Advanced Sorting for Circularity

How Advanced Sorting using Markers and Object Recognition Can Contribute to Plastics Circularity and Traceability in Europe

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Report For

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TOMRA

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EXECUTIVE SUMMARY

Background And Objectives

The plastic packaging industry is currently facing a growing demand for increased sustainability, particularly in increasing recycled content and fostering a circular economy. This pressure varies across Europe but is predominantly driven by public and governmental demands, leading to brand owners voluntarily adopting sustainable practices. European Union (EU) legislation also enacts requirements around packaging, particularly the expected successor to the Packaging and Packaging Waste Directive (PPWD), the Packaging and Packaging Waste Regulation (PPWR). The PPWR is expected to drive forward increased circularity in two significant ways relevant to this study:

- It will set recycled content targets which will need to be met in nearly all forms of plastics packaging; and
- It will effectively drive out the supply chain plastic packaging formats which cause recyclability issues.

This study explores how marker and object recognition sorting technology, collectively termed 'advanced sorting technology', can contribute to circularity and traceability in plastic packaging recycling, specifically within the EU, Norway, Switzerland, and the United Kingdom. The term circularity is used to mean packaging to packaging recycling which will be necessary to meet the recycled content targets of the PPWR. The study focuses on recycling from household like waste streams and mechanical recycling processes.

Study Approach

The methodology involved identifying polymers and packaging material formats not adequately sorted by existing technologies for achieving circularity. The current adequacy of sorting by existing technologies was assessed for a wide range of packaging types based on their polymer type and format. The study identified a specific problem set of packaging types where current sorting technologies cannot sufficiently sort for circularity. It then evaluated new technologies (i.e., advanced sorting technologies) that could enable classification and sorting of these post-consumer plastic packaging types. A range of new sensor- and marker-based sorting technologies were examined. Three were shortlisted for detailed cost and performance modelling: Object Recognition (OR), chemical markers, and digital watermarks.

This study focuses on sorting solutions required to provide a suitable feedstock for mechanical recycling processes producing material suitable for packaging manufacturers. This project focus is due to the underlying assumption that the potential for circular recycling using mechanical processes should be explored before defaulting to the assumption that chemical recycling processes would be used to process the relevant material. It was also determined that the challenges for sorting will be greater for material being processed by mechanical recycling processes. The study does not directly examine problem sets for existing sorting that may exist for sorting for chemical recycling processes. It is likely that if this had been examined as part of this project, problem sets would differ and be lower in number. Nonetheless, it should not be assumed that there would be no problems with existing sorting technologies for chemical recycling.

Findings

The findings in this report are divided into the following sub-sections:

1. **Findings for circularity**
    a. Findings for rigid plastic applications;
    b. Findings for flexible plastic applications;
2. **Findings for traceability;** and

3. Findings for implementation.

Key findings under each sub-section are described below.

1a. Circularity Findings – Rigid Plastic Applications

This study reveals that existing technology allows adequate sorting for circularity in most rigid plastic applications. Advanced sorting would not contribute significantly more post-consumer plastic packaging into recycling processes and therefore will not contribute significantly to overall plastic packaging recycling rates. A focus on collecting more material and optimising the use of existing sorting technology will be far more important in reaching recycling rate targets. A more detailed discussion of how advanced sorting can impact the quantity and quality of recycling can be found in Section 3.2.

However, for a small but significant subset, particularly contact-sensitive separations in PP and HDPE rigid containers, which account for around 11% of the total rigid tonnage placed on market in Europe, advanced sorting is necessary to meet PPWR recycled content targets. For these materials, which were defined as the 'problem set' where existing technology is neither sufficient nor reasonably expected to be sufficient to ensure circularity, advanced sorting solutions were modelled.

The modelling found little difference in performance between the solutions examined. In terms of the yield of target material recovered, the advanced sorting technologies show similar effectiveness to each other and existing methods, with no significant superiority in sorting efficiency (Figure E-1 and Figure E-2 below). However, cost analysis indicates that OR technology emerges as the most cost-effective solution (when measured in terms of cost per tonne of material sorted for recycling), particularly for HDPE and PP rigids, due to the absence of additional costs associated with marker systems (Figure E-3).

