the feeding zone. Modix is a novel extruder developed by VTT (Figure 7). In Modix two cylinders are nested, and the input material passes in between enabling a large contact area for accurate temperature control. The product of Modix processing is compacted homogenous material without any pre-treatment required for the input. The product can be used for example in pyrolysis treatment, that othervice would have been impossible to feed directly into a pyrolysis unit.

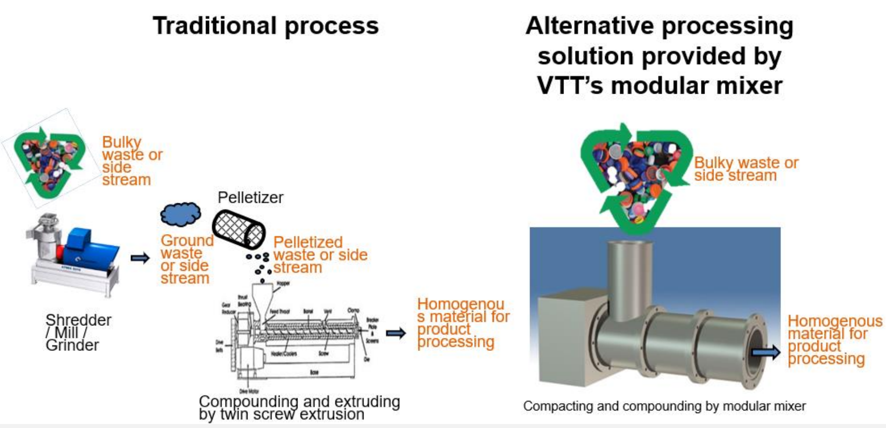

Figure 7. Tradition extrusion vs. Modular mixer (Modix) (VTT, 2018)

The benefits of Modix are a large feeding zone, which allows feeding bulky material directly without any pre-treatment. By Modix treatment efficient mixing with short screw length is achieved while having a possibility for a long processing time in a compact system requiring minimal floor space. The investment costs of the Modix extruder are relatively low due to simplified design and easy maintenance with decreased costs.

4.2.1 Sorting

The sorting steps are typically based on size, shape, density, colour, or chemical composition and sorting is usually done in a sequence of sorting steps (Lange, 2021; Ragaert et al., 2017). Some widely used sorting units are waste screening, air separation, ballistic separation, magnetic separation, eddy current separation, sensor-based sorting, and to some extend manual sorting (Kol et al., 2021). However, recently emerged promising technologies such as watermark and bar-coding are being investigated to enhance the sorting of plastics (PlasticsEurope, n.d.).

Sorting on size is typically done manually or by using sieves. Plastics can be separated from other materials such as metal and glass by using various methods. Common methods are the use of gravity in air flow or density-based separation in water. However, metals can also be removed efficiently by magnetic separators utilizing magnetic attraction of ferrous metal. Some plastics can be separated of each other by taking advantage of their differences in density. For example, density of polyolefins is around 0,9 g/ml and density of PET and PVC is around 1,4 g/ml. (Lange, 2021)

Commonly used infrared detectors (e.g., near or short-wave infrared (NIR or SWIR)) are utilized to identify the plastic in sorting units. Plastics are outspread on conveyor belt, identified by the detector, and sorted accordingly. Hyperspectral imaging spectroscopy (HIS) can be used to detect full-shape products or heavy elements such as Cl and Br by an X-ray fluorescence. HIS can be used together with IR, and it is reported to enhance challenging sorting such as HDPE/LDPE and PET/PLA or black plastics that NIR is not able to detect. (Lange, 2021)

4.2.2 Purification

Generally cleaning of plastic waste is necessary for mechanical recycling but also highly beneficial for chemical recycling. Often contaminants and dirt can hamper the reprocessing. Hence even well sorted plastic is often not suitable for reprocessing without washing. Cleaning is typically done by water and could be assisted by caustic agents or detergents. Washing unit is often integrated after size reduction into sink-float sorting step. Purification step is relatively expensive, requiring washing and drying equipment as well as wastewater treatment. Moreover, even with the most efficient washing for example odorous components are not removed entirely even by caustic wash and nonpolar components require additional detergent or organic solvent to be removed more efficiently, which requires effective wastewater treatment unit. (Lange, 2021)

Good example for sorting: HolyGrail 2.0

HolyGrail 2.0 is a digital watermark initiative driven by AIM – European Brands Association and powered by the Alliance to End Plastic Waste. The objective of this pilot project is to prove technical and economic viability of digital watermarks to enhance sorting of packaging waste on large scale. (AIM, n.d.)

Digital watermarks contain codes that are invisible for the naked eye (Figure 8). They are small barcodes placed on the surface of the plastic product containing information about the plastic. The idea is to use high resolution cameras on the sorting line that will detect and decode the barcodes on the objects and sort them according to the information received from the watermark (e.g., polymer type, food vs non-food usage, manufacturer etc.) Additionally, to sorting and recycling, markings can have benefits for various sectors in plastics lifecycle, where product data can be utilized. (AIM, n.d.).

The results achieved were highly promising in terms of detection (99%), ejection (95 w-%) and purity (95 w-%). Approximately 125 000 pieces of packaging from 260 stock-keeping units were processed. Industrial tests are set to begin in 2022. (AIM, 2022, n.d.)

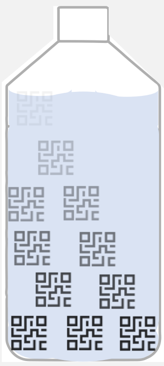

Figure 8. Illustration of watermark technology where camera sees QR-codes, but consumers see a regular water bottle. (Own illustration, modified from AIM, n.d.)

4.3 Mechanical recycling

Mechanical recycling is currently the main recycling process for plastics. In 2020 of all collected post-consumer plastic waste 34,6% was sent to recycling of which only 0,2% was chemically recycled and the rest mechanically (PlasticsEurope, 2021). Mechanical recycling is mature technology and widely used for processing single-polymer plastic waste, such as PET, PE, PP, and polystyrene, but also mixed plastic waste steam can be treated mechanically in some cases (Hahladakis et al., 2020).

Mechanically recycled plastic can replace virgin plastics in the production of the same, similar, or completely different product. Mechanical recycling is categorized into two categories based on the properties of recycled plastic, known as closed-loop and open-loop (Hahladakis et al., 2020).

Closed-loop recycling or upcycling is more desired of the two. In closed-loop recycling the properties of the recycled plastic remain the similar as the virgin material. Therefore, recycled plastic can be reprocessed into same original products and thus reduce the dependence on the virgin plastics. One of the most successful and widely implemented closed-loop recycling of plastic is turning PET bottles into new PET bottles. (Hahladakis et al., 2020)

On the contrary, open-loop recycling also known as downcycling or cascading the properties of the recycled plastic are downgraded to lower quality making it not suitable for production of same products. Plastic can undergo mechanical treatment only few times before it loses its too much of its quality for closed-loop applications. However, it can be used to produce other products that do not require as high-quality plastic. Being less desirable of the two, it is still the inevitable fate of the plastics in mechanical recycling and a viable solution for material recovering. The material from PET bottles that has undergone mechanical recycling a few times and thus degraded, can be still reprocessed for example to street furniture or plastic lumber. (Hahladakis et al., 2020)

4.3.1 Extrusion

By far the most used method for mechanical recycling of plastic waste is an extrusion process. More precisely single-screw extrusion due to its relatively cheap operation, simplicity and ability to provide continuous output at ease (Dynisco, 2017). Thermoplastics are fed into extruder through hopper where high temperature softens plastic waste. The temperature is specified according to the plastic type (Figure 9). Volatile substances such as monomers and solvents are removed through suctioning system (Feil and Pretz, 2020). Alongside melting plastic waste is also homogenised and compressed by the rotating screw (Feil and Pretz, 2020). The rotating screw conveys the melt forward and through a filter with opening widths of 0,06-9,2 mm. to remove solid impurities (Feil and Pretz, 2020). Additionally, post-extrusion forming can also take place for shaping the product and fixed by cooling the plastic (Dynisco, 2017).

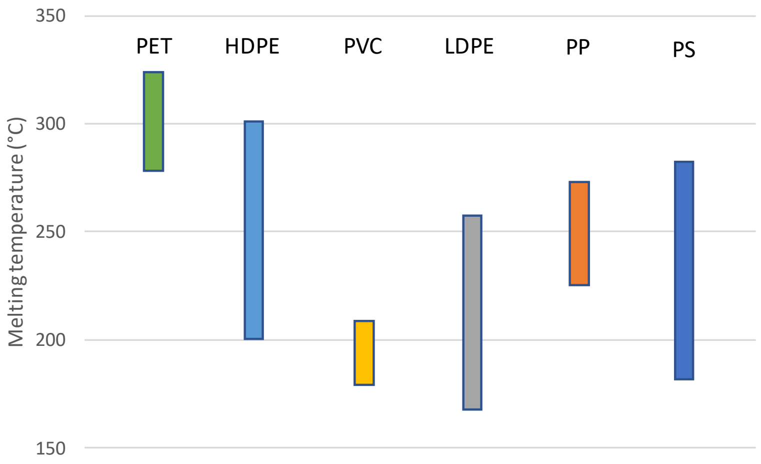

Figure 9. Examples of processing temperature ranges of thermoplastics. (Modified from Schyns and Shaver, 2021)

4.3.2 Degradation

Degradation of polymers during mechanical recycling is inevitable. Degradation is caused by the heat and shear stress targeted on polymers in the extruder. Both factors induce chain scission, chain branching or crosslinking of the polymer and cause reduction in the polymer chain length degrading its mechanical properties and processability. Formation of radicals is the main mechanism to cause degradation. (Schyns and Shaver, 2021)

However, extrusion process is not solely the reason for degradation but also contamination of the plastic waste can accelerate degradation. Colorants used to dye plastic can contribute to the degradation. Printing inks or labels emit volatile compounds and fatty acids that can cause unpleasant odours in the recyclate. Additionally, improper sorting within plastics themselves can cause issues. As an example, existence of PVC in PET stream causes hydrodechlorination at high temperatures resulting in HCl release which accelerates PET degradation and can lead to process failure by damaging the equipment. (Schyns and Shaver, 2021)

Degradation of the polymer can be reduced but not completely avoided by operating at the moderate temperature and screw speeds as these parameters are shown to be directly correlated to degradation. Due to unavoidable degradation some recyclers choose open-loop or semi-closed-loop recycling by feeding virgin polymer during the recycling to balance the degradation. (Schyns and Shaver, 2021)

Good example for mechanical recycling: VAREX extrusion line

Value Retention Extruder (VAREX) extrusion line is an advanced mechanical recycling technology developed by VTT (Figure 10). With this innovative tandem extrusion line, the properties of mechanically recycled plastics can be upgraded to reach ideally virgin-like properties by using in-line measurement of melt rheological properties (e.g., shear and extensional viscosity). (Rytöluoto and Pelto, 2022)

Filtrated melt is fed through melt flow index (MFI) measurement unit and data is transferred to the second extrusion which is a twin-screw extruder. These extruders are constantly communicating with adaptive controller, sending process values from the extrusion line, and receiving new feeder set points if feedstock quality is changing. Several feeders can be connected to the twin-screw extruder, depending on a case-by-case basis. The feeders can be used to feed virgin polymers, additives, stabilizers, compatibilizers etc., and added to the melt according to the set points received through the extruders. In the outlet before processed plastic is collected there is in-line elongational rheometer, which measures shear and extensional viscosities of the final output material. This viscosity data is then utilized in controlling of material feeding and extrusion process. At the end stabilized recycled plastic with upgraded rheological properties is collected. The full system is described in figure 10. (Rytöluoto and Pelto, 2022)

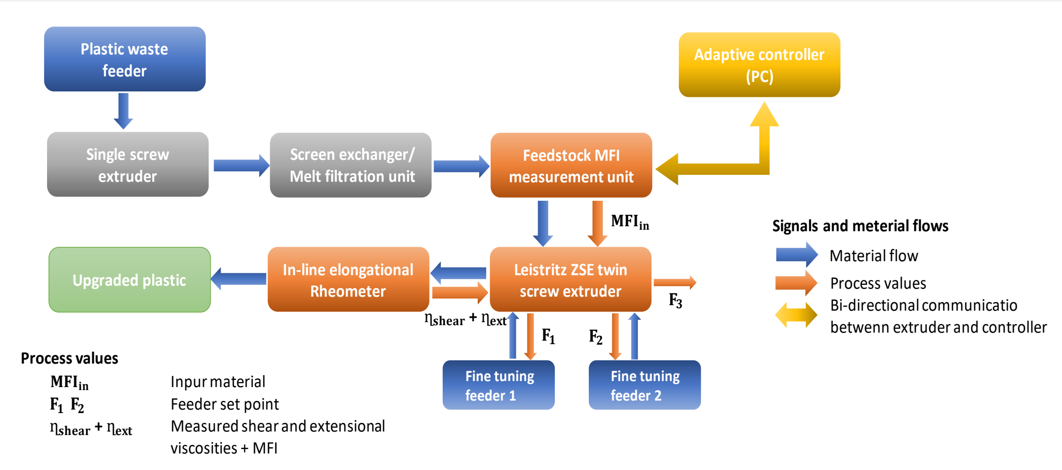

Figure 10. VAREX mechanical recycling line with adaptive in-line rheology control (Own illustration, modified from Rytöluoto and Pelto, 2022).

The advantages of the VAREX extrusion line are in-line measurement and collection of rheological data of the recycled polymers, compounds, and blends. Said data can be directly presented to plastic converters to certify rheological properties of recycled plastic. The process is adaptive which allows it to be modified and to reach desired target viscosity of recycled plastic via smart addition of various compounds within the batch or batch to batch variations. However, if the feedstock is severely degraded or contaminated to begin with a high-quality product is not likely to be achieved, unless significant amount of virgin polymer is added. To conclude, the main benefits of VAREX extrusion line compared to standard mechanical recycling is the in-line data collection with so called "on the fly" addition of compounds to enhance the quality of the final product. (Rytöluoto and Pelto, 2022)

4.4 Chemical recycling

While mechanical recycling is more established technology and has the potential to address the most of waste streams in the future, there is a place for a technology with greater tolerance of contamination and complexity. Chemical recycling can be more suitable to treat waste streams that are contaminated, flexible, multilayer composites, degraded mono-materials, and mixed plastics to produce recyclate with properties equivalent to virgin polymers. (SYSTEMIQ, 2022)

Chemical recycling is relatively novel technology for plastics recycling. Only few commercial-scale plants are currently operating. There are uncertainties regarding policy and full value chain economics at scale. The uncertainties make it hard to estimate development and future impact of these technologies. However, the pledged investment by the European plastics industry is set to increase chemical recycling capacity up to 3,4 Mt per annum. (SYSTEMIQ, 2022)

Chemical recycling technologies are classified into four main technologies: dissolution, depolymerisation, pyrolysis and gasification. These technologies have different principles but all of them can produce virgin like polymers. They all differ by for example, feedstock tolerances to impurities and organic contamination, yields, emissions factors, costs, levels of maturity and types of outputs. Due to nascence of chemical recycling technologies, there is yet to be a clear path of which of the four technologies will scale up the most. (SYSTEMIQ, 2022)

4.4.1 Solvent-based chemical recycling

Depolymerisation or solvolysis is one of the solvent-based chemical recycling technologies for plastics. The principle of this technology is depolymerization of polymers into monomers using solvent and relatively high temperatures up to 280°C (Jiang et al., 2022). Solvolysis is a technology that allows selective monomer recovery. Recovered monomers can be further purified from additives and colorants. Purified monomers can be then repolymerized to virgin-like quality polymers. Some of the most common solvolysis reactions are hydrolysis, glycolysis, ammonolysis and methanolysis. Reactions used in solvolysis processes break ether, ester and acid amide bonds and thus their utilisation is limited to polymers containing these bonds or condensation polymers. Therefore, research has been mainly on PET and polyurethane (PUR) but also on polyamides (PA), polycarbonate (PC) and polylactic acid (PLA). (Vollmer et al., 2020)

As solvolysis can be applied only for condensation polymers which are polymerized by polycondensation reactions. Polycondensation reaction is equilibrium reaction and can be reversed, enabling chemical processes for controlled depolymerization. Depolymerization is typically conducted in homogeneous solutions, meaning that polymers are either dissolved or in a molten state. A typical mechanism for solvolysis is a reaction of active hydrogen atoms in chemical compounds with polar groups in the main chain of condensation polymer. However, for polymers such as polyolefins this is not possible due to main chain containing only carbon atoms. (Pohjakallio et al., 2020)

Selective dissolving is similar to solvolysis. The difference is that in selective dissolving polymers do not degrade at the temperatures used. Thus, whole polymers are recovered rather than monomers. Ideally recovered polymers do not contain any contaminants and can be used for any kind of application with same or close to virgin polymer properties. Feedstock requirement for selective dissolving is a large enough difference in solvation and there is a need to use of strong organic solvents, for example, tetrahydrofuran, toluene, or xylene. Selective dissolving can be applied on two-layer materials by direct contact of polymer and the solvent. The method can also be used for multilayer materials through diffusion in a case when target polymer is protected by outer layers. (Pohjakallio et al., 2020)

Good example for pre-treatment: CreaSolv® Process

CreaSolv® is a selective dissolution process developed by Fraunhofer Institute for Process Engineering and Packaging IVV (Figure 11). The process can be classified as a separation process or as a direct recycling process. The process produces high quality recycled plastic with virgin-like material properties. Various contaminants and additives such as printing inks and brominated flame retardants (BFRs) are removed in process. In addition, targeted plastics can be removed in mixed plastic waste including composite plastic such as laminated films and waste electronic and electrical equipment (WEEE). Therefore, developers claim it to be the first process for closed-loop recycling of contaminated plastic waste. (Fraunhofer IVV, n.d.)

The solvent based CreaSolv® Process begins with selective dissolving of the target polymer. Important note is that only non-hazardous solvents certified with Globally Harmonized System (GHS) criteria are used ensuring safety for users, operators, and the environment. Solvent is recovered from every step and treated by distillation, allowing its reuse. After the dissolving step the material is cleaned. Mechanical separation is done for undissolved material and special purification steps at the molecular level are performed to dissolved material such as non-target polymers, inks, and hazardous substances. Solution of macromolecules of targeted polymer with the size and molar mass distribution corresponding to virgin like material is removed from the solvent by precipitation and dried. Achieved product is high quality plastic recyclate for new material production. (Fraunhofer IVV, n.d.)

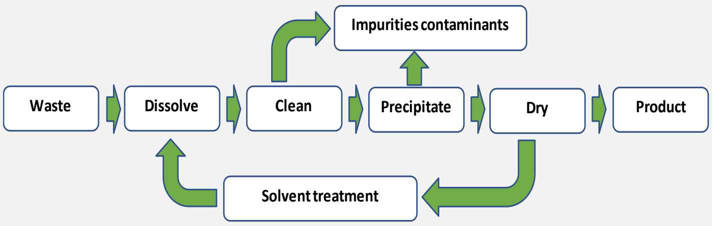

Figure 11. Illustration of CreaSolv® Process. (Own illustration, modified from Fraunhofer IVV, n.d.)

4.4.2 Pyrolysis

Pyrolysis can be used for thermochemical recycling of almost all kinds of organic material including plastics (Krause et al., 2022). Pyrolysis is a process where material is heated and degraded in a relatively high temperature and in absence of oxygen (Figure 12). By pyrolysis plastic waste can be processed back into mixture of hydrocarbons. The mixture of hydrocarbons can be used as a feedstock for new virgin-grade polymers. (Pohjakallio et al., 2020)

Solid plastic waste is first turned into vapor in reactor under relatively high temperatures. Vapor consists of hydrocarbons with carbon numbers ranging from 1 to over 20. The heavier hydrocarbons can be condensed into liquid or wax while lighter fraction that is non-condensable remains as gas. The gas fraction has a relatively high heating value of 25-45 MJ/kg making it a suitable energy source to circulate it back to the process. (Qureshi et al., 2020)

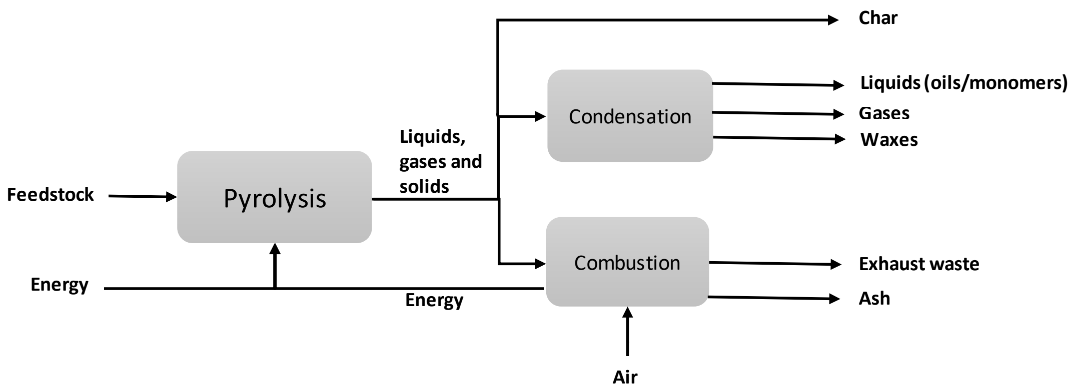

Figure 12. Typical process diagram of pyrolysis of plastic waste (modified from Krause et al., 2022).

The product distribution is affected by various factors such as waste feedstock, catalyst, reactor type, operating conditions (mainly temperature), residence time, heating rate and pressure. Generally liquid fraction or pyrolysis oil is the desired product, but the process can be optimized into production of wax, monomers, aromatics, or selective chemicals using different catalysts. (Qureshi et al., 2020)

Pyrolysis oil is a crude oil-like mixture rich of hydrocarbons which can be refined into fuel or preferably refined to produce new monomers and polymers (Pohjakallio et al., 2020; Vollmer et al., 2020). Even though the refinement of pyrolysis oil to fuel can be considered easier and could also have positive impact on CO_2 emissions it is not a circular solution. Polymers refined from pyrolysis oil have a virgin grade properties and could be used in production of new high-quality plastic products. While pyrolysis oil could be converted to monomers in similar way as from crude oil, the production of monomers directly from pyrolysis is desired option for economic reasons as additional refining steps are avoided. (Vollmer et al., 2020)

The feedstock for pyrolysis can be more flexible than for mechanical recycling. Separated or even mixed polyolefins are considered as an ideal feed for pyrolysis (Qureshi et al., 2020). Additionally, to some extent more contaminated plastic waste can be fed into pyrolysis reactor without major issues (Pohjakallio et al., 2020). However, there are some limitations in terms of monomer production from pyrolysis. For example, PET and PVC are almost impossible to process to monomers without additional pre-treatment step of selective removal of HCl in the case of PVC presence (Vollmer et al., 2020). PET on the other hand decomposes into phthalic acids which worsens the oil quality (Qureshi et al., 2020). However, high monomer recovery of up to 70% from polystyrene pyrolysis can be achieved (Artetxe et al., 2015). Polyolefins can be converted directly to monomers but with rather low yield of around 35 wt% (Vollmer et al., 2020).

Good example for pyrolysis: Depolymerisation of polystyrene to styrene oil

INEOS Styrolution has developed a proof of concept for depolymerisation technology of polystyrene waste. The feedstock must be sorted and shredded before feeding into the depolymerisation process. The process can handle contaminations of polyolefins but is limited to <1% of PET and ABS content. The process requires high temperature of 500-700˚C and as short as possible residence time to depolymerise PS into its monomers. The product is crude styrene oil that needs to be purified by distillation before repolymerisation. According to the research led by the company up to 75% of the product can be fed into distillation and polymerised to new PS. Life cycle assessment (LCA) was conducted for the technology and showed around 35% savings in greenhouse gas (GHG) emissions compared to fossil-based monomer production. (Krause et al., 2022)

Another technology to depolymerise PS is developed by Pyrowave which is a catalytic microwave depolymerisation (CMD) technology. The demonstration plant is planned to begin its operation in 2023. Similarly, to INEOS technology feedstock needs to be shredded and cleaned by removing contaminants such as labels and films. The technology uses microwave energy to transfer heat to reactor by mixing silicon carbide in feedstock. Obtained monomers are purified by distillation to produce styrene oil. A capacity of the unit is 100-200 kg/h with a yield of up to 95% of monomers. Compared to production of styrene monomers from crude oil energy demand is 15 times less for this technology. (Krause et al., 2022)

4.4.3 Gasification

Gasification is a processes where organic material can be converted into a gas known as syngas. Syngas or synthesis gas contains mainly hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4) and nitrogen (N_2) (Lopez et al., 2018). The focus of plastic waste gasification products has been mainly for energy production, energy carrier or chemicals from syngas (Lopez et al., 2018). However novel technologies have been emerging to produce virgin olefins that can be used in production of virgin grade polymers such as Olefy technology (VTT, 2022).

Gasification is an energy intensive process. Typically, the required temperature is over 700 ˚C (Krause et al., 2022). The advantage of gasification is even more flexibility in feedstock compared to pyrolysis. Feedstock for gasification can be plastics of different composition, mixtures or mixed with another feedstock (Lopez et al., 2018). Product (syngas) may need purification such as removal of N_2 or adjustments in concentration and ratio of CO and H_2 depending on the intended use (Krause et al., 2022).

Good example for gasification: Olefy technology

Olefy technology is single step gasification process for plastic waste. The technology can recover over up to 70% of virgin grade plastics and chemical raw material components from plastic waste. The company claims the technology to be an economically viable to recycle plastic waste by gasification. The process requires feedstock with minimal sorting by consumers and businesses tolerating some contaminants in the feed. The Olefy process requires the same amount of PE or PP waste to produce a ton of virgin grade olefins as the amount of naphtha would be required in traditional way of olefin production, which has a higher cost. The process is also self-sufficient in terms of energy as it produces enough energy to be circulated back into the process. The Olefy pilot is running at VTT Bioruukki Pilot Centre in Espoo, Finland and its first industrial demonstration operation is expected in 2026. (VTT, 2022)

4.5 Landfill and incineration

Landfill and incineration are to be avoided for achieving circular economy of plastics. According to PlasticsEurope (2021) 42% of collected post-consumer plastic waste was sent to incineration and 23,4% to landfill. So, over 65% of potential resource is lost, of which at least a part could have been used for recycling with current technologies.

Incineration has been an effective and the most common way of plastic waste disposal in Europe. While incineration has benefits such as efficient way to reduce total volume of plastic waste sent to landfill and energy recovery, it has no benefits in circularity of plastics as material is lost after the process (Idumah and Nwuzor, 2019). Additionally, incineration contributes to air pollution and release of hazardous gases even though incineration techniques have improved over time with energy efficiency and pollution control (Idumah and Nwuzor, 2019).

Landfilling is traditional approach to waste management. In a well-managed landfill, there are no further environmental harm except from collection and transportation of waste to a landfill. However, there might be long term possibilities of groundwater and soil contamination caused by additives and breakdown of plastics. Main drawback of landfill is that there is no material or energy recovery involved. Therefore, it is not circular solution and should be completely avoided. (Siddiqui and Pandey, 2013)

5 Challenges of plastic waste recycling

The plastics recycling industry is facing various challenges. The challenges affecting the plastic waste recyclability begin already at the production stage and cascade throughout the whole life cycle. All the stages such as design, production, use, separation, disposal, collection, and sorting have implications on the recyclability of plastic waste stream. In this section challenges found from literature are reviewed across plastic waste recycling and the uptake of recycled plastic as it is the most important factor to make recycling feasible.

5.1 Challenges related to collection and sorting

It is estimated that in Europe 57,2 Mt of plastics were produced in 2021. Collected amount of post-consumer plastic waste in 2020 was 29,5 Mt. According to the data approximately 50% of waste is either mismanaged or still in use by consumers. Of the collected post-consumer plastic waste only 35% (10,3 Mt) was sent to recycling. By accounting the certain share of rejects of technological processes the actual recycling rate is even less. Majority (42% or 12,4 Mt) of collected post-consumer plastic waste was still incinerated for energy recovery. Amount sent to landfill was the lowest but still significant (23% or 6,8 Mt). By analysing the data provided, there is a need to increase both collection and recycling rates of plastic waste. (PlasticsEurope, 2022)

Current collection schemes vary around the world and even across Europe. Differences in the collection schemes can create confusion for people moving around constantly. Improper sorting caused by the lack of awareness and further enhanced by confusion across different collection schemes have a direct impact on the quality of plastic waste stream. (Hahladakis and Iacovidou, 2019)

Majority of plastic products are designed with advantageous properties from a use-phase perspective such as durability, low density, and non-degradability but not so much from recycling-phase perspective. Besides the high volume of plastics, they are used by many different sectors. Generally, each of the sectors require plastic with different properties. To achieve some of the technical specifications, various fillers and additives are added to plastic including hazardous substances such as brominated flame retardants (BFRs) or phthalates. Some of these additives are often hard to identify and can cause problems in recycling such as safety issues or compromise the quality of the recyclate. High variety of plastics application and in composition creates a complex challenge for waste management. (Ragossnig and Agamuthu, 2021)

Sorting efficiency and accuracy is largely affected by the composition of plastic waste stream. Mixed plastic waste stream is often complex and may include multi-layered, flexible, and black plastics that are challenging to sort or to recycle. Often due to lack of economically viable ways to sort or recycle these materials get rejected. Additionally, labels or sleeves may cover over 60% of the plastic component and may cause errors in the identification of the polymer type. According to study of Siltaloppi and Jähi (2021), low market value of plastic inhibits the private actors to invest in R&D and bigger capacity without an incentive or enforcement from regulations. (Hahladakis and Iacovidou, 2019)

Near infrared (NIR) technology is typically utilized in technologically advanced sorting facilities. However, the technology has its limitations. The main flaws of the NIR technology are inability to detect carbon black, false readings such as detection of a label made of PP instead of the bottle made of PET, and detection of only one type of polymer in multilayer plastics. As a result, there is a need to couple NIR technologies with different physical based sorting or manual sorting. Still in less advanced sorting facilities approximately 13-18% of target plastic waste gets rejected. Additionally, losses with non-target plastic waste of approximately 12-15% equal to quite high rejection rates overall of plastic material due to inability to sort the waste stream properly. (Hahladakis and Iacovidou, 2019)

5.2 Challenges related to mechanical recycling

One of the greatest challenges faced by recycling industries relate to the quality of the output material. There are numerous factors affecting the issue such as application, diversity of polymers, collection schemes, additives and materials mixed with the polymer and degradation of material properties. As seen majority of the issues are consequences of factors before the waste stream arrives to recycling plant. (Hahladakis et al., 2020)

Composition of the input material can vary a lot depending on the source of plastic waste and sorting techniques. From only 7 thermoplastic resin codes thousands of different types of plastics are on the market (Hahladakis et al., 2020). The mechanical processing of mixed plastic waste is complicated as the properties such as melting points will differ according to the plastic type and the output will be a polymer blend often with low-quality properties (Ragaert et al., 2017).

The lack of information of additives such as fillers, antioxidants, plasticizers, dyes, flame retardants that are used to achieve desired looks or properties for plastic products further complicate the process. Hence, the output of mechanical recycling will often be lower quality and contain the market-average of additives if not sorted and purified from the additives. Currently only a minor fraction is recycled in a closed loop, which are the purest and the cleanest waste stream. (Hahladakis et al., 2020; Lange, 2021)

Foreign materials are also contributing to contamination of plastic waste stream. Contamination can be consequence of designed and created factors. Designed factors can be for example labels, adhesives, or additives. Created factors on the other hand are results of mismanaging the plastic waste for example by mixing with other materials at the collection point. Contaminants can affect the properties of plastic material such as tensile strength and rheological properties and thus making it hard to predict its behaviour and achieve high quality output. (Hahladakis et al., 2020)

There are currently limited ways to remove odour, ink, or other additives to achieve clean plastic input for recycling plants. The inability to remove these issues leads to material losses or unpleasant odour or colour of the recyclate. Pre-treatment is one of the most important steps of recycling process to ensure good quality plastic waste, but even the most advanced processes cannot turn all the plastic waste streams into sufficiently clean input for recycling. Therefore, there is a need for further develop universally agreed design choices, standards and information of additives present in plastics to ease the recycling industry and ultimately help progress towards circular economy (Hahladakis et al., 2020).

An obvious challenge regarding mechanical recycling is degradation of polymers caused by the high temperature and mechanical shear force of the process. These degradation mechanisms affect polymers' molar mass and its distribution, crystallinity, and chain flexibility. Chain scissions can also cause branching and cross-linking which compromises plastic materials properties. There are ways to combat the degradation such as blending the virgin polymer to the recycling process. However, this solution is not the most ideal in terms of circularity of plastics, but it extends the number of cycles the polymer can undergo. (Hahladakis et al., 2020)

There is no incentive for recycling some of the plastics with low density or low market value (e.g., PS) (Carey, 2017). Only high-value and high-volume plastics are sorted and recycled on a larger scale including PET, PE, and PP (Hahladakis et al., 2020). However, even part of the collected high-value plastics is still discarded by recyclers due to issues in sorting or contamination (Hahladakis and Iacovidou, 2019).

Because of combinations of these problems faced by mechanical recycling, it is often easier and safer for businesses to use virgin plastics for specific application with well-known properties without substantial price difference (Hahladakis et al., 2020).

5.3 Challenges related to solvolysis and selective dissolving

Although solvolysis can be applied to treat some of the waste streams that cannot be treated mechanically, it still has its limitations. Waste stream should still have plastics with good enough quality, cleanliness and the most notably containing only condensation polymers. Even if its theoretically possible to remove additives and separate plastic mixtures, purification stage would need to be very complex and expensive in order to produce high quality monomers without comonomers, degraded monomers, or additives. (Lange, 2021)

Fore discussed methods that are methanolysis, hydrolysis and glycolysis, have their own drawbacks. In methanolysis the reaction product of post-consumer PET consists of glycols, alcohols, phthalate derivatives and the desired product dimethyl terephthalate (DMT). Such a mixture makes it costly to separate and refine the wanted end products. Also, catalyst is poisoned by water that is formed during the reaction and forms various azeotropes. Major drawback of hydrolysis is the low purity of terephthalic acid (TPA), and the process is slow as water is a weak nucleophile. Glycolysis is not suitable for removing low levels of copolymers, colorants, or dyes, but is suitable for high quality plastic waste from post-industrial waste. (George and Kurian, 2014)

5.4 Challenges related to pyrolysis and gasification.

Both pyrolysis and gasification are yet to have significant impact on circular economy of plastics. However, research has been going on to implement these technologies in the commercial stage. Many challenges that these technologies are facing are related to factors prior recycling such as variations in feedstock quality and composition (Lopez et al., 2018).

Naphtha can be produced by pyrolysis of plastic waste, but according to review by Dai et al. (2022) there are no reports for achieving the same quality as fossil naphtha. A suitable catalyst that is economically viable is needed to improve naphtha quality. The plastic-based naphtha could then be used in existing petrochemical infrastructure to replace fossil-based naphtha to produce new polyolefins with virgin-grade properties. (Dai et al., 2022)

Heteroatoms are atoms that are not carbon or hydrogen. Plastics containing heteroatoms such as PET and PVC are problematic for pyrolysis (Jiang et al., 2022). Due to imperfect separation, input will almost always contain some PVC. Therefore, input requires careful inspection prior processing as formed HCl will prevent products use as a petrochemical feedstock (Ragaert et al., 2017). PET, on the other hand, will liberate a lot of gas and oxygenated fragments such as benzoic acid in the oil deteriorating its quality (Lange, 2021).

Proposed solution to complex plastic waste stream is to divide it into three fractions, i.e. polyolefins (PE and PP), aromatic plastics such as PS, and others (Dai et al., 2022). Then selective catalyst and optimized process needs to be developed for each stream. Polyolefins can be converted to naphtha, polystyrene to its monomers and other plastics to energy or through additional steps to raw material for petrochemical industry. However, according to Ragaert et al. (2017) pyrolysis is only economically viable when operating in large volumes. So, efficient sorting would be still required to supply pyrolysis plants with stable, large volume of well sorted and quality plastic waste (Ragaert et al., 2017). Otherwise if such sorting is not realistic or economically viable, plastic waste mixture could be treated producing wide range of products. (Dai et al., 2022). Hence, the former path requires larger investments in separation and purification of the products.

Reactions that occur in pyrolysis process are complex, especially when processing mixed plastic waste. Reactions are difficult or impossible to control to influence desired product spectra. Additionally, impurities can promote formation of undesired products and thus cause a loss of products value. For example, PE and PP tend to randomly fragment, requiring additional processing after pyrolysis to replace fossil-based naphtha. (Ragaert et al., 2017)

A main challenge in gasification technology is tar formation which causes operational problems. Tar formation reduces process efficiency and quality of the gas produced (Lopez et al., 2018). Additionally, similarly to pyrolysis there are high capital costs and high energy demand for gasification (Li et al., 2022). According to literature, gasification is not considered as an option for plastic to plastic recycling, but rather as a production of replacement feedstock (syngas) for other fossil-based chemicals such as methanol (Jiang et al., 2022; Ragaert et al., 2017; Zeller et al., 2021). It must be said that ways for monomer production seem to exist according to earlier discussed Olefy technology. However, there is no information available of the working principles of the process. Hence, more research is required for monomer productions by gasification to impact circularity of plastics. The discussed technological challenges are collected in the Table 1.

Table 1. Main challenges of plastics recycling technologies.

	Main challenges	Description	Source
Collection	Lack of collection	57 Mt of plastics produced and 30 Mt collected in the EU 2021	(PlasticsEurope, 2022)
	Variety in collection schemes	Confusion/lack of awareness of consumers	(Hahladakis and Iacovidou, 2019)
Sorting	High variety in plastic waste streams	Various sectors and applications within the sectors for plastics	(Ragossnig and Agamuthu, 2021)
	Design	Recyclability is often not considered in products	(Hahladakis and Iacovidou, 2019)
	Rejects	No circular solutions for high amount of rejects	(Hahladakis and Iacovidou, 2019)
	Unability to invest in new sorting	Private actors are unable to invest into new sorting equipment	(Siltaloppi and Jähi, 2021)
Mechanical recycling	Input quality	Highly dependant on sorting and product design	(Ragaert et al., 2017)
	Output quality	Output quality is highly dependant on the input quality	(Hahladakis et al., 2020)
	Odour	Limited ways to remove unpleasent odour from recycled plastic	(Hahladakis et al., 2020)
	Degradation	Unavoidable polymer degradation from high temperature and shear forces	(Hahladakis et al., 2020)
	Fillers, hazardous substances plasticizers etc.	Lack of information and tracebility of substances	(Hahladakis et al., 2020)
Solvent-based recycling	Input quality	Purification becomes too complex for complicated waste stream	(Lange, 2021)
	Limited input	Reactions only apply to condensation polymers	(Lange, 2021)
	Cost	Capital investments, scale of operations and low cost of product	(George and Kurian, 2014)
Pyrolysis	Catalyst	Economically viable and effective catalyst is needed	(Dai et al., 2022)
	Volume	Stable supply of large amount of feedstock is required	(Ragaert et al., 2017)
	Cost	Investment costs and high energy demand	(Ragaert et al., 2017)
	Limited input	PVC and PET may contaminate the product	(Lange, 2021)
	Output quality	Requires further refinement to be used by existing petrochemical industries	(Dai et al., 2022)
Gasification	Tar formation	Reduces process efficiency and output quality	(Lopez et al., 2018)
	Cost	High capital costs and high energy demand	(Li et al., 2022)
	Monomer/polymer production	Mainly considered as a technology to produce syngas for other fossil-based chemicals	(Jiang et al., 2022; Ragaert et al., 2017; Zeller et al., 2021)

5.5 Uptake challenges of recycled plastic

As seen plastic waste recycling has plenty of challenges to overcome in transition to circular economy. The challenges can be divided into technological, economical, operational, and regulatory barriers. (Siltaloppi and Jähi, 2021)

Technological barriers mainly relate to the material properties of recycled plastic, making it challenging or unattractive choice for designers and converters to adopt. Furthermore, the complicated and expensive process for recycling plastic inevitably drives the price higher compared to virgin plastic. Thus, advancements in technology development are needed to be able to supply the market with higher quality recycled plastic to increase its price to quality ratio. (Siltaloppi and Jähi, 2021)

Current limited and inefficient recycling system including collection, sorting, and recycling limits the supply and thus also increases the price of recycled plastic for large volume buyers. These limits can affect the acquisition of recycled plastic and thus, acting as a barrier of its adoption by large brand owners. Additionally, there may be a lack of competence on the brand owners or manufacturers side to reform the product design using recycled plastic, which further hinders the increase in the use of recycled plastics. (Siltaloppi and Jähi, 2021)

As mentioned, the higher price of recycled plastics does affect converters, brand owners and manufacturers choice between fossil-based and recycled plastic. Especially considering the extra obstacles of recycled plastics such as smaller production volumes and variable quality further makes it an unfavourable choice. Industries operating on small profit margins are unable to factor in additional costs of recycled plastics. Often even the larger brand owners are willing to endure the extra cost to a limited extend. As seen, there are currently no clear gain for industries to integrate or replace fossil-based with recycled plastic. (Siltaloppi and Jähi, 2021)

6 Methodology

Methodology for this work consists of three parts: stakeholder interviews, questionnaire for researchers, and Modix-trial runs. The section will discuss the research methods used for this work.

6.1 Stakeholder interviews

Stakeholder interviews were conducted to gather information from the stakeholders in plastic recycling field. By the information gathered from the interviews the challenges faced by the stakeholders and gaps in the plastics recycling field were identified and compared to the extensive literature review.

Stakeholders were chosen with the aim of covering an extensive range of stakeholders in the field across Europe. In total 16 stakeholders were contacted and invited to an interview. Of the 16 stakeholders 8 participated in the interview. The types of organizations who participated in the interviews were organizations actively advancing circularity of plastics, recyclers from various sectors including WEEE, post-consumer plastic packaging, PET bottles and post-consumer plastic waste, and recycling system and machine developers. The countries of organizations were Finland, Austria, Netherlands, Italy, and Belgium with the sizes of organizations ranging from <50 to >1000.

The interview was a structured interview meaning that each interview had the same questions in the same order. The interviews were conducted online and scheduled for 90 minutes. During the interviews, main points were written down and the interviews were recorded for revision afterwards. The interviewees received the project information sheet and privacy notice and signed a consent form. Interviewees were informed that the participation is completely voluntary, and they can interrupt participation or leave out from the research and withdraw the consent at any time without any specific reason or its explanation. Furthermore, any personal information or contact details were not and will not be used for research purposes. Collected data through interview questions were anonymized and was not connected to the interviewee in any way.

The interview had 19 questions divided into four topics: feedstock, recycling, market, and regulations (Appendix I). The questions for the interview were developed based on the information gathered from the state-of-the-art review and regulatory review.

The questions about plastic waste as a feedstock focused on challenges, quantity, quality, and acquisition of feedstock. For questions related to recycling, the questions were related to the effects of the feedstock quality, recycling capacity, mechanical and chemical recycling, and rejects. Market related questions covered the effects of current energy crisis, demand of recycled plastic, and uptake barriers of recycled plastic. Questions related to plastic waste regulations were about clarity of regulations, regulations on different sectors, European recycling targets, incentives, and regulation affecting the technology development.

6.1.1 Qualitative data analysis using thematic analysis.

Thematic analysis is a method used for analysing qualitative dataset by systematically identifying, organising, and offering insight into recurring patterns (themes) (Braun and Clarke, 2012). Thematic analysis enabled to identify challenges by themes regarding plastic waste recycling across the interviews.

Thematic analysis can be divided into following 6-phases (Braun and Clarke, 2012):

1) **Familiarising with the data**

   The first phase involves immersing into the data. The goal of the phase is to become familiar with dataset's content. Familiarization can be done by re-reading transcripts of interviews and re-watching video data and making notes in the process.

2) **Generating initial codes**

   In the second phase the systematic analysis of the data begins. Coding means applying a label describing the content of the data. By coding each individual data item, they are collated according to the code creating the first groups of data.

3) **Searching for themes**

   Themes are created by reviewing the coded data and identifying areas of similarities and overlap. The process of generating themes is to cluster codes with unifying features together.

4) **Reviewing potential themes**

   The reviewing of themes can include combining initially different themes or splitting broad themes into more specific themes or discard theme if ascertained to be not meaningful.

5) **Defining and naming themes**

Themes should be defined to clearly state what is unique and specific about each theme. Name for a theme should be informative, concise, and catchy.

6) **Producing the report**

Writing the report describing the steps of the data analysis.

Thematic analysis method was chosen to analyze and present the large amount of data in a straightforward and accessible way. As plastic waste recycling is a complex issue and certain challenges affect each other, cascade, or overlap, analyzing data by themes was selected rather than question by question for clarity and to avoid extensive overlapping. Major advantages of thematic analysis are accessibility and flexibility while staying relatively rigorous (Braun and Clarke, 2012).

6.1.2 Applying thematic analysis to the dataset from stakeholder interviews

Familiarization to dataset was done by re-watching video recordings of the interviews. During re-watching all relevant issues were noted into separate interview forms for further analysis.

The interview notes were imported to NVivo software. NVivo was utilized for coding and constructing themes. During coding phase interview notes were read through and data items relevant to identification of plastics recycling challenges or gaps were coded according to the content of the data item. As progressing through the dataset and identifying relevant data items, they were either coded by previously generated codes or new code was created if the data item did not fit under previous codes.

Following three examples are presented to demonstrate the thought process of coding:

> **Data item**: "Competition to acquire recyclable plastic waste is growing, especially in central Europe."
> **Identified challenge**: The challenge is related to acquisition of feedstock to recycle.
> **Code**: Acquisition of feedstock

> **Data item**: "Lowering the number of rejects and finding ways to utilize it."
> **Identified challenge**: The challenge is related to rejects.
> **Code**: Rejects

> **Data item**: "Uncertainties regarding ownership of the waste."
> **Identified challenge**: The challenge is uncertainties in the plastic recycling field.
> **Code**: Uncertainties

In total, 32 individual codes were generated. The number of data items under an individual code were ranging from 1 to 33. Total number of references was 333.

Grouping was done by analysing similarities within codes and creating static sets (themes) by utilizing NVivo software. As the codes were analysed the following themes were identified: feedstock and its quality, recycled plastic and its uptake, technology, and policies. The codes consisting of challenges related to the feedstock for recyclers such as acquisition of plastic waste, product design, quality etc. were grouped into the feedstock and its quality theme. The technology theme included codes such as sorting, recycling technologies, economics of processes etc. Same principles were applied in creating policies theme, which included regulations, mandates and incentives, and recycled plastic and its uptake theme including codes such as recyclate quality and barriers of its uptake.

Created themes were further divided into subthemes to distinguish overarching matter within a theme. Feedstock theme was divided into two subthemes: acquisition of feedstock and feedstock quality. From policies theme regulations, incentives and mandates were separated into subthemes. Technology theme was divided into sorting and recycling. Recycled plastic and its uptake theme was not divided into subthemes as the content was closely related.

6.2 Questionnaire

The questionnaire was designed with a goal to identify current status and challenges as well as knowledge and research gaps within the plastics recycling and circular economy of plastics. The questionnaire was targeted to be answered by RDI professionals like scientists, researchers, and professors. The goal was to identify relevant gaps in the field based on the experience and observations of the respondents.

The questionnaire was prepared utilizing Microsoft Forms. The questions were designed based on the state-of-the-art and regulatory review. The questions were divided into five sections: Background, Feedstock management, Recycling, Markets and policy and Circular strategies. The questionnaire consisted of 22 questions including open questions, multiple choice questions and Likert scales.

The questionnaire had 13 responses in total of which 6 were senior researchers or scientists, 4 researchers or scientists, 2 professors or similar and 1 other. The organization sizes of respondent varied between <50 and >1000. Countries of respondents' organization were Finland, Germany, Belgium, and Austria from public, private, university or academia, and governmental sectors.

6.3 Modix trial runs

The goal of the trial runs with Modix was to showcase how very low-density material can be efficiently compacted to ease, for example, handling, transportation, further treatment (e.g., pyrolysis) of the material.

The feedstock for the trial runs was separately collected agricultural plastic waste. The feedstock was mixed and consisted of 6 different types of agricultural plastic packaging. The 6 different types of packaging are shown and numbered in the Figure 13. The feedstock had minimal number of impurities typical for agriculture such as hay and soil. The feedstock was known to contain mainly LDPE. However, the polymer type of some packaging was unknown. Additionally, film number 5 had an unknown type of plastic valve for vacuum.

Feedstock was manually sorted into 6 separate stacks according to the Figure 13 by the type of the packaging. Most of the feedstock was type 5 packaging, which was used as a base material during processing.

Figure 13. Different plastic films found in the feedstock of agricultural plastic waste.

All types of the plastic films and the valve was analysed by using Fourier-transform infrared spectroscopy (FTIR) and differential scanning calorimetry (DSC). Analyses were used to identify the composition of the material. The analysis confirmed that all polymer types were LDPE or linear low-density polyethylene (LLDPE).

In total four combinations of input were prepared for Modix treatment (Table 2). Batch I, II, III were not washed while batch IV was washed with water and detergent to remove contaminations of soil and hay. Type 5 packaging was the base material as the feedstock contained mainly type 5 packaging. The amount of total material per batch was 5 kg. Type 2 packaging was excluded from the trials due to significantly higher amount of contamination.

Table 2. Configurations of materials used for Modix trials.

Batch I	Batch II	Batch III	Batch IV
100 % type 5 Not washed	95 % type 5 5 % type 3 Not washed	95 % type 5 5 % type 1,3,4,6 Not washed	100 % type 5 Washed with water and detergent

The first trail run was conducted with a batch consisting of only type 5 packaging (Batch I), to study how the material will generally behave during the processing. The sample size was 5 kg of packaging material. The temperature was set to 140°C to ensure complete melting of the material. Rotating speed of the screw was set to 20 rpm after ascertained that 10 rpm caused the screw to get stuck. The material was fed into Modix one by one at an even pace. During processing the material was melted and homogenized by the rotating screw. Treatment of batches II-IV were conducted under the same conditions as the batch I.

7 Results

This section will present results and findings of this work. The results are divided into results from stakeholder interviews, questionnaire and Modix trial runs. For results of the questionnaire, the bolded questions are used to indicate the question under discussion and are answered below it based on the respondents' views.

7.1 Stakeholder interview findings

The findings from stakeholder interview were divided into four topics. These topics are feedstock acquisition and its quality, recycled plastic and its uptake, technology, and policies. The findings are presented separately under the corresponding title.

7.1.1 Feedstock acquisition and its quality

Acquisition of recyclable plastic waste has been identified as a challenge. Four out of eight stakeholders shared thoughts on the lack of input waste for recycling in Europe. Especially in Central Europe there is growing competition between recyclers to acquire high quality plastic waste to recycle with current technologies. At the same time plastic waste in mixed waste and with mixed quality is largely underutilized.

As an example, a recycling plant in Finland is not operating on its full potential due to the lack of supply by the local supplier. It has been reported that there would be enough supply to achieve higher potential of a local recycling plant, but due to high demand of high quality and well sorted plastic waste, and diversification of risks of the supplier, the supply is divided for multiple recycling plants in Europe.

While local recycling plants are not operating on full potential, exports of well sorted and high-quality plastic waste are taking place, which leads into unnecessary transportation of the waste that otherwise could have been treated locally. However, in other sectors such as post-consumer packaging waste the export outside of Finland is a consequence of a lack of local sorting and recycling capacity.

There also exists uncertainties regarding ownership of the plastic waste. Current ownership of the plastic waste in Finland is fragmented into producer responsibility, municipal waste management and private waste management. Such fragmented ownership makes it unattractive to invest into sorting facility as there might not be full certainty for enough feedstock.

In WEEE sector it was noted that illegal exports outside Europe are happening taking away feedstock from local recyclers. A stakeholder from a WEEE sector estimated around 30 % of WEEE to be illegally exported, while another stakeholder said that situation is getting better, and export has become harder.

Regarding impacts of feedstock quality, design for recycling was mentioned frequently. While there have been small improvements especially in packaging sector, there is still room for improvement. Multi-material packaging such as bottles with aluminium caps are still causing problems for recyclers. Certain adhesives tend to cause problems during washing stage by precipitating and clogging filters. Carbon black plastics cannot be identified by optical sorters. Multi-layer packaging when layers cannot be separated cannot be treated efficiently.

In WEEE sector, the design for recycling is not visible. However, when comparing for example packaging and WEEE sectors the changes are noticed considerably slower in WEEE sector due to significantly longer lifetime of the product. As majority of the electrical equipment is designed to last it is not serving the recycling sector, making the recycling complicated. Furthermore, recyclers have noticed the share of plastics increasing in WEEE and new polymers are used for which WEEE recyclers are not prepared to recycle.

Composition and quality of the feedstock received by recyclers has constant fluctuations due to complex plastic waste management and its diversity. Recyclers must tackle uncertainties regarding the feedstock quality and quantity. The factors affecting the quality negatively according to the interviewees are the lack of consumer and businesses' awareness, sorting quality, washing quality, foreign material or polymers, humidity, exceeding the limitations of regulated substances (e.g., BFRs), other contaminants and plastic waste that is not appropriate for certain recycling technology. All the listed factors above contribute to the lower output quality or higher number of rejects that are generally sent to incineration. These factors have a direct impact on the sustainability and feasibility of recycling industries. Lower quality output has a lower price on the market and rejects are lost feedstock that recyclers have bought and must deal with disposal costs. Thus, recyclers are facing a major challenge on how to lower the number of rejects and finding ways to utilize it better to increase profitability.

7.1.2 Recycled plastic and its uptake

The challenges discussed regarding recyclate are based on the quality, quantity and stability that affect the uptake of recycled plastic. Inarguable limitation of mechanical recycling being degradation of polymers, changes the properties of plastics and thus the use in more demanding applications may not be possible. In many sectors there exist unawareness or lack of investments by converters, OEMs, or brand owners to increase their uptake of recycled plastics that would have sufficient properties for their products. Safety of the recyclate is also an important factor considered by converters, OEMs, and brand owners. According to the interviewees, depending on the feedstock there is a possibility of harmful substances existing in recycled plastic even if it is unlikely. However, a lack of certainty that there are no possibilities of harmful substances in recycled plastic is an important barrier for increasing the uptake.

Recycling field acknowledges that currently manufacturers or converters may need to modify their process to be able to use or replace virgin polymers due to different properties of recycled polymers. Some technical properties that cannot be achieved by recycled plastic pose a challenge for industries to redesign or lower some of the specifications of their products. Thus, communication between these sectors is needed to understand the needs and possibilities of both sides and come up with solutions or compromises to integrate recycled plastics more.

High volume buyers such as brand owners are the most interesting customers to greatly increase the uptake of recycled plastic. According to an interviewee, good, unbiased, and trustworthy proofs of environmental benefits of the use of recycled plastic are needed to increase the demand for recycled plastic naturally. Additionally, recyclate with stable quality and quantity should be available to guarantee constant production of high-volume industries.

Price of recycled plastic is another factor considered by interviewees to affect the uptake. The price to quality ratio is not competitive between recycled plastic and virgin plastic thus, efforts on improving the quality is needed before increasing capacity. A following example provided by PET bottle recycler shows that the price is a major factor affecting the uptake. According to PET bottle recycler many companies are only targeting the minimum amount of rPET content in their products as the first mandates regarding recyclate content in PET bottles are taking place in 2025. So, there seems to be no willingness to pay more than needed for a recycler plastic.

The current energy crisis has impacted the plastics recycling field by having to increase the price of recyclate to compensate the processing costs. While the demand has been reported to be still generally growing, there was also a mention of agreement with customer for recycled plastic being on hold due to the rapid increase in price.

7.1.3 Technology

Stakeholders were unanimous of the fact that more recycling technology development and capacity is needed in both mechanical and chemical recycling. The European recycling goals are very ambitious, and stakeholders believe that recycling target of 50 % of packaging waste by 2025 is not achievable, while target set for 2030 was possible but still requires a lot of effort from the whole value chain. While some member states could achieve the targets in Europe, densely populated areas must be optimized to meet the overall recycling rate targets. It was also noted by stakeholders that while some recycling plants are operating on high capacity, some recycling plants are not operating on their maximum potential. Additionally, some investments may be delayed due to the current geopolitical situation further pushing the targets in the years to come.

However, for recycling capacity to increase, sorting efficiency and capacity must increase as well to provide feedstock for recycling plants. Sorting turned up to be a major problem. All stakeholders mentioned the sorting to either being inefficient, not providing sufficiently separated and stable waste flow or the lack of capacity. More flexible recycling technologies such as chemical recycling would increase the feasibility of sorting industries as more waste fractions could be sold to recyclers thus reducing the number of rejects during sorting.

When asked stakeholders about their thoughts about mechanical and chemical recycling, the main conclusion was that chemical recycling is needed to only compliment mechanical recycling. Complementation should be in a way such as treating the waste fractions that are not suitable for mechanical recycling or when sufficient quality of the output cannot be achieved by mechanical recycling. Challenges and uncertainties arose from interviews that are specific for chemical recycling. As chemical recycling is highly energy intensive, and part of the output is often used as an energy source for the process there are unavoidable and relatively high material losses. Following on the high energy intenseness the economics of the chemical recycling on the industrial scale are uncertain and environmental footprint is not as good as for mechanical recycling. While the increase in energy prices affects chemical recycling significantly more than mechanical recycling both are suffering from drastically increased processing costs. Additional economic factors related to chemical recycling are high investment costs, high capacity is needed, complex process, and relatively low market value for the product which is tied to oil prices.

While chemical recycling is more flexible in terms of input requirements it still cannot be used to treat all the plastic waste and without pre-treatment. Certain limitations of substances such as halogens and PVC require well developed sorting and separation units. Therefore, chemical recycling cannot be considered as a solution for everything but rather opening more new possibilities. Chemical recycling is also largely in a development stage and the more problematic waste streams chemical recycling will be able to treat the faster adoption will occur.

There seems to be a rapid increase of investment plans regarding plastic waste pyrolysis in Europe. While there is a rapid increase in interest to pyrolysis of plastic waste, the regulations and understanding of chemical recycling by authorities seems to be deficient. To prevent plastic waste treatment chemically that is suitable for mechanical recycling legislations are needed.

Based on the interviews, mechanical recycling should be established as primary way of recycling. Technologies should not compete with each other. For that clear guideline should be established for the feedstock used in chemical recycling. Development in mechanical recycling technology is also needed. Solutions for mechanical recycling to treat more challenging waste streams and increase the output quality are needed.

7.1.4 Policies

Stakeholders would rather see natural growth of recyclate use and recycling rates to increase rather than with the mandates. However, if nothing else works then introduction of more mandates is necessity. Recycling targets should be in line with possibilities and focus on developing processes producing high quality outputs which requires time, experience, and investments before introducing high recycling target. Stakeholders would like to see the effects of PET bottle mandates on the market before introduction of new mandates. However, more mandates are expected and perhaps needed on other sectors to boost the demand.

Regarding incentives there is a need for ways to prompt to the use of recycled plastic and consumers to dispose plastic waste properly. Currently there are no incentives to directly improve operations of recycling industries. However, there is also a question of whether incentives distort the market. Hence, the introduction of incentives for recyclers might not be a viable solution especially without precisely planning the incentives.

According to the interviewees some of the current regulations are limiting the uptake by restricting the use of recycled plastic in certain applications. While it was mentioned that in some applications for safety reasons it is justified to restrict the use of recycled plastic, in some cases the views of an expert were different from the regulation alignment.

The stakeholders especially in WEEE sector were discussing the lack of communication with authorities regarding the difficulties for recyclers associated with changes in limitations of certain substances. Example was given of revision of chemical regulation which can establish limitations for additives used in plastic products. By fast changes and reductions of threshold limits of substances, recycling industries can have a hard time to keep up and, in some cases, they cannot adopt to the required changes. Furthermore, the changes of regulations are hard to predict and thus it is hard for researchers and businesses to prepare which can cause hold backs in technology development and investments. Thus, stable, and clear legal environment is needed, and recycling should be considered more especially in the chemical regulations.

Support for plastic recycling was discussed with an interviewee. Investment funding and permission admission for plastic recycling should be available easier especially in Finland. Additionally, allowing and easing the competition across the field by for example, businesses from outside of Finland.

Regulations have highly focused on separate collection, but mixed waste has not been considered as much. Mixed waste has a large amount of plastic waste that is not utilized by recyclers. Also, chemical recycling is not recognized in regulations while some commercial chemical recycling plants are already operating. A technology neutral regulation would be beneficial. However, developing a regulation is a complex issue and innovations are developing fast. Thus, regulations can only consider validated technologies that are proven to operate on a commercial scale.

The focus of European strategies and policies on plastic packaging has left other sectors to a lesser priority. Generally, stakeholders agreed that more attention to other sector is needed already or in the future. Sometimes plastic packaging is only a small part of environmental footprint of the product, so some of the targets could be shifted to other sectors as well. There is currently no balance as plastic packaging is heavily regulated and has clear policy guidelines while other sectors not. According to a stakeholder, balance is needed which means deregulating packaging and giving more focus to other sectors as the plastic problem is not solved by only targeting packaging. Additionally, implementation of more general regulation for plastic would be beneficiary, such as, plastic focused end-of-life criteria. According to a stakeholder in WEEE sector, by focusing more on plastic recycling of WEEE the sector could achieve similar results as packaging sector, or at least improve significantly. However, another stakeholder noted that other sectors are also regulated, and the regulations are updated. These are just not as visible as in packaging sector and consumers do not have a direct influence over those sectors.

7.2 Questionnaire findings

Questionnaire findings are separated into four sections: participant's background, feedstock management, recycling, and markets and policy. Results are presented question by question under the bolded questions.

7.2.1 Participant's background

What has been the focuses of respondents' organizations or teams research?

Participants of the questionnaire have been focusing on variety of topics (Figure 14). The majority of the participants have been focusing on mechanical recycling, material development and circular economy as 8 out of 13 participants have focused on these. The least focus has been on collection, sorting, pre-treatment, reuse, product manufacturing, and tracking and digitalisation with only 2 or less participants working with these. On the other topics less than half of the participants have focused on.

Figure 14. Respondents' team or organizations research focus.

The feedstock on which the research has been focusing or dealing with is presented in the Figure 15. Majority (12 out of 13) of respondents are saying that they have worked with WEEE at some point. Over half of the participants have worked on packaging, CDW and automotive sectors. On remaining sectors less than half of the participants have dealt with.

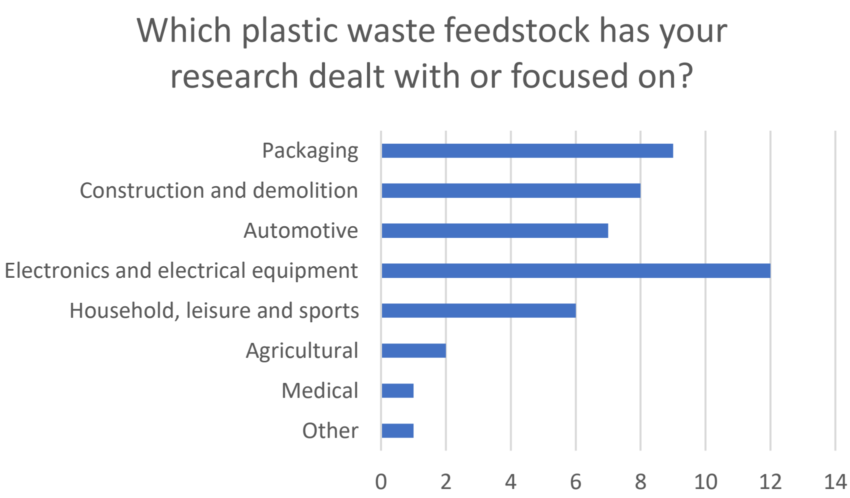

Figure 15. Respondents team or organization feedstock that their research has dealt or focused on.

7.2.2 Feedstock management

What type of issues have participants encountered related to the feedstock?

When asked about the issues they have experienced related to the feedstock they have worked with, participants indicated experiencing issues in all factors listed in Figure 16. Most have been experiencing issues related to odour, halogenated content, and hazardous substances (85 %). At least half have been experiencing issues related to all the listed factors excluding other additive related issues (45 %), indicating issues in all of the factors in Figure 16. The most major issues are related to difficulties to wash and separate (39 %), multi-materials or multilayers (46 %), halogenated content (46 %) and hazardous substances (54 %).

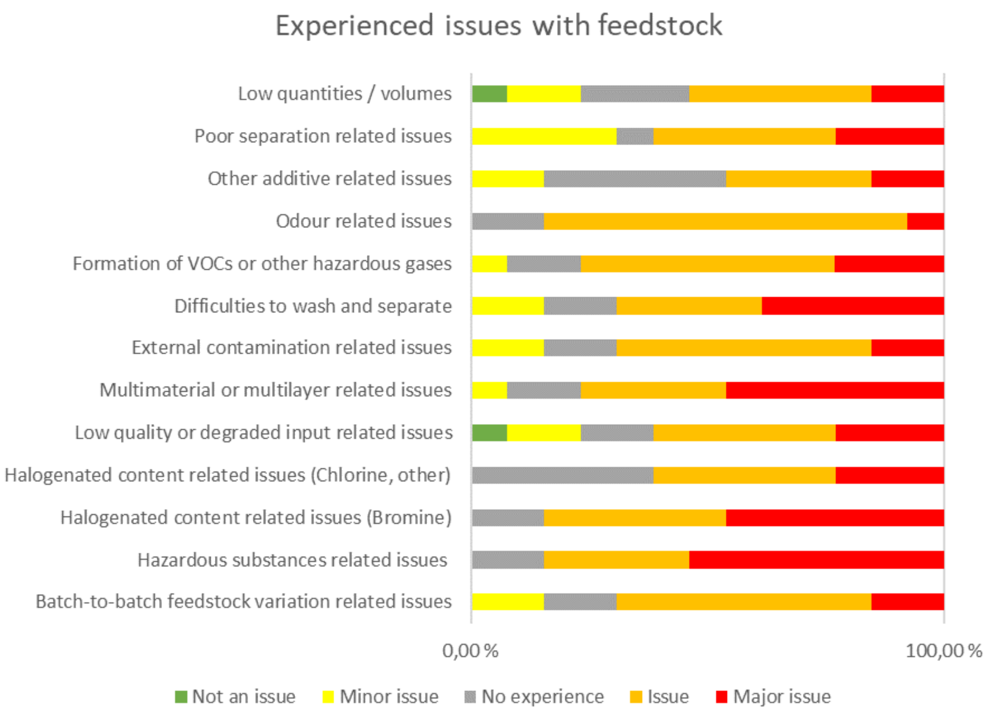

Figure 16. Issues experienced related to feedstock.

When asked to elaborate on the experienced issues, quality variations in feedstock was a highly discussed topic. Variations in quality can be due to time/place of collection of the waste, degradation, wearing outs, contamination, mixed plastic waste, hazardous additives, and polymer blend waste. Variations in quality of the feedstock are challenging from the research point-of-view as comparison of the results is difficult. Variations in quality are impacting the quality of the product and requires upgrading/upcycling to match the end-user's specifications.

Lack of the best sorting techniques are also a highly discussed problem. Sorting technologies have a considerable number of materials, which are detected wrong and end up in the wrong waste fractions. Multi-layer materials are challenging for detection and sorting and often not feasible to separate. The deficient sorting leads to poor recyclability. Furthermore, identification of multi-materials can be sometimes challenging and contain harmful substances, thus they are not ideal for mechanical recycling.

Participants also elaborated on the challenges of hazardous, toxic, or carcinogenic compounds. Identification of hazardous substances can be a significant challenge. This can lead to formation of hazardous by-products during converting and analysis that may pose a health risk. Safety hazards can happen during waste treatment requiring special measures to prevent the exposure. Additionally, the compounds might end up in the product during recycling such as acrylonitrile from ABS and hydrogen cyanide (HCN) from polyamides.

Other factors discussed by participants are the lack of maturity of chemical recycling for all polymer types and its high carbon footprint especially for thermal cracking-based technologies. Odour issues are present in almost each feedstock that require additional measures. Other contaminations complicate mechanical recycling such as legacy substances, inks, and adhesives. Finally regulatory interventions are still missing.

Which plastics or fractions get typically rejected or respondents do not handle in their work?

When asked what fractions are rejected or not handled by the respondent the following results were obtained (Figure 17). Six respondents mentioned rejecting or avoiding plastic waste fractions containing hazardous substances. Other reasons with several mentions were heavily mixed plastic and too much foreign material. Remaining reasons for rejection or not handling was mentioned once and according to one responded they have not rejected any fractions yet.

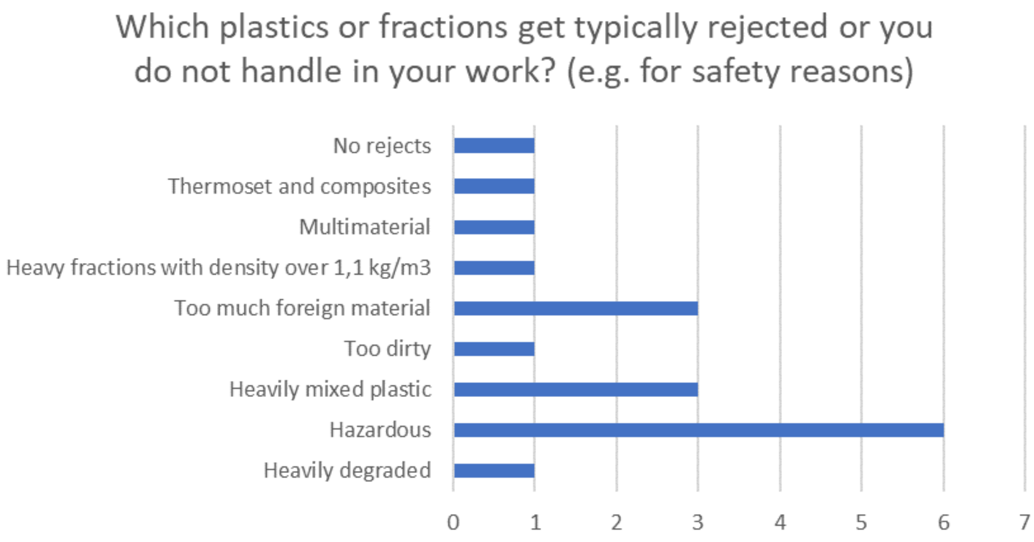

Figure 17. Number of times certain plastic waste fraction were mentioned to get rejected or not handled.

How could the collection, washing and pre-treatment be improved to assist feedstock management?

When asked about how the collection, washing and pre-treatment could be improved to assist feedstock management, two main factors were mentioned several times: separate collection and development in sorting technology. Respondent implied, that in research at low volumes there exist different routes to improve the material quality. However, in industry only a few plants have a good equipment for material separation, and majority operate with rather old and outdated equipment. Improved sensor-based sorting (e.g., NIR, Raman, XRF) in terms of speed, reliability and price combined with digital watermarking technology would help improve sorting efficiency. To assist recycling and sorting, the change should happen already at manufacturing level by minimizing multi-material packaging.

Respondents also highlighted separate collection and gave examples. Collection and treatment of smaller more homogenous groups (e.g., printers) would help to lessen the variations in feedstock. Additionally, for households, mandatory separate plastic waste collection would be beneficiary to prevent contamination of the plastic fraction with for example bio-waste. For industrial waste, separate collection for different materials even if they are consisting of same plastic type as they might be made of different qualities (e.g., PE pipes and PE boxes). Additionally, separation by colour would be beneficial to produce nongrey or non-black recyclate. By maximizing separate collection, one receives cleaner and higher quality recyclate. A respondent suggested better initiatives and tax benefits for consumers to sort the waste better and more localized collection and sorting inside the municipalities.

Other factors mentioned by respondents to improve feedstock management were openness regarding the feedstock origin and composition. Additionally, proper mechanical washing infrastructure seems to be deficient. Lastly, in the case of e-waste, higher value and priority to the plastic fraction is needed as it is currently mostly treated as a waste fraction.

7.2.3 Recycling

What are the repeated/regularly encountered barriers, technology, or knowledge gaps that respondents experience when working with plastic waste recycling?

When asked about the repeated or regularly encountered barriers, technology, or knowledge gaps the most discussed topic was the lack of information on the waste. When polymers are mixed, it is challenging to elaborate the chemical structures in the waste. Additionally, there can be a lack of information for example on how many times the material has been recycled and presence of substances of concern. Furthermore, the analysis and detection of contaminants and hazardous substances especially at low levels that are unevenly distributed is very challenging. As even slight differences can change the recycling cycles and may require adoption and research to reach technical data sheet standard for the products. Combined with the lack of knowledge on the final use of the recovered material, it can be challenging to reach the required specifications of the material.

There is also a challenge of the lack of infrastructure for pre-treatment, sorting, shredding, washing, decontamination, and multilayer film separation. Safety related issues are also faced regularly involving toxic or harmful substances, for example, during the plastic pyrolysis. Additionally, there is sometimes a lack of knowledge required to produce a high-quality secondary raw material with stable parameters. Lastly the lack of consumer knowledge is noticeable in composition of post-consumer plastic waste, which complicates plastic recycling.

Have design changes in products had an impact on the recyclability of plastic waste?

When asked if respondents have experienced any impact on the recyclability of plastic waste related to design changes in products three respondents have experienced at least some positive impacts such as labels that are easier to wash off, less colour print and more non-black trays, and more monomaterials. However, one respondent indicated no impacts yet as there is still a lot of older products in the waste stream. Another respondent has noticed a reduction of plastic use in some products, while in some cases the impacts have been negative. As an example, in margarine package where inner liner is plastic and outer layer is cardboard, the cardboard is so heavily glued that the separation of these is challenging.

Other respondents did not give a yes or no answer on whether they have experienced impacts or not, but rather gave examples on how design for recycling can impact the recyclability of plastic waste. The replacement of hard-to-recycle materials with more circular and sustainable solutions such as mono-material products would ease the whole sorting, pre-treatment and recycling process and ultimately optimize production target product with higher quality. Additionally, if potential hazardous substances in the products can be reduced or replaced the recyclability would increase.

There seems to be a significant possibility of design for recycling to impact the recycling field greatly, but this takes more time and effort to further improve this to a meaningful level. More effort into technology development and re-design of products to monomaterial-based solutions are needed instead of the continuing the use of multi-material packaging. However, design for recycling can contradict other sustainability related design goals of brand owners. These can be for example electronic equipment that is designed to last by covering it with silicone, however this makes the recycling of it more challenging.

How important did the respondents rank the following RDI topics to improve mechanical and chemical recycling?

When asked to rank the importance of RDI topics to improve mechanical recycling, all the listed topics mainly lean towards important and very important side, except better sorting by colour is generally neutral (Figure 18). When combined important and very important topics the better identification of additives was ranked with the highest in importance (92 %). Other topics with higher importance are better sorting by polymer type and quicker and more reliable sampling and analysis of feedstock (83 %). Other noted topics that are rated with slightly less combined important and very important amount are better material separation (75 %), better pre-treatment or processing to remove odour (58 %), advanced processing to handle material degradation (58 %) and better sorting by colour (33 %).

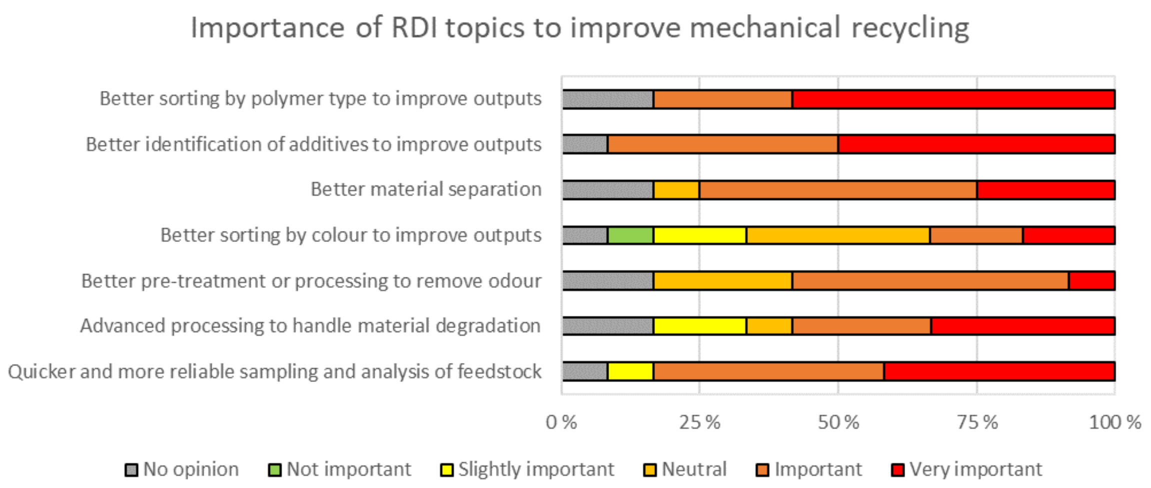

Figure 18. Importance of RDI topics to improve mechanical recycling.

When asked to rank the importance of RDI topics to improve chemical and thermochemical recycling the results are as follows (Figure 19). The topics which received the most very important ratings were yield improvement (67 %), improvements in upgrading (50 %) and better analytical methods for processing outputs (42 %). When combined important and very important selections the forementioned topics were rated on a higher importance 58-67%. Other topics with higher amount of combined important and very important selections were better sorting by polymer type (67 %), better identification of additives (58 %) and better material separation (50 %). With the less than 50 % of amount of combined important and very important selections were better processing to be able to handle feedstock mixtures (42 %), quicker and more reliable sampling and analysis of feedstock (42 %), and the topics with no very important selections were better sorting by colour and better pre-treatment or processing to remove odours (17 %).

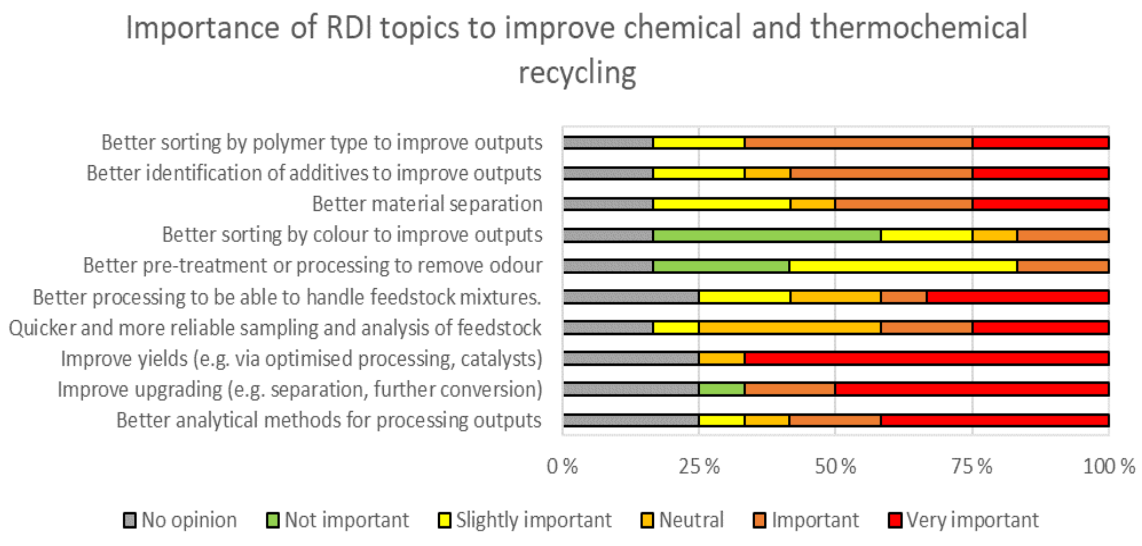

Figure 19. Importance of RDI topics to improve chemical and thermochemical recycling.

What are the thoughts of respondents about statements related to recycling technologies?

When presented with statements about mechanical and chemical recycling and asked whether respondents agree or disagree with statements the following results were obtained (Figure 20).

Over half of respondents (54 %) agreed or fully agreed that mechanical recycling does have a lot of limitations, but also even more decisively disagreed or fully disagreed (92 %) when stated that chemical recycling does not have major limitations. When stated that mechanical recycling has achieved its limits all of respondents either fully disagreed (46 %) or disagreed (54 %).

54 % of respondents agreed or fully agreed on the statement that chemical recycling is needed due to the limitations of mechanical recycling, but also fully disagreed or disagreed (92 %) that chemical recycling will not replace mechanical recycling. When stated that feedstock suitable for mechanical recycling should not be treated by chemical recycling majority fully agreed and agreed (75 %), and when stated that only mechanical recycling rejects should be treated by chemical recycling 69 % fully agreed or agreed.

Regarding sustainability, when stated that mechanical recycling should be the only recycling method used, since it is more sustainable, respondents mainly fully disagreed (54 %) or disagreed (31 %). Statement about chemical recycling being not sustainable due to higher energy consumption was mostly disagreed on (46 %). When stated about drivers that should drive the combined approach of both mechanical and chemical recycling the sustainability was fully agreed the most (77 %), then by technical capabilities to produce high-performance products (62 %) and lastly by economic feasibility (31%).

Figure 20. Statements about recycling technologies.

7.2.4 Markets and policy

How would respondents increase the market demand for high quality recycled plastics?

When asked about how respondents would increase the market demand the responses can be divided into three categories: product quality and standards, awareness, and policies. Further increasing quality to near prime and guaranteeing availability is needed with competitive price, so recyclate could replace virgin material and could be processed in existing lines. Furthermore, the performance of the recyclates needs to be promoted before the quantity. Additionally, there is a need for generation of clear product standards for recyclate to facilitate their use.

Regarding policies the following suggestions were mentioned by respondents: clear rules for using recycled plastic, higher recycling targets where difference between down- and upcycling is accounted, recyclate content mandates in products, EPR schemes for more products, and providing more transparent data and documentation on the quality of upcycled plastics.

Increasing the awareness was also discussed with suggestions by respondents. Correction of the old presumptions is needed of that recycled plastics cannot be high quality by demonstrating data, which could be achieved by better marketing and running campaigns of the recycled plastics and the improvements the material has made during the last decade.

How would respondents increase the market demand for low-quality recycled plastics?

When asked about how the respondents would increase the market demand for low quality recycled plastic there were two main topics discussed including the price and finding suitable uses for them. The suggestions regarding price were lower the price of low-quality recycled under virgin plastics and fees on virgin plastics or reward on using recyclate. However, it was mentioned by one responded that there is a high demand due to already low price.

Respondents also discussed the need to find suitable solutions by product design changes and work on quality improvements to as good as required for certain applications as value-retention should be always strived for, rather than increasing the demand for low-quality recycled plastics.

There was also a discrepancy regarding incineration being a solution for low quality plastics as one responded considered it as helpful tool while another stated that they should not be incinerated at all.

What are the main barriers and risks associated with increasing the uptake of recyclate and their share in products?

When asked about main barriers and risks associated with increasing the uptake of recyclates and their share in products the main topics discussed by respondents were unstable quality and quantity, and the presence of substances of concern.

According to responds, the quality and quantity of some recycled plastics have fluctuations and the current stable supply in terms of quality and quantity is lacking. One respondent mentioned high energy intensity of recycling. There is a need to ensure constant quality in the long term which may be challenging due to increased use of recycled plastics and thus changes in the input material for recyclers. Furthermore, as every plastic is tailored for the application, ideally recyclate should be utilized in a closed loop and fit in the current industrial manufacturing process which complicates the situation. There is also a lack of trust and knowledge to increase the use of recycled plastic, even though there is an increase in the use of recycled plastic, more time is needed before significant changes in the behaviour of product manufacturers are seen. To partly tackle the stable quantity and quality more demonstration of large-scale chemical recycling is needed and more design for recycling.

Additional frequently mentioned topic was the presence of substances of concern that can impact negatively human health and/or the environment. According to respondents these can occur as unintentionally added or as legacy additives that are no longer used but may still be present in recycled plastic, which can threaten product qualification for new products. As there are regulations on a maximum threshold of substances of concern, the recyclate containing an amount over the threshold is a barrier for using it in new products.

What are the key factors to support creating a market for currently non-recycled plastics?

When asked about key factors to support creation of market for currently non-recycled plastics the main factors were better sorting and pre-treatment, and regulations.

Improvements in the quality of the plastic waste are needed to be able to recycle currently non-recycled plastics. Respondents suggested a need for better sorting, pre-treatment, and quality control along the whole value chain. Additionally, more research on identification of past use and hazardous substances is needed.

Main factors discussed to create market for currently non-recycled plastics were regulations and taxes. Legislations and recycling targets are needed to force and support the demand for both ecological and economical sustainability, and to make the use of recycled materials easier. Taxes for using virgin raw material to make them less attractive choice as well as higher taxes on incineration to financially encourage recycling. Price increase of the recycled plastic was also suggested by one respondent to create a business case to recycle these plastics. Additionally, more export bans are needed to support recycling in the EU and domestic recycling.

Development in chemical recycling including thermochemical and solvent-based recycling was also discussed by two of the respondents. These are needed to be improved and be more energy efficient to treat e.g., multi-layer and -material blends. Furthermore, according to one respondent energy recovery should be seen as a positive factor to replace fossil fuels.

Additional factors mentioned by respondents were a good mapping of where to use the material to not deteriorate the current plastic processing, increase collection rates to increase the available volume, and challenges in availability of virgin plastics which are increasing the value of recycled plastic.

What are the thoughts of respondents regarding policy landscape?

When presented with statements regarding policy landscape the following results were obtained (Figure 21). Regarding the statement ‘regulations being clear’, most of the respondents were neutral, but more respondents disagreed or fully disagreed (42 %) than agreed with the statement. When further stated that there is enough understandable guidance and supportive documents available to understand the regulations affecting recycling and circular economy more people disagreed (42 %) and fully disagreed (25 %). When stated that there are enough policy incentives to increase recycling rates 33 % disagreed and 17 % fully disagreed. And when stated that there are enough regulatory actions and social pressure across plastics value chain to transition to circular economy majority of respondents disagreed (25 %) or fully disagreed (33 %).

From statements regarding different sectors using plastic respondents indicated heavy target on packaging sector with 33 % agreeing and 33 % fully agreeing as well as regulations should target other sectors with 42 % agreeing and 42 % fully agreeing. Additionally, respondents mainly agreed (42 %) or fully agreed (17 %) that there should be more mandates on recyclate use in EU, but substantial amount were neutral regarding the need of introduction of more mandates. Furthermore, majority of respondents indicated that there are also not enough targets for sectors using plastics by 42 % disagreeing and 17% fully disagreeing.

For the last two statements vast majority of respondents agreed on. By 58 % agreeing and 17 % fully agreeing with separate collection targets are needed for different plastic waste categories, and 58 % agreeing and 33 % fully agreeing on the statement that there should be separate recycling targets for producing high-quality recyclates.

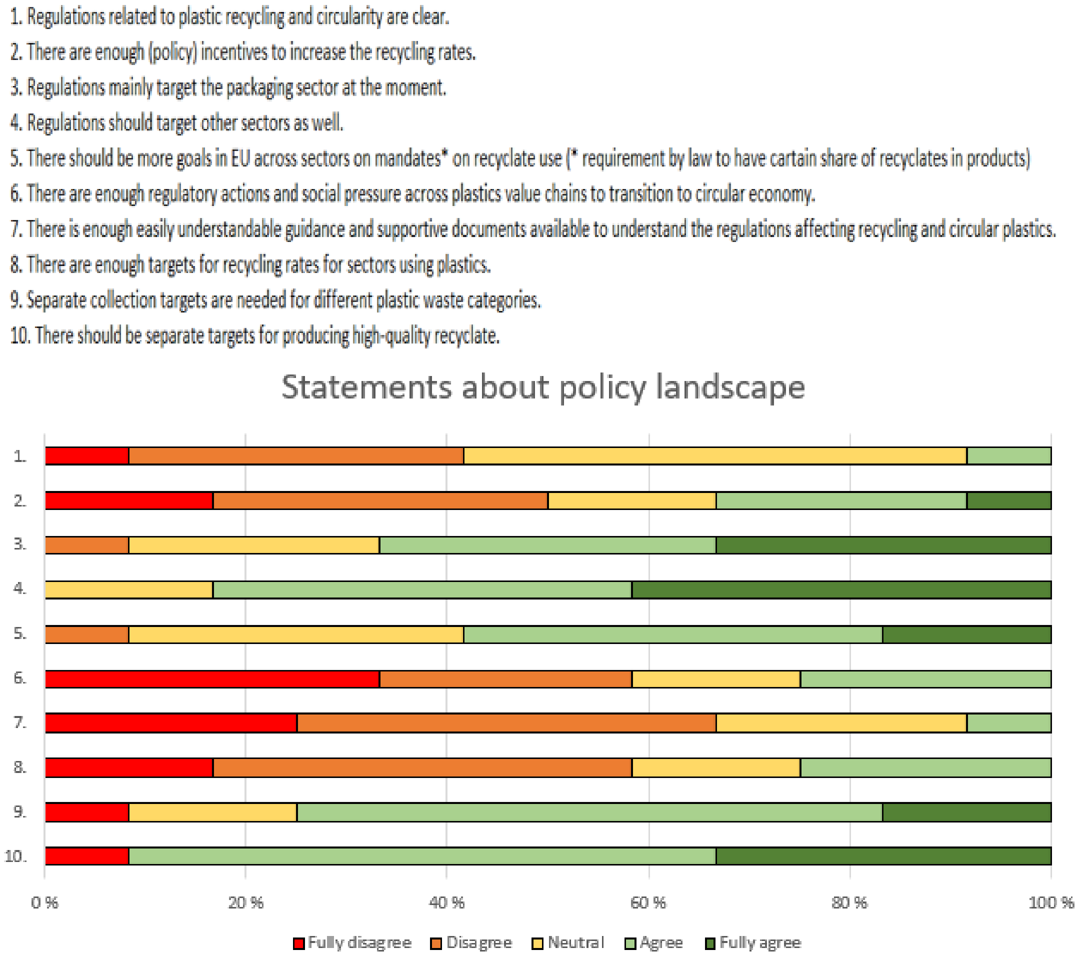

Figure 21. Statements about policy landscape.

Which sector(s) require more attention from EU policies?

When asked about which sectors require more attention from EU policies, the following results were obtained (Figure 22). Building and construction was mentioned 5 times, electrical and electronic waste 4 times, household including textiles 4 times, automotive 3 times, medical 3 times and other non-packaging sectors once.

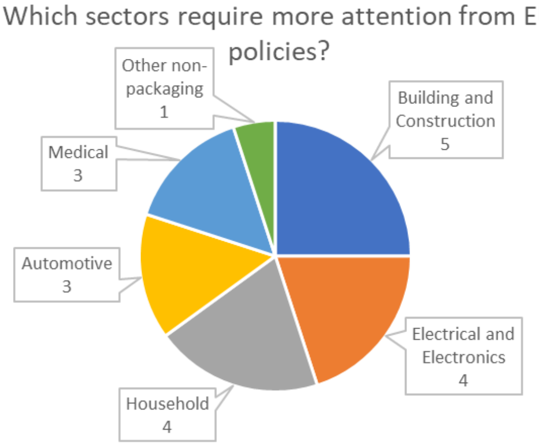

Figure 22. Sectors requiring more attention from EU policies according to respondents.

Justifications for more attention needed for electronics and electrical waste were their complex structure and lower probability of recycling as well as its increasing share in waste streams. Similarly building and construction was justified by the increasing share in waste streams. For plastic waste from medical sectors, there is currently no requirements for separate collection of plastics according to a respondent even though there is a high amount of plastic waste. Additionally, collection of plastic waste from household should be made easier, for example with obligatory separate collection from household.

Additional topics mentioned by respondent were clear coordination of policies, need for end-of-waste regulation for plastics, more regulations for durable goods and more policies that really focus on circular plastics including high-quality recycling and replacing virgin plastics.

Should plastic waste recycling targets be implemented (or increased if already implemented) on specified sectors by 2030 in the EU?

When asked respondents' thoughts regarding whether plastic waste recycling targets should be implemented or increased on specified sectors by 2030 in the EU, the responses were mainly in favour of implementing or increasing the targets (Figure 23). For packaging 58 % of respondents would like to see increased targets by 2030. For the other sectors the following number of respondents would like to see recycling targets to be implemented 75 % for construction and demolition, 75 % for automotive, 75 % for electronics and electrical equipment, 67 % for household, leisure and sports, 75 % for agricultural and 50 % for medical.

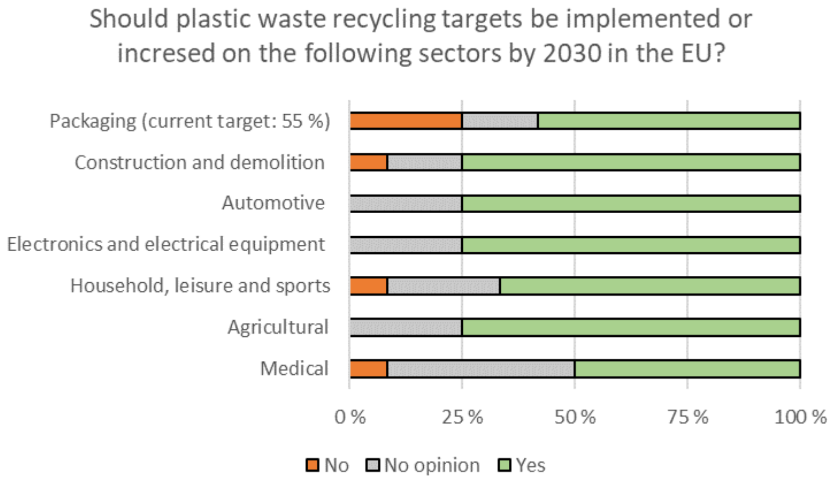

Figure 23. Respondents' thoughts whether plastic waste recycling targets should be implemented or increased on these sectors by 2030.

7.2.5 Circular economy strategies

What is the importance and impact of circular economy strategies now and in the future?

When asked to rank in importance and impact the following circular economy strategies to focus now, the most important strategies indicated by the respondents were repair and reuse with 100 % of respondents ranking them important or very important (Figure 24). Following these recycle, refurbish, reduce and rethink were ranked next in importance and impact with over 80 % indicating them being important or very important. Slightly less important strategies were repurpose and remanufacture, but still with over 60 % of respondents indicating important or very important. Lastly rankings of recover and refuse strategies were the most dispersed with only 33 % saying important or very important.

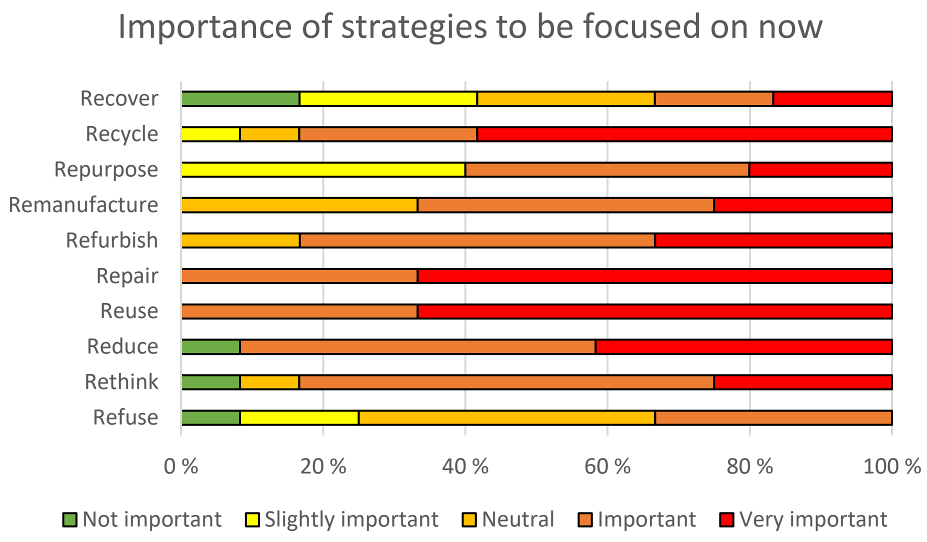

Figure 24. Importance of circular economy strategies to be focused on now.

When asked the same question but in the future the following results were gathered (Figure 25). Now the most important strategies were inclined more to the most circular strategies such as rethink, reduce, reuse, repair with over 80 % indicating important or very important. Recycling was also indicated with over 65 % ranking it as very important. Refuse, remanufacture and refurbish strategies were indicated by over 70 % to be important or very important. The least important strategies to focus in the future were repurpose and recover, with recover being the most dispersed. The overall trend, when comparing the importance of strategies now and in the future seems to be a move towards more circular strategies, while importance of recycling staying high.

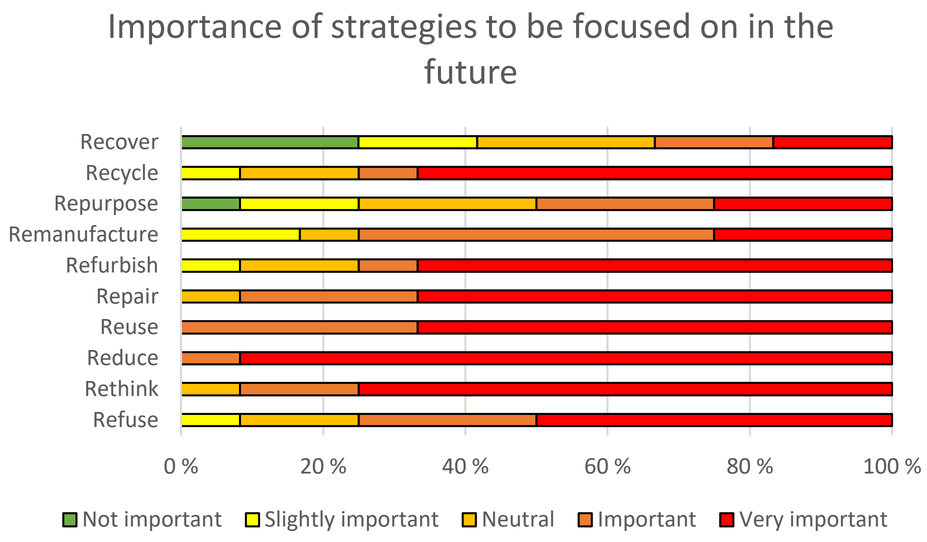

Figure 25. Importance of circular economy strategies to be focused in the future.

How respondent evaluated the circular economy strategies in terms of easiness of implementation?

When asked to evaluate circular economy strategies in terms of easiness of implementation the following results were gathered (Figure 26). The most challenging is to repurpose, repair and refuse with around 50 % indicating challenging or very challenging. Recycling was indicated to be challenging by 33 % of respondents. From all the strategies remanufacture, refurbish, reuse, reduce and rethink were in the middle in terms of easiness of implementation with 33 % indicating very challenging or challenging. The easiest strategy to implement was energy recovery with over 60 % saying very easy.

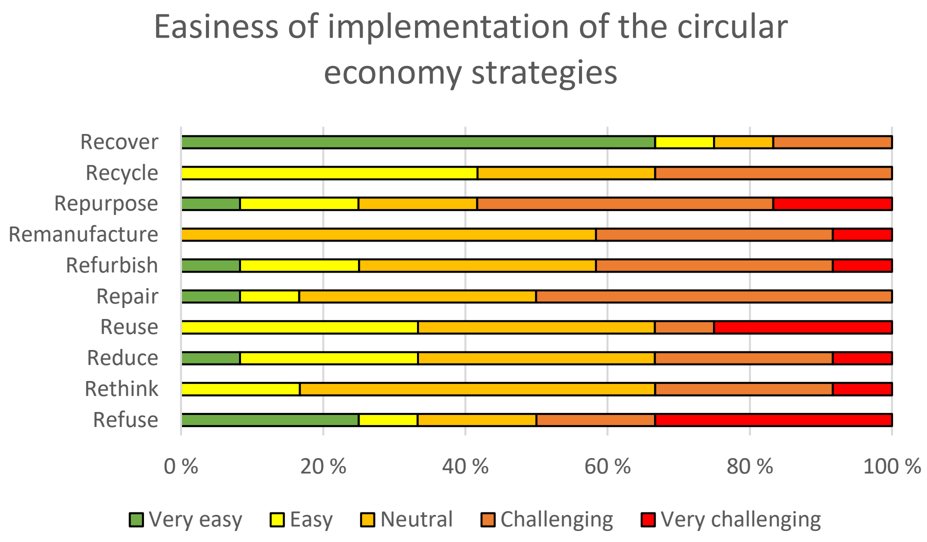

Figure 26. Easiness of implementation of the circular economy strategies.

Were the discussed strategies familiar to the respondents?

When asked whether the respondents were familiar with circular economy strategies most of them were familiar with all of them or most of them (Figure 27). One respondent was familiar with less than 50 %.

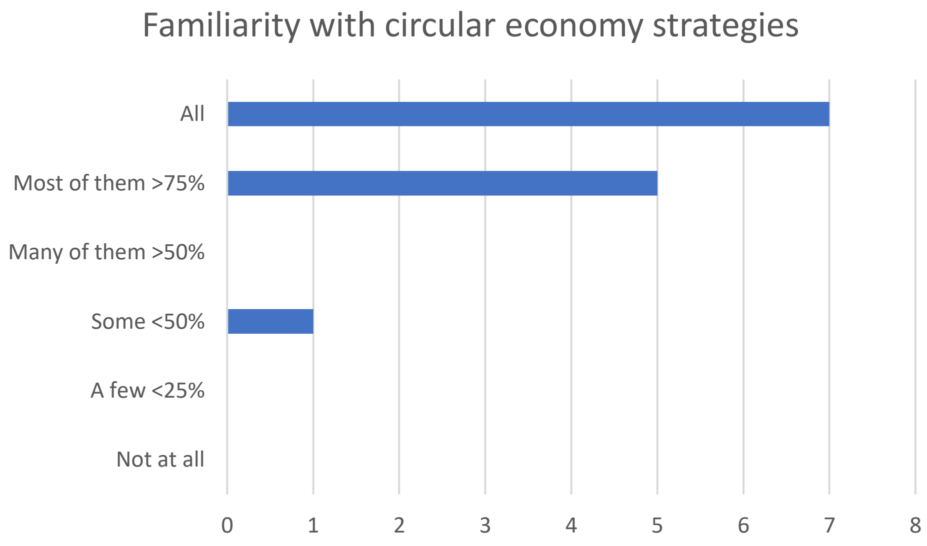

Figure 27. Familiarity with circular economy strategies.

What circular strategies should be further researched and what kind of challenges or obstacles do the respondents identify with said strategy?

When asked which strategies should be further researched the respondents mentioned all of them. Specifically mentioned strategies were recycling, repair, refurbish, remanufacture, and repurpose. Challenges with recycling mentioned were lack of design for recycling, technical challenges, lack of transparency of additives and chemicals used in products. For repair, refurbish, remanufacture, and repurpose there is lack of infrastructure, and these are not very visible in the current system. Mentions of all of them discussed the challenge and importance of involving the entire value-chain and cooperation with each other.

7.3 Result of Modix trial runs

The product of all batches was visually similar black, homogenous, and greatly compacted. The product of batch III with the highest variety of material is shown in the Figure 28.

Figure 28. Example of the Modix output.

The output was further crushed into 2,8-, 4,0- and 6-mm. bits for further property analyses and pyrolysis treatment. However, these were not in the scope of this work. The Modix trial runs results of this work came down to the demonstration on how novel extruder can be utilized to turn bulky plastic waste into an easy to handle and substantially less space requiring product for storing or transporting the plastic waste. In this work this was achieved by Modix treatment. The bulky plastic waste that would not be possible to pyrolyze as it is, was processed into a form which allows its feeding into pyrolysis. After processing the bulk density of plastic waste was approximately 100 times less, and its form potentially allows feeding it directly into a pyrolysis reactor. There were no visual differences in output of the different configurations of the input for the Modix treatment. However, product analysis from pyrolysis of this material is required to determine whether the sorting or washing has an impact on the final product (Figure 29).

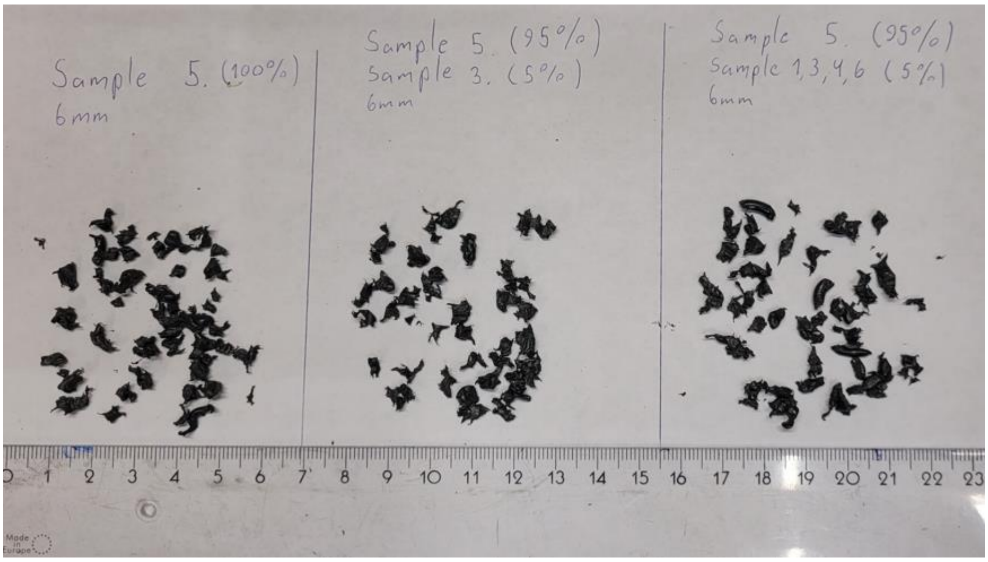

Figure 29. Product after grinding.

8 Discussion

The information for this work was collected by the ways of literature review, 8 stakeholder interviews and 13 responses on the questionnaire. Due to the very limited number of interviews and responses absolute conclusions should be drawn carefully. Still useful insights of challenges, technology and knowledge gaps related to plastics recycling in circular economy were gathered.

8.1 Feedstock acquisition and its quality

In literature review the challenges were mostly related to the complexity of plastic waste streams and their diversity. This comes down to mainly because of various sectors using different types of plastics and countless of applications within these sectors factoring in all the possible additives, hazardous substances, and contaminations.

While stakeholders also recognize the challenge of the complexity of plastic waste stream, they also brought up a challenge of acquisition of plastic waste to recycle. The acquisition of plastic waste was not a prominent challenge discussed in the literature. This might be explained by the fact that majority of actors operating in the plastics recycling field are targeting similar relatively well-established plastic waste streams or fractions. Thus, high competition across the highest quality plastic waste is created, while for the abundantly available lower quality plastic fractions demand is minimal.

The literature review and questionnaire responses were in line on the fact that currently research effort is targeted towards the lower quality or problematic waste fractions. The research is being done to either develop technologies to enable treatment of these fractions or sorting/pre-treatment technologies to provide better separation of the waste streams. It seems feasible to conclude that when the treatment of lower quality feedstock becomes easier and more profitable, more actors shall be interested in acquiring currently lower quality plastic waste making it more valuable resource.

The information gathered by literature review was highly supportive towards EPR schemes. Interestingly from stakeholder interviews it was noted that in some cases EPR schemes can cause additional uncertainties for example in ownership of the plastic waste. Therefore, careful planning of EPR schemes is needed not to interfere already complex waste management of plastic waste.

The views on design for recycling were fully in line with literature review. There seems to be a major opportunity behind the challenges on how to encourage majority of the manufacturers to transition from multi-layer/material or hard to recycle packaging to mono-material and easy to recycle packaging.

Overall responses of the questionnaire were closely in line with the literature findings which is not surprising as the respondents were mainly researchers. Findings from stakeholder interviews were mostly in line with the literature findings with some exceptions that were not specifically mentioned in the literature. Key takeaways are presented in the Figure 30.

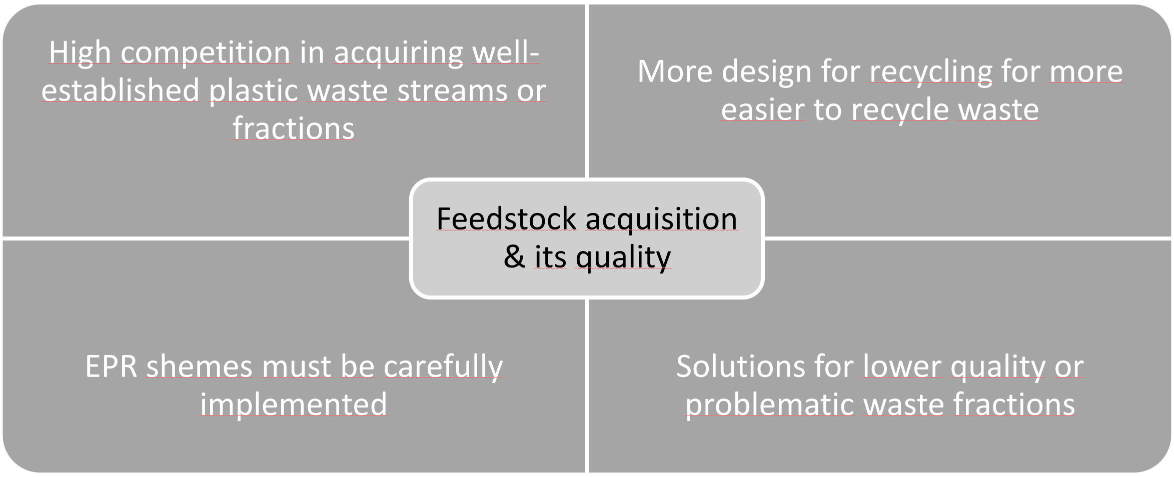

Figure 30. Key takeaways related to feedstock acquisition and its quality.

The Modix trial runs are an example on how novel technology can be utilized in compacting bulky plastic waste, which enables its feeding into pyrolysis reactor. Additional benefits of the technology can be to enhance the feedstock quality by avoiding contamination or save on the transportation costs. Modix could be used for example as on-site treatment unit of waste to allow its separate treatment and thus avoiding mixing with other waste streams. After compacting the plastic waste by Modix it can be transported more efficiently to chemical recycling plant. The processed feedstock can be then fed into pyrolysis reactor that was not possible before Modix treatment, and the thermochemical processing can be conducted potentially without any further pre-treatment required.

8.2 Technology

Regarding the technology environment the challenges, the stakeholders and questionnaire responses strengthen the findings from literature. Currently all the recycling technologies including mechanical and chemical recycling technologies have limitations. The limitations can be broadly classified into input, costs, and output. Recycling technologies are also strongly dependent on efficient sorting of the waste, which currently is a challenging space to operate in. Plastic waste sorting industry has very limited waste fractions from a very complex and diverse plastic waste stream. Moreover, a very small profit margin to sell sorted plastic waste for recyclers inhibits the investment for a larger capacity or the best equipment.

Mechanical recycling generally needs well sorted and clean monomaterial input. Solvent-based technologies also require relatively clean and a feedstock consisting of condensation polymers. Pyrolysis and gasification can be considered as the most tolerant for the impurities and they can be used to process mixed plastics excluding high amount of PVC and PET.

Technology development in both types of recycling is needed in terms of for mechanical recycling to be able to process more problematic waste fractions and for chemical recycling to be able to process the most problematic waste fractions. Former development, complimented by the fact that interest in novel technologies especially in chemical recycling is rising, is beneficial for tackling a large share of challenges faced by sorting industries. When a more different waste fractions can be treated, sorting facilities will have less reject material and thus larger amount and spectre of waste fractions to supply increasing its profitability and viability.

Challenges identified from stakeholder interviews were mainly related to chemical recycling such as high energy demand, material losses, uncertainties on a large scale, high environmental footprint, and high investment costs. Whereas from questionnaire responses, a major gap related to feedstock analysis methods were identified. This indicates a challenge of guaranteeing complete safety and absence of substances of concern in the product or safety hazards during processing when there is a lack of information of the waste.

As it is clear there is no silver bullet offered by the current technologies the key takeaways are presented in the Figure 31. Effort is required not only from the technology side but also again across the whole value chain to improve recyclability of plastic waste. While chemical recycling has a huge potential in increasing the recycling rates it is not likely to replace or even be a primary way of recycling in the near future considering its higher costs and environmental footprint. Being said, chemical recycling is still needed and it plays an important role in achieving the circularity of plastics. Currently it is challenging to assess the full impacts of the chemical recycling as the technology is novel and there is yet to be an operation at significant large-scale. Thus, more research and experience are needed to be able to estimate the impacts.

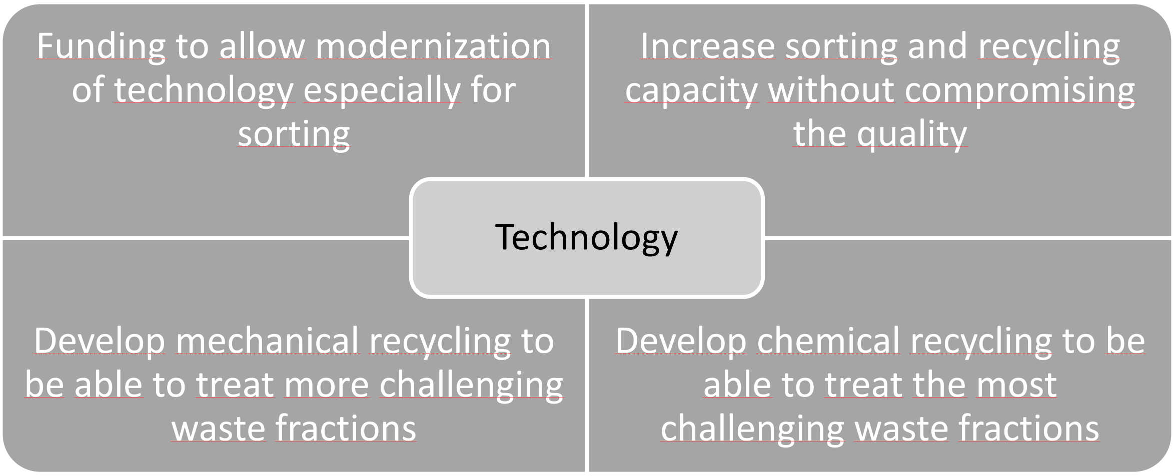

Figure 31. Key takeaways related to technology.

8.3 Recycled plastic and its uptake

Challenges identified from both stakeholder interviews and questionnaire regarding the recycled plastic and its uptake were mostly in line with the reviewed literature. The challenges and gaps identified related to the recycled plastic are also closely related to the challenges in adoption of recycled plastic. Challenges that were identified across all research methods were insufficient quality, unstable quality, unstable quantity especially for large volume buyers, price to quality ratio, inapplicable material for current production lines or product designed for virgin-based plastics. These challenges are mostly impacts from the line of actions across plastics value chain. Improvements on every stage of plastics value chain are needed to facilitate its recyclability into stable recycled plastic in terms of quality and quantity.

While mostly the stakeholder interview results and questionnaire results were in line with the carried-out literature review, some additional challenges were identified from these. Safety of the recycled material is naturally very important. Depending on the feedstock used for recycling the risks of hazardous substances or other substances of concern can vary accordingly. However, for certain application full guarantee of absolutely no such substances is needed, which is also regulated in the regulation on plastic material intended to contact with food. Currently no such guarantee can be given without knowing exactly the origin and composition of the feedstock. Thus, research on identification and extraction of such substances from the recycled plastic is needed.

From the interviews and questionnaire responses it was identified that there are still some old presumptions that recycled plastic cannot be of a high quality. Thus, there would be a benefit of more unbiased and trustworthy proofs and data of environmental benefits and capabilities of recycled plastic. Best proof would be for large brands to demonstrate it in their products. However, for that there needs to be willingness or incentives for them to do so. Key takeaways of this section are presented in the Figure 32.

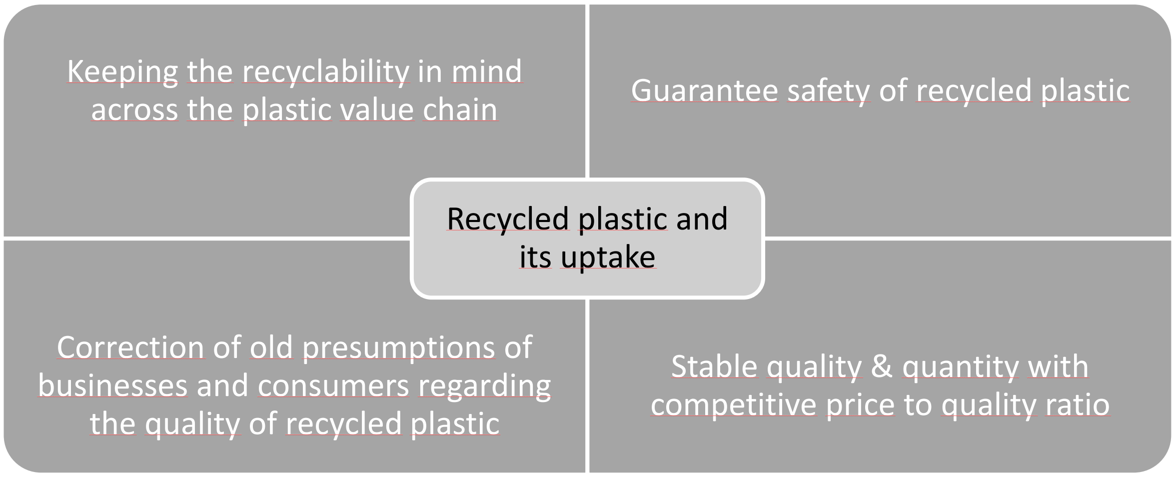

Figure 32. Key takeaways related to recycled plastic and its uptake.

8.4 Policies

Based on a regulatory review it is clear that European Union is taking actions towards circular economy of plastics. The challenge of various sectors and applications within these sectors is also visible in the policy landscape. Additionally, an extra priority to plastic packaging in the policy landscape was noticed from the review and by stakeholders and questionnaire respondents.

Certain gaps in the regulatory environment to be filled were identified. Starting from the recycling targets, it would be beneficial to have separate targets for high-quality recycled plastic. The current collection of recycling rate data can be misleading by accounting downcycling that generally should be avoided as value retention should always be a priority.

Furthermore, high focus on separate collection of plastic waste has given less priority for treatment of mixed waste, which consists of approximately equal amount of plastic waste. Solutions for plastic waste in mixed waste are lagging and it could be beneficial to address in policies. Similarly, high focus on plastic packaging sector has undoubtedly achieved good progress at the said sector, however other sectors have not been in a such high priority and plastic fraction recycling from these sectors could and should be improved and given more priority in regulations.

Lack of awareness or communication between experts in the plastic recycling field and the authorities was also noticed. This in some cases has led to disagreements whether recycled plastic is suitable for certain applications or not. Additionally, especially at WEEE sector, lack of communication has led to unachievable or hard to achieve threshold limits of some substances in the recycled plastic. For this, European funded projects are very important and provide realistic and accurate data to support decision making in the future.

While in a new Circular Economy Action Plan plastics are treated separately from sectors such as packaging, vehicles, and construction and demolition, a plastic focused end-of-life criteria has not been established. A plastic focused end-of-life criteria could benefit the recycling industry by providing standardization in plastic waste management across European Union that are currently missing. This was also supported by interviewees and the survey respondents.

Interviewees and questionnaire respondents would introduce recycling targets for other sectors as well to increase the recycling rates. However, if such targets are set, they must be carefully thought through to be in line with the possibilities and they should prioritise high-quality recycling.

Overall, regulatory environment for plastics is very complex and in some cases open to interpretation. Respondents supported this fact and indicated that there are no easily understandable guidance and supportive documents to study the regulatory environment. It was also noted that development of regulation is a complex process, and it is unrealistic to assume for regulations to be able to keep up with all of the novel technologies and changes in this quickly developing field. Key takeaways of the challenges related to policies are presented in the Figure 33.

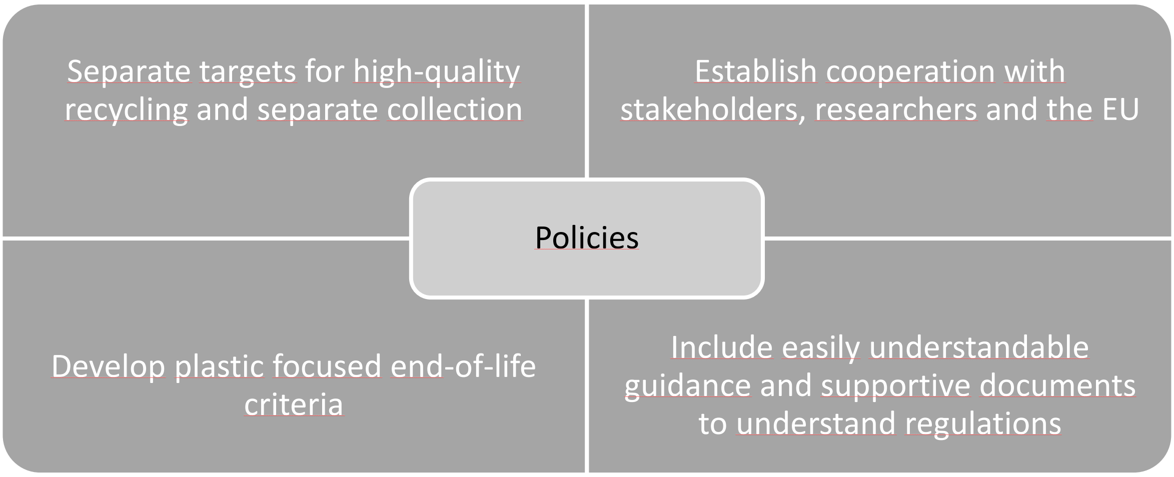

Figure 33. Key takeaways related to policies.

8.5 Research limitations

First, response bias, which may be caused by various factors such as interviewer bias or social desirability bias. Response bias was prevented by the authors best ability by asking neutral questions and by anonymized data analysis as well as asking the respondents to base their answer on their experience.

Second, sampling bias, which may be caused by the limited number of interviews and questionnaire responses. This was prevented to the best ability by interviewing stakeholders from various European countries and sectors of the value chain and including perspectives of researchers through questionnaire. However, the number of interviewees and questionnaire responses was relatively low, meaning that risk of sampling bias is relatively high. For this reason, the reader should carefully draw absolute conclusions from this work.

Third, limited depth of information, which may be caused by the nature of interview and questionnaire as a research method. This was tackled by asking further questions or to elaborate on certain answers to increase the depth of the responses.

Fourth, limited scope of the questions, which may be caused by the complexity and diversity of the topic. As the topic of this work is complex and sometimes very application-dependent capturing all aspects of the topic is not feasible in the limited time frame and knowledge. To capture input from as wide scope as possible questions were designed to cover most of the aspects of the topic.

9 Conclusions

This research has identified numerous issues to be solved in the transition to circular economy of plastics. The findings include the most major challenges as well as general and very application-dependant challenges and gaps. The research has shown that there are no one silver lining or even one major challenge but rather multiple sometimes very situational or as mentioned application-dependant issues. However, even situational issues can be solved with novel ideas and technology, which was demonstrated in this work by Modix trials. Overall effort across every stage of the plastics life cycle is required to develop and implement circular solutions. The challenges begin at the production of the products such as by certain design choices and cascade across the life cycle such as getting contaminated, mixed with other waste and improperly disposed.

The identified root challenges and gaps generally coincide with the literature findings. However, certain additional and valuable insights were identified from the stakeholders and researchers that were not prominent at the literature. Research found in the literature mostly identified challenges from a narrow scope. As the topic of circular economy of plastics is a wide topic involving various parties, extensive research done in this work has identified challenges from a wide scope. The future research should deal with further data collection by conducting more Europe-wide stakeholder interviews and questionnaire. From the findings of this work the future research should develop solutions from bottom up across the value chain.

The challenges and gaps were divided into feedstock acquisition and its quality, technology, recycled plastic and its uptake, and policies. From these, issues were identified around the recycling stage and during the recycling stage. These findings highlight the fact that issues exist at every stage of plastics value chains.

The challenges and gaps identified in this work need to be solved to achieve circular economy of plastics. Upon solving the challenges and filling the gaps the dependence on fossil raw materials will decrease and Europe will be a step closer to its major goal introduced in The European Green Deal of carbon neutrality.

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Appendix 1. Stakeholder interview questions

Feedstock related questions

1. What are the challenges in plastic waste that you recycle?
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2. Is there currently enough/excess amount of feedstock to recycle?
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3. Is there fluctuation in composition or quality of feedstock that you recycle, and how does it affect your recycling process?
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4. Which pre-recycling steps needs to be developed more to increase your feedstock quality?
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    -

5. What kind of revenue and/or costs are related to the acquisition of your feedstock?
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Plastic waste recycling

6. In your experience, is there a noticeable change in feedstock quality through plastic products design changes?
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7. Do you think that there is enough recycling capacity to achieve Europe's recycling goals (50% of plastic packaging by 2025 and 55% by 2030)? And what about collection capacity?
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8. What are your thoughts on mechanical and chemical recycling? (Are they both necessary for CE? Why chemical recycling is not in commercial use yet? Is chemical recycling considered as a threat to mechanical recyclers?)
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9. What are typical reasons for plastic waste to get rejected for recycling in your plant and what could be done to avoid it?
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10. What would you change in the plastic value chain to better facilitate your business operations and possible growth?
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Market for recycled plastic

11. How does the energy crisis affect chemical and mechanical recycling?
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12. Which sectors are your main customers for recycled plastic and how do you foresee it to change in the future?
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13. Is there enough market demand for recycled plastic to encourage expanding or new recyclers to enter the plastics recycling market?
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14. What are the main barriers to increase converters and/or original equipment manufacturers (OEM) and/or brand owners' uptake of recycled plastic?
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Questions related to plastic waste regulations.

15. Are regulations related to plastic recycling clear? Is guidance and support easily available?
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16. Do you think it is justified for regulations to mainly focus on packaging sector? Should other sectors be focused more?
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17. Do you think that current incentives for recycling plastic waste are enough to achieve European recycling targets? Should there be more goals on mandates on recyclate use (in addition to recyclate content in PET bottles by 2025 25% and by 2030 30%)?
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18. Do you think that there are enough policy incentives for recycling industry to operate and grow?
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19. Do you find that regulations are keeping up with recycling technology development?

- ____________________
- ____________________
- ____________________
- ____________________
- ____________________
- ____________________
- ____________________
- ____________________

Appendix 2. Questionnaire

Background information

1. Name (your name will not be connected with your results)

Enter your answer

2. E-mail (If you provide an e-mail we will send you the results. E-mail will not be used for any other purposes).

Enter your answer

3. Title *

- Researcher or scientist
- Senior researcher or scientist
- Professor or similiar
- Other

4. Organization *

Enter your answer

5. Size of your organization (personnel) *

- <50
- 50-249
- 250-1000
- >1000
- Other

6. Country of organization *

Enter your answer

7. Is your organisation *

- ◯ RTO (public)
- ◯ RTO (private, independent)
- ◯ RTO (private, company-owned)
- ◯ University or academia
- ◯ Other

8. What is your organization's or team's research focused on? *

- ☐ Collection
- ☐ Identification solutions
- ☐ Sorting
- ☐ Pre-treatment
- ☐ Reuse
- ☐ Mechanical recycling
- ☐ Thermochemical recycling (pyrolysis, gasification)
- ☐ Chemical recycling (e.g. solvent-based)
- ☐ Other recycling
- ☐ Converting or upgrading
- ☐ Material development
- ☐ Product design
- ☐ Product manufacturing
- ☐ Circular economy
- ☐ Operational environment (including policy and regulations)
- ☐ Equipment and process design
- ☐ Tracking and digitalisation
- ☐ Modelling, algorithms and software
- ☐ Other

9. Which plastic waste feedstock has your research dealt with or focused on? *

- [ ] Packaging
- [ ] Construction and demolition
- [ ] Automotive
- [ ] Electronics and electrical equipment
- [ ] Household, leisure and sports
- [ ] Agricultural
- [ ] Medical
- [ ] Other

Feedstock management

10. Experienced issues with feedstock (after this Q10, please specify in Q11) *

	Not an issue	Minor issue	No experience	Issue	Major issue
Batch-to-batch feedstock variation related issues	○	○	○	○	○
Hazardous substances related issues	○	○	○	○	○
Halogenated content related issues (Bromine)	○	○	○	○	○
Halogenated content related issues (Chlorine, other)	○	○	○	○	○
Low quality or degraded input related issues	○	○	○	○	○
Multimaterial or multilayer related issues	○	○	○	○	○
External contamination related issues	○	○	○	○	○
Difficulties to wash and separate	○	○	○	○	○
Formation of VOCs or other hazardous gases	○	○	○	○	○
Odour related issues	○	○	○	○	○
Other additive related issues	○	○	○	○	○
Poor separation related issues	○	○	○	○	○
Low quantities / volumes	○	○	○	○	○

11. Please elaborate on the issues you have encountered, especially mention if the issue relates to specific recycling technology. Also, please elaborate on further issues that were not listed in the previous question that you have encountered. *

Enter your answer

12. Which plastics or fractions get typically rejected or you do not handle in your work? (e.g. for safety reasons) *

Enter your answer

13. How could the collection, washing and pretreatment be improved to assist feedstock management? If possible, you may identify separate recommendations for both research and industrial scale. *

Enter your answer

Recycling

14. Are there some repeated/regularly encountered barriers, technology or knowledge gaps that you experience when working with plastic waste recycling? *

Enter your answer

15. In your experince, have design changes in products had an impact on the recyclability of plastic waste? Please share examples if possible. *

Enter your answer

16. In your opinion, how important would you rank the following RDI topics to **improve mechanical recycling**? (1 = Not important, 5 = Very important) *

	No opinion	1	2	3	4	5
Better sorting by polymer type to improve outputs of mechanical recycling.	○	○	○	○	○	○
Better identification of additives to improve outputs of mechanical recycling.	○	○	○	○	○	○
Better material separation to improve processing of mechanical recycling. (e.g. sand and metals from plastics)	○	○	○	○	○	○
Better sorting by colour to improve outputs of mechanical recycling.	○	○	○	○	○	○
Better pre-treatment or processing to remove odour to improve mechanical recycling.	○	○	○	○	○	○
Advanced processing to handle material degradation in mechanical recycling. (e.g. smart additivation or reactive extrusion)	○	○	○	○	○	○
Quicker and more reliable sampling and analysis of feedstock to understand composition and impurities before processing	○	○	○	○	○	○

17. In your opinion, how important would you rank the following RDI topics to **improve chemical and thermochemical recycling?** (1 = Not important, 5 = Very important) *

	No opinion	1	2	3	4	5
Better sorting by polymer type to improve outputs of chemical recycling.	○	○	○	○	○	○
Better identification of additives to improve outputs of chemical recycling.	○	○	○	○	○	○
Better material separation to improve processing of chemical recycling. (e.g. sand and metals from plastics)	○	○	○	○	○	○
Better sorting by colour to improve outputs of chemical recycling.	○	○	○	○	○	○
Better pre-treatment or processing to remove odour to improve chemical recycling.	○	○	○	○	○	○
Better processing to be able to handle feedstock mixtures.	○	○	○	○	○	○
Quicker and more reliable sampling and analysis of feedstock to understand composition and impurities before processing	○	○	○	○	○	○
Improve yields (e.g. via optimised processing, catalysts)	○	○	○	○	○	○
Improve upgrading (e.g. separation, further conversion)	○	○	○	○	○	○
Better analytical methods for processing outputs (e.g. pyrolysis oils)	○	○	○	○	○	○

18. Statements about recycling technologies (1 = Fully disagree, 5 = Fully agree) *

	1	2	3	4	5
Mechanical recycling has a lot of limitations.	○	○	○	○	○
Due to the limitations of mechanical recycling, chemical recycling is needed.	○	○	○	○	○
Chemical recycling does not have major limitations.	○	○	○	○	○
Chemical recycling will replace mechanical recycling.	○	○	○	○	○
Mechanical recycling should be the only recycling method used, due to the fact that it is more sustainable.	○	○	○	○	○
Feedstock suitable for mechanical recycling should not be treated by chemical recycling.	○	○	○	○	○
Chemical recycling is not sustainable due to higher energy consumption.	○	○	○	○	○
Mechanical recycling has achieved its limits.	○	○	○	○	○
Only mechanical recycling rejects should be treated by chemical recycling.	○	○	○	○	○
A combined approach with both mechanical and chemical recycling is needed that should be driven by sustainability.	○	○	○	○	○
A combined approach with both mechanical and chemical recycling is needed that should be driven by technical capabilities to produce high-performance outputs.	○	○	○	○	○
A combined approach with both mechanical and chemical recycling is needed that should be driven by economic feasibility.	○	○	○	○	○

19. Feel free to elaborate on your views or give further inputs relating to the previous questions or recycling in general

Enter your answer

Markets and policy

20. How would you increase the market demand for **high quality recycled plastics**? *

Enter your answer

21. How would you increase the market demand for **low quality recycled plastics** in products? *

Enter your answer

22. What are the main barriers and risks associated with increasing the uptake of recyclates and their share in products? *

Enter your answer

23. In your opinion, what are the key factors to support creating a market for currently non-recycled plastics? *

Enter your answer

24. Statements about policy landscape (1 = Fully disagree, 5 = Fully agree) *

	1	2	3	4	5
Regulations related to plastic recycling and circularity are clear	○	○	○	○	○
There are enough (policy) incentives to increase the recycling rates	○	○	○	○	○
Regulations mainly target the packaging sector at the moment	○	○	○	○	○
Regulations should target other sectors as well	○	○	○	○	○
There should be more goals in EU across sectors on mandates* on recyclate use (* requirement by law to have certain share of recyclates in products)	○	○	○	○	○
There are enough regulatory actions and social pressure across plastics value chains to transition to circular economy	○	○	○	○	○
There is enough easily understandable guidance and supportive documents available to understand the regulations affecting recycling and circular plastics	○	○	○	○	○
There are enough targets for recycling rates for sectors using plastics	○	○	○	○	○
Separate collection targets are needed for different plastic waste categories	○	○	○	○	○
There should be separate targets for producing high-quality recyclates	○	○	○	○	○

25. Which sector(s) require more attention from EU policies and why? *

Enter your answer

26. In your opinion, should plastic waste recycling targets be implemented (or increased if already implemented) on the following sectors by 2030 in the EU? *

	Yes	No	No opinion
Packaging (current target: 55 %)	○	○	○
Construction and demolition	○	○	○
Automotive	○	○	○
Electronics and electrical equipment	○	○	○
Household, leisure and sports	○	○	○
Agricultural	○	○	○
Medical	○	○	○

27. Please feel free to elaborate on the previous questions

Enter your answer

Implementation of circular stragies

28. In your opinion, how would you evaluate the following in terms of importance and impact that should be focused on **now** to address the plastic products and waste that has already been generated? (1 = Not important, 5 = Very important) *

	1	2	3	4	5
Refuse (eliminate product or certain functions)	○	○	○	○	○
Rethink (make product use more intenstive)	○	○	○	○	○
Reduce (use less resources and materials)	○	○	○	○	○
Reuse (use again in same original project function)	○	○	○	○	○
Repair (repair and maintain product to keep in original function)	○	○	○	○	○
Refurbish (restore and update old product to bring it up to date)	○	○	○	○	○
Remanufacture (Use parts of discarded product ina new product with the same function)	○	○	○	○	○
Repurpose (use discarded product or parts of it in new product with different function)	○	○	○	○	○
Recycle (all technologies)	○	○	○	○	○
Recover (energy)	○	○	○	○	○

29. In your opinion, how would you evaluate the different circular strategies in importance to address **future** plastic production, use in products, and generation and management of plastic waste to best mitigate environmental and climate impacts as well as excess resource use?
(1 = Not relevant, 5 = Very relevant) *

	1	2	3	4	5
Refuse (eliminate product or certain functions)	◯	◯	◯	◯	◯
Rethink (make product use more intensive)	◯	◯	◯	◯	◯
Reduce (use less resources and materials)	◯	◯	◯	◯	◯
Reuse (use again in same original project function)	◯	◯	◯	◯	◯
Repair (repair and maintain product to keep in original function)	◯	◯	◯	◯	◯
Refurbish (restore and update old product to bring it up to date)	◯	◯	◯	◯	◯
Remanufacture (Use parts of discarded product ina new product with the same function)	◯	◯	◯	◯	◯
Repurpose (use discarded product or parts of it in new product with different function)	◯	◯	◯	◯	◯
Recycle (all technologies)	◯	◯	◯	◯	◯
Recover (energy)	◯	◯	◯	◯	◯

31. Were these Circular strategies (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover) familiar to you prior to this survey?

- ○ Yes, all
- ○ Yes, most of them (at least 75 %)
- ○ Yes, many of them (at least 50 %)
- ○ Yes, some (less than 50 %)
- ○ Yes, a few (less than 25 %)
- ○ Not at all

32. In your opinion, what circular strategies should be further researched? What kind of challenges or obstacles do you identify with that circular strategy/strategies? *

Enter your answer

33. Thank you, you made it!

If you wish, feel free to leave any further comments or views here

Enter your answer