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European alliance for innovation training
& collaboration towards future packaging

MODULE 3 : Recycling Systems & novel business models for the second life of residues

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2.1. Optimization of plastics recycling

Prior to the actual reprocessing of recycled materials into new products, the conversion from waste to new raw materials needs to occur. This phase is generally termed the 'End-of-Waste' and begins after the collection step. The process can include the following steps, each of which can occur anywhere between not at all and multiple times throughout the sequence:

-Separation and sorting: this occurs based on shape, density, size, colour or chemical composition.

-Baling: if the plastic is not processed where it is sorted, it is often baled in between for transport purposes.

-Washing: removal of (often organic) contaminants.

- Grinding: size reduction from products to flakes.

-Compounding & pelletizing: optional reprocessing of the flakes into a granulate, which is easier to use for converters than flakes.

2.1.1. COLLECTION

Systems that include collection of post-consumer plastic waste can be roughly divided into three overall categories:

› Monomaterial collection: The waste collection is designed in order to obtain only one source separated material fraction such as plastics. The waste collection can include several plastic types together or targeting specific plastic types (e.g. PET bottles, or rigid plastic such as pots, tubs and trays).

› Multimaterial collection: The collection is designed to collect several types of source separated recycable materials such as metals, glass and plastics.

› Mixed collection: The waste origining from this type of collection is often very contaminated and needs intensive further treatment. This stream may include the organic waste.

The monomaterial collection of plastic can be designed very differently. The collection systems can be designed for only one or few polymers (e.g. PET bottles), for plastic types (e.g. rigid or flexible plastic) or plastic in general.

A broad collection of a large variety of plastic types also requires a more thougroug fine sorting afterwards resulting in a larger proportion of rejected material and in some cases a lower quality of the output fraction (secondary plastic).

The efficiency of many separation techniques depends on the general surface cleanness of the plastic. Coatings such as labels and paint may affect, for example, identification methods that are based on spectroscopic analysis.

Moreover, the size reduction (comminution) of the material to be separated is often a key process step. It generally improves the separation efficiency, allowing the generation of high purity products.

2.1.2. CLEANING OF PLASTICS

2.1.2.1. Dry cleaning

Air is blown through the bed of the material removing light contaminants. This cleaning process is often linked with size reduction, with fine contaminants being removed as they are liberated by techniques such as screening, using screens, hydrocyclones or filters.

2.1.2.2. Washing to Remove Contaminants

Liquid and food residues may be removed by washing with the aid of an appropriate surfactant if necessary. Washing is also required to remove labels from bottles. Glues that hold the labels to the bottle may be used only on the edge or may totally cover the back of the label. Hot melt glues are particularly troublesome as they soften at much higher temperatures than conventional glues. Some ink may also be water soluble, and may contain toxic metals such as lead. The treatment of contaminated water generated from the washing process adds to the cost of the sorting operation.

2.1.2.3. Removal of Coating Using Abrasives

As it was explained before, the coating has to be removed at the analysis site to enable the correct identification to be made. The surface is typically cleaned using an abrasive disc. This is a time consuming process and therefore only worthwhile for large items.

2.1.3. SIZE REDUCTION

Size reduction is often an important step since it is useful to improve liberation of materials from mixtures of constituents, to increase the bulk density of the plastic to minimise transportation costs, to produce material of a size that can be more accurately metered and to generate material of the correct size range for the separation process. There are several techniques used for that purpose.

2.1.3.1. Shredders and Rotary Grinders

Shredders reduce the size of plastics using a cutting action. The plastic is drawn into a set of asynchronized contra-rotating shafts equipped with cutting discs and distance collars. Rotary grinders take symmetrical bites from the material to be ground with steel blocks mounted on a rotor. Rotary grinders typically run at low speed (approximately 80-100 rpm) and high torque.

2.1.3.2. Rotary Knife Cutters

The rotary knife cutter is reported to be the most widely used device for plastics size reduction. The device uses a combination of stationary and rotating blades to reduce the plastic in size. The cutting action is produced as the plastic moves ween the stationary and rotating blades. The rotating blades are set at a slight angle with respect to the rotor shaft and the fixed blades are set at the same angle but in the opposite direction.

2.1.3.3. Cryogenic Grinding

The temperature can be utilised to improve the energy efficiency of grinding and to improve the liberation of glues, labels and composite materials. The cooling of the plastic also prevents thermal degradation of polymers such as PVC, which can occur with other comminution processes. Liquid nitrogen may be sprayed onto the plastics, or the plastics may be drawn through a bath of the liquid, in an enclosed tunnel.

2.2. Mechanical recycling

Sorting and separation of the collected plastic have the overall purpose to enable high quality recycling. Separation of different polymers is particularly important for mechanical recycling because processing mixed materials would otherwise produce recyclate of low quality, which could only be used in a limited number of applications The sorting and separation technologies are aiming at reducing the quantity of non-plastics and reducing the quantity of non-targeted plastic polymers.

The technique selected for the sorting will depend on several factors:

-complexity of the plastic mixture

-quality (level of contamination)

-physical form of the polymer

-end use of the plastic

-economy (cost of separating operation)

The output from the sorting plants can be single polymer or different mixes of polymer types (single colours or mixed colours).

Several types of sorting are available depending on the collection (monomaterial or mixed), size...

2.2.1. Manual sorting

Manual sorting is typically used to separating large items as 2D plastic films from other plastics/mixed recyclables. Moreover, it can be used to remove non-targeted materials from mono-origin waste streams. Non targeted materials can be impurities or non certified types of packaging waste materials.

The mode of operation is based on the visual identification of the plastics by an operator. Is cheap in terms of capital investment but it is slow and labour intensive.

2.2.2. Manual sorting with a degree of automatization

Feedstock passed along a conveyor belt for operator to identify visually and sort by polymer category by activating automatic ejection mechanism.

2.2.3. Automatic sorting tecniques

There are several automatic sorting tecniques. The following table is a summary of them

The use of infrared involves the unsorted plastics with near infrared waves (600-2500 metres in wavelength). When exposed to near-infrared light waves each polymer reflect an identification spectrum. Therefore, this method can accurately identify different polymers. Nevertheless, this method is not suitable for identification of dark coloured plastics. The method has a high speed of identification.

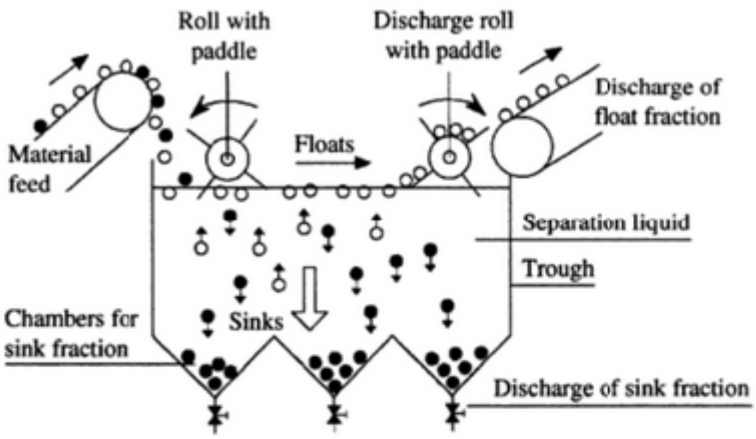
Moreover, X-Ray fluorescence has been also used for sorting. Most of this technology is being applied to the PVC sorting since the chlorine atoms in PVC give a unique peak in the X-Ray spectrum that is easily detectable.

Addition of markers or tracers added during manufacture: infrared dyes in PET or fluorescent dyes. It provides a high detection accuracy for different polymers or even different grades of polymer (up to 90% for coloured particulate contamination from clear PET flake3).

Identification Method	Advantages	Disadvantages	Application
Optical	Only effective means of sorting by colour	Does not identify the polymer	Used to remove coloured impurities and to sort one polymer by colour (such as PET)
Mid Infrared	Proven and established technology. Can identify dark plastics	Not applicable for high speed identification systems. Requires relatively smooth, clean surface. Object to be identified must be brought to the instrument's measuring window	Assisted manual separation of car components
Near Infrared	Fast - photodetectors have short response times. Suited for analysis of transparent or lightly coloured objects	Unsuitable for dark objects such as those containing carbon black which absorbs and scatters at NIR frequencies	Bottle sorting
UV fluorescence	With the use of tracers the system is capable of identifying polymer blends	Not discriminating enough without tracers. Cost of tracers prohibitive	General application to all polymers with inclusion of tracers
X-Ray	Proven and established technology for the identification of PVC	Elemental analysis - many polymers are composed of the same elements	Separation of PVC from PET

2.2.4. Flotation tanks

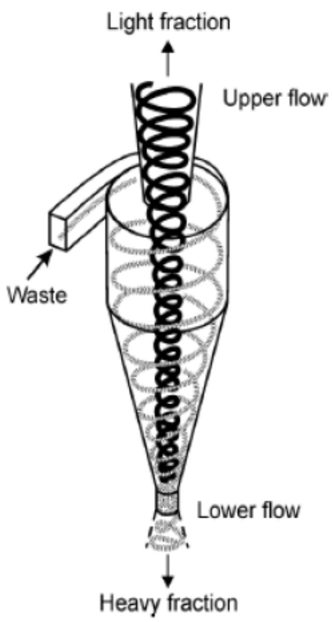
It is based on separation in liquid by means of differences in polymer densities. Improvements are being examined with supercritical fluids and other non-organic solvents to replace water.



(Sorting of Waste Plastics for Recycling. R.D. Pascoe)

2.2.5. Hydrocyclones

Density sorting based on the centripetal force to fluid resistance. The waste will be fed into the hydrocyclone in a suspension. Lighter fractions will be transported upwards, while more dense particles will end in the bottom of the cyclone. Size reduction is usually done before treatment in hydrocyclones. Allows better separation thanstatic flotation tanks. May separate PE from heavier PVC, PET or PS. Higher throughout than static float and sink tanks.



(Plastic ZERO - Public Private Cooperations for Avoiding Plastic as a Waste)

2.2.6. Air classifier

Separate according to materials’ falling velocity" in an air stream. The function is to separate in light and heavy parts. Different types of air classifiers are available.

2.2.7. Ballistic separator

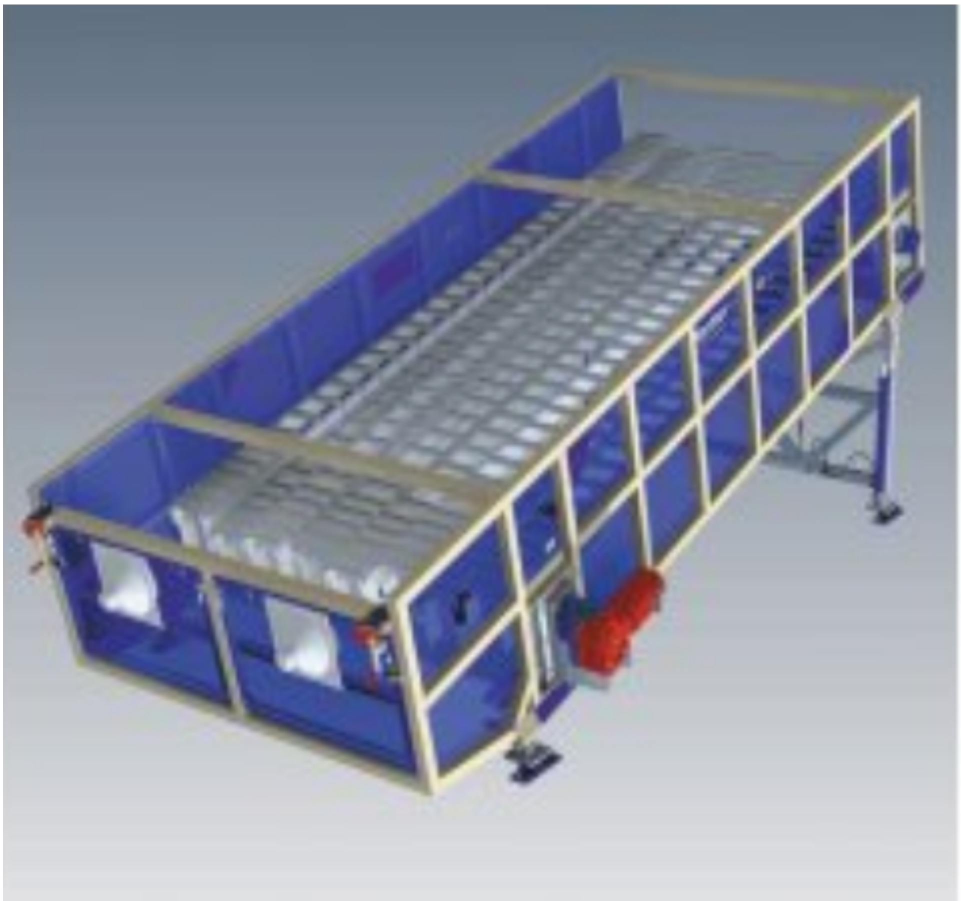
Automatic sorting according to size, density and rigidness. The sorting results in three fractions;

› Light fraction (light and flat parts)

› Heavy fraction (heavy and cubical parts)

› Fine fraction (e.g. less 20 mm)

A ballistic separator is in principle a vibrating perforated deck. A small incline in the deck causes heavy materials to fall to the lower level of the deck while lighter materials such as plastic foils are transported upwards. Fine materials fall through the perforated bottom.

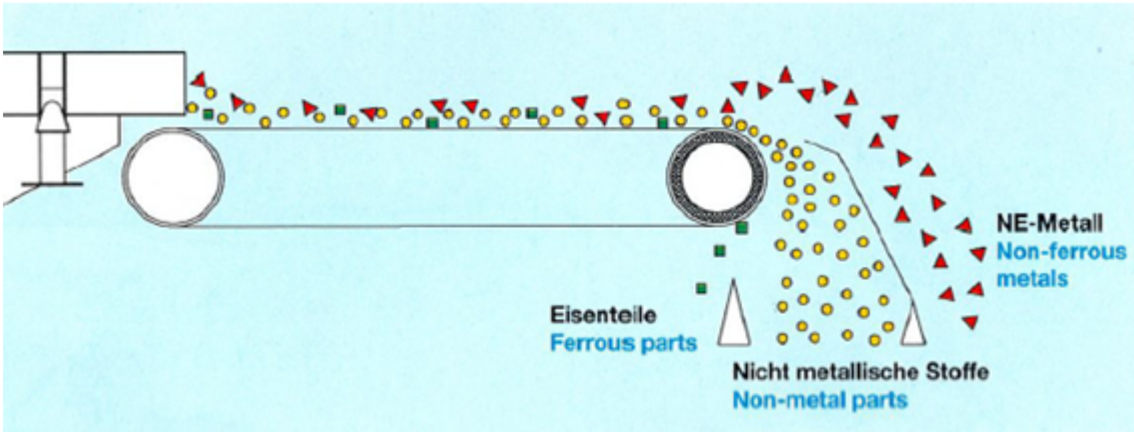


(BRT HARTNER ballistic separator)

2.2.8. Magnetic and eddy current separation

This equipment is applied for sorting out magnetic iron and non-ferrous metals (e.g.aluminium).

The magnet is able to separate ferromagnetic parts from non ferromagnetic materials. Stainless steel and other metals will not be separated in such equipment.



(Eddie Current separator - principle of function)

2.2.9. Electrostatic separation

Separation can also be achieved by employing electrostatic charging of different plastics. This method separates the plastic materials through their differences in electrostatic charges. The materials are sorted by letting them fall freely through an electric field produced between two parallel sets of oppositely charged electrodes and are separately collected according to the triboelectric charge that they have.

2.2.10. Selective dissolution

It is the batch dissolution of mixed plastics using solvents. The polymers have different solubility in organic solvents (differences amplified by the action of temperature). Different steps like to make soluble, then precipitation, then filtrations and finally evaporation of solvents. This technique helps in complete separation of the polymers by careful control of temperature and selection of appropriate solvent. Individual polymer can be separated from complex mixture, contaminations such as dirt or soil. The disadvantage of this technique is amounts of solvents used, even though most of the solvents are recycled within the process.

2.2.11. Sorting by melting

This sorting technique is suitable for sorting only two plastic kind at the time. To be able to use this method, it is essential that melting temperatures of the plastics are significantly different. This technique consists of an heated roll belt separator. Sorting takes place by the selective thermo adhesion of the softened particles to the rolls or belt.

Most European sorting plants consist of a mix of the above mentioned technologies to ensure an economical and efficient sorting of the input material with satisfying output quality. The exact composition of the specific plant should be adjusted according to input material as well as required output quality.

Mechanical recycling involves the use of relatively simple processes and generates polymer materials of high quality. However, this process is mainly suitable for homogene ous waste streams which often requires clean waste of the same type or a high degree of sorting, which can increase the costs of operation.

2.2.2. Main challenges related to mechanical recycling

Different challenges arise when recycling both mono- and mixed plastics. The principal issue is the fact that polymers will degrade under certain conditions. These conditions are amongst others heat, oxidation, light, ionic radiation, hydrolysis and mechanical shear.

2.3. Secondary plastic products. Examples and market trends

2.4. Chemical routes for recycling. Disolving, catalytic and thermochemical technologies

2.4.1. Depolymerisation and leaching

In this section different routes for the chemical recycling of plastics are presented. They can be grouped in two technology categories: chemical depolymerisation and solvent-assisted separation.

2.5. CHEMICAL DEPOLYMERISATION

Process overview

Chemical depolymerisation consists on breaking down polymer chains through the use of chemicals. It can be also referred in literature as chemolysis and solvolysis.

The plastic wast is first pre-treated to remove solid contaminants before initiating the process. Chemicals are used to break down the polymer chains into either shorter chain oligomers (partial depolymerisation) or the monomers (full depolymerisation).

Once the depolymerisation is completed, monomers are recovered and purified.

Applications.

1. The chemical depolymerisation process is only applicable to certain types of plastics. The most significant ones are condensation polymers. Their name comes from the way in which they are formed (polymerysation by condensation).
2. Polyethylene Terephthalate (PET) and other polyesters, Polyurethane (PU=, Polyamides (PA) and Polylactic Acid (PLA) are the most relevant polymers that can be subjeted to chemical depolymerysation.

Polymer	Waste stream
Polyethylene Terephthalate (PET)	Bottles Films and trays Textiles including polyester and polyester/cotton blends
Polyurethanes (PU)	Mattress foams Rigid foams
Polyamides (PA)	Fishing line and nets Textiles including fabrics and aparel
Polylactic Acid (PLA)	Beverage cups

Products by chemical input

- The way in which the depolymerisation process works is essentially the same for each polymer. The bonds uniting monomers are broken apart. However, the reaction pathway by which the chemical bonds are broken depends on the molecule used for depolymerisation.
- There are five main chemical inputs, each with a distinct reaction pathway and, therefore, a different monomer output. The table below shows the different outputs that can be obtained for PET.
- Table: PET depolymerisation products by chemical input.

Chemical input	Reaction pathway	Monomer output	Other product(s)
Glycol	Glycolisis	bis(2-Hydroxyethil)terephthalate (BHET)	Ethylene Glycol
Water	Hydrolysis	Terephthalic acid (TPA)	Ethylene Glycol
Methanol	Methanolysis	Dimethyl Terephthalate (DMT)	Ethylene Glycol
Amines	Aminolysis	bis(2-hydroxyethylene) terephthalamide (BHETA)	---
Ammonia	Ammonolysis	Terephthalamide	Ethylene Glycol

These pathways are not right now commercially exploited. Glycolysis, hydrolysis, and methanolysis have demonstrated success at pilot plant level or larger, glycolysis being the most advanced in terms of demonstrating commercial viability on a larger scale. For aminolysis and ammonolyisis there is no evidence to date that these have progressed beyound laboratory trials.

Environmental performance

Several attempts have been carried out to assess the environmental performance of chemical depolymerisation processes. In general, chemical depolymerisation is still too demanding in terms of energy requirements and mechanical recycling is still considered the most favourable technology overall.

However, chemical depolymerisation allows addressing the issues with unavoidable contaminants in mechanically recycled PET, especially after a number ofrecycling cycles. So this aspect should not be obviated.

Summary

According to the report on Chemical Recycling by Hann and Connock (2020) here you are a summary of the advantages and disadvantages of chemical depolymerisation.

Advantages:

Monomer outputs can be utilised to produce plastic products of equal quality to virgin equivalents, potentially suitable for food contact applications.

Demonstrated examples of systems that allow the recovery and reuse of chemical reagents such as catalysts and solvents.

High yields demonstrated for a number of technologies.

Demonstration of commercial viability for bottle and fibre inputs.

Disadvantages:

- Can currently handle only material inputs that are largely homogenous in nature.
- Often requires stringent pre-sorting and or pre-treatment steps to prepare for purification.
- Typically necessitates high energy requirements, in particular the post-purification drying stages.
- Typically, cannot remove contaminants entirely.
- Has not been demonstrated to provide food-grade outputs.
- Lack of clarity regarding the solvent types and toxicities for larger scale examples.
- Does not allow for limitless recycling of the material, due to thermal degradation of the chains during reprocessing and conversion to form new plastic products.
- Current lack of clarity regarding environmental performance.

- Yet to demonstrate economic viability on a commercial scale.

2.6. SOLVENT PURIFICATION

Process overview

- The basis of solvent purification is to use the principle of solubility to selectively separate any contaminating substances from the plastic waste. These contaminants typically consist of:
- Additives such as flame retardants, stabilisers, impact modifiers, colourants and pigments;
- Non-target polymers; and
- Non-Intentionally Added Substances (NIAS), which are compounds both absorbed and produced within the plastic material during use. This can include side products from the manufacturing process, as well as degradation products, both from partial breakdown of the polymer itself as well as the additives contained within the plastic.
- The plastic is shredded and dissolved within a solvent, exhibiting a high solubility of the polymer whereas contaminants have low solubility. Contaminants will remain solid and will be separated off form the liquid phase.
- Once the purification process is complete, the polymer is extracted from the solution by placing it in a non-solvent to re-solidify the polymer, in a process known as precipitation. Further treatment of the polymer follows, including filtration, washing and drying, to remove the non-solvent.

Applications

As the effectiveness of this technology is dependent on solubility, it can be theoretically be applied to almost any polymer, provided a suitable solvent can be found.

The table below shows the current application for solvent purification by polymer type and waste streams.

Polymer	Waste stream
Polystyrene (PS)	Expanded polystyrene foam (EPS) Houshold PS waste
Polyethylene Terephthalate (PET)	Polyester/cotton textile Packaging
Polyethylene (PE)	Multilayer bags
Polyamide (PA)	Multilayer bags
Polypropylene (PP)	Carpets

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Critical aspects.

- The effectiveness of polymer purification is very dependent on the exact composition of the waste input in terms of contaminants. Regretfully, there is a lack of clarity for the majority of technologies regarding the impurities dealt with.
- Ideally, if all the types of polymer contained within the plastic waste are known, as well as the full range of contaminants, the process could be used to purify multi-material waste streams, provided there were sufficient stages of solvent selection.
- Theoretically, this could avoid the costs associated with segregated collection and advanced sorting infrastructure required to separate specific polymer types. However, the added complexity required to ensure selectivity for each polymer type leads to higher environmental and economic costs from increased solvent, energy and time inputs.
- Screening and sorting of the materials is a common pre-treatment step to separate external contaminants such as stickers, glue, tape, and so on. Even following purification, the risk of residual impurities is still often an issue due to the reduction in the material properties compared with the virgin polymer.
- Another important limiting factor is that the process may have a stressing influence on the polymer structure, as thermal and physical stresses do during the reprocessing of

the plastic. This means that the method will not likely allow an infinite recycling of a plastic material.

Environmental performance.

- A study funded by the Dutch government, conducted several studies screening LCA studies of chemical recycling technologies with the aim of determining whether they may fit within the Dutch waste management system.
- Although the results of the study are not detailed enough to make general assumptions, comparison of waste-to-energy methods with solvent purification of expanded polystyrene (EPS) found significant climate change benefits for the latter.
- However, as this technology is yet to reach commercial scale, it is difficult to draw solid conclusions. Studies up to date have been based on scenarios defining very specific waste stream inputs to ensure successful purification.

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Summary.

According to the report on Chemical Recycling by Hann and Connock (2020) here you are a summary of the advantages and disadvantages of solvent purification.

Advantages:

- Has been demonstrated to separate polycotton textile blends.
- Environmentally benign solvents have been tested successfully at a lab scale.
- Generally, allows recovery of the solvent for reuse.
- The process has been demonstrated to recover non-target by-products for valorisation.

Disadvantages:

- Typically requires homogenous waste streams as an input, often requiring extensive pre-treatment/sorting technologies.
- Lack of information concerning the quantities of chemical reagents and other supplementary materials e.g. catalysts.
- Lack of clarity as to the overall energy inputs associated with the technologies, processes often requiring high energy inputs.
- Lack of yield information at plant level.

- General lack of understanding around the level of contamination that the technologies can handle, nor how the contaminants are dealt with following monomer purification.
- Little consideration in published information given for hazardous inputs/by-products.
- Lack of verified environmental performance data for the majority of technologies.