Figure E-1: Modelled Material Flow, HDPE Rigids

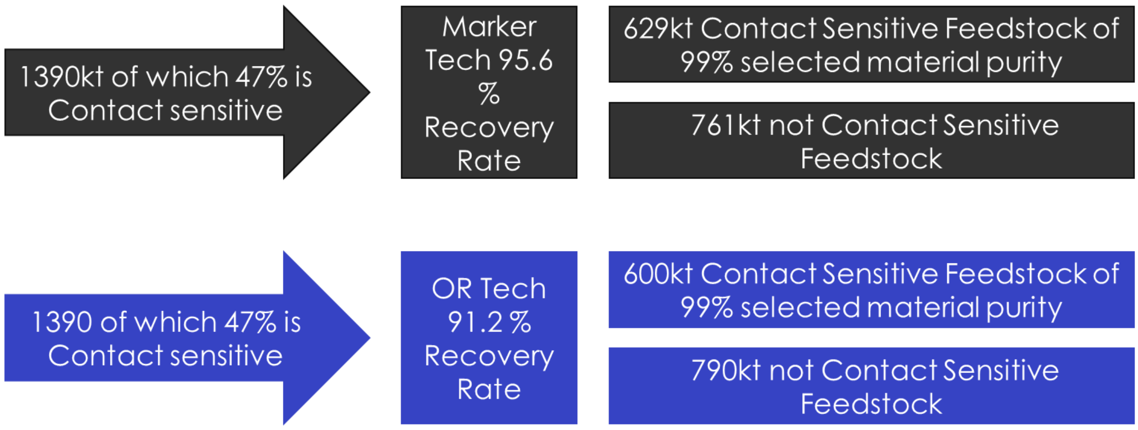


Figure E-2: Modelled Material Flow, PP Rigids

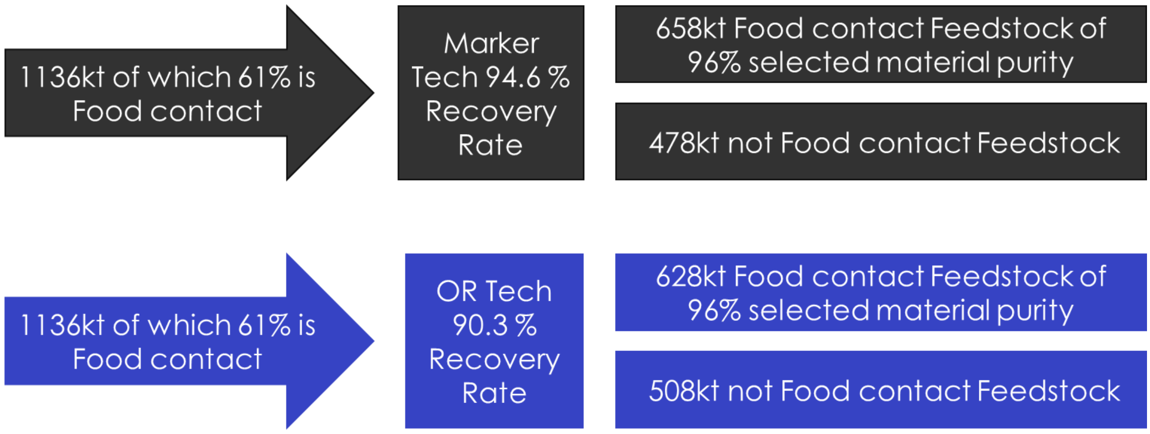
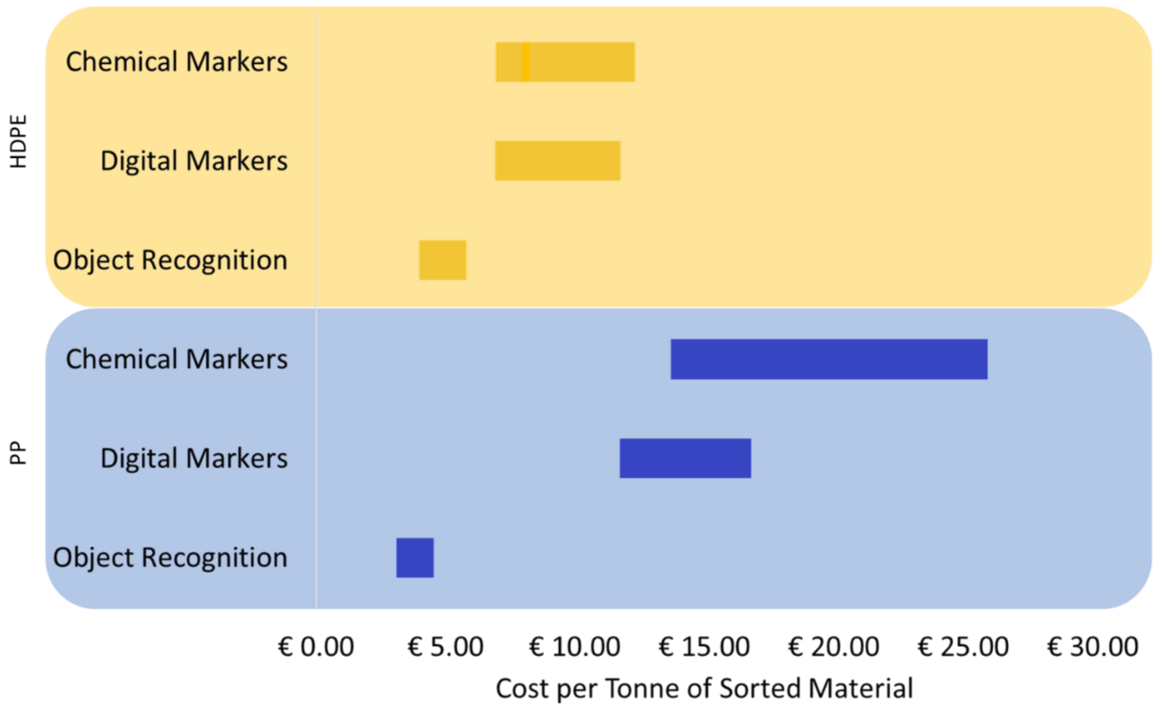


Figure E-3: Cost range estimations for sorting HDPE and PP Rigids using UV markers, digital watermarks, and OR technology.



The likely cost range of the two different marker technologies overlaps. A large part of the difference between them is due to different approaches to costing the licensing for each technology provider. The difference between HDPE and PP in terms of the gap between OR and the marker systems can be explained by the weight of products in each polymer. HDPE products are on average heavier, which means a tonne of sorted material has fewer products or labels associated with it, and so less of these costs which are associated only with the marker technologies. PP products are on average lighter, so there are more labels per tonne of material, which means that the marker costs increase. Conversely, as the modelled PP stream has a higher incidence of target materials than the modelled HDPE stream, OR costs reduce for PP as the same capital and operational costs are divided across a higher yield of target material.

1b. Circularity Findings – Flexible Plastic Applications

The situation with flexible plastic packaging was found to be more complex. Ceflex have undertaken relevant studies on sorting flexible plastics, concluding that market ready and relatively straightforward optimisations to existing technology could produce grades of material suitable for mechanical recycling from the vast majority of flexible plastic inputs to the sorting process. In addition, these can also produce recyclate from mechanical processes that is suitable for packaging conversion.

However, it is clear that contact sensitive packaging is a significant proportion of flexible packaging and, if mechanical recycling processes are to produce contact sensitive recycled content, further advancements in sorting beyond existing technology would be necessary. Furthermore, due to a wide range in resin specifications used in packaging arising in household-like recycling streams, there could be a need to produce more granular sorting on mono material grades according to resin specifications for inclusion of recycled content at higher recycled content levels. If this were to be the case, then further advancement of sorting beyond existing technologies would be necessary.

The extent to which the advanced technologies examined in this study could produce material suitable for contact sensitive mechanical recycling and produce resin specifications suitable for higher recycled context specifications remains uncertain. There also remains uncertainty on the distribution of contact sensitive material in the collected flexible plastic composition and considerable uncertainty on what sorting would actually need to achieve for recycled content resin specifications.

Furthermore, whilst theoretically the role of the advanced sorting technologies studied can be considered, there is no available data to effectively examine the performance and costs of these technologies across the full range of flexible packaging materials. The study findings are that digital markers and OR are yet to be proven as a solution across the full range of relevant flexible packaging materials in a real-world environment. From a theoretical perspective, it could be possible for OR to perform relatively effectively in identifying specific flexible packaging, making it a more cost-effective solution.

Due to the range of uncertainties existing with advanced sorting in flexible plastics, it was determined that it would not be reasonable to produce a performance and costs projection.

2. Traceability Findings

The problem set for traceability is different to that of sorting for circularity. Improving traceability through advanced technologies could improve regulatory processes and could potentially improve the efficiency and fairness of Extended Producer Responsibility (EPR) processes. Sorting for circularity may require a smaller amount of sorting technology only applied at certain points of the recycling supply chain. Traceability will require more technology and potentially applied at different points of the recycling supply chain. None of the modelled advanced technologies have been demonstrated to achieve a high level of traceability across all post-consumer plastic packaging formats. However, of the three technologies examined in detail it seems likely that watermarking might offer the most granular tracing solution. Achieving a reasonable degree of traceability will produce substantially more cost than sorting for circularity. The key unanswered question is whether European producers would be willing to pay for better data and potentially improved efficiency and fairness in EPR systems that effective tracing could unlock.

3. Implementation Findings

The implementation timelines for the various advanced technologies differ significantly. Implementing any marking convention would mean wholescale adoption at a national market level at the very least and possibly at an EU level. OR can be adopted on a plant-to-plant basis as demand requires. The benefits of OR could therefore be experienced at a far quicker timeline than would be likely for the mass adoption from marker technology.

Conclusions

The insights from this study provide a clear direction for targeted investment and innovation in sorting technologies, emphasising the importance of aligning technological choices with specific recycling objectives and the unique requirements of different packaging types. As the industry moves towards meeting the EU recycling targets, this nuanced understanding will be essential in guiding efforts towards more effective and sustainable plastic packaging recycling practices.

In summary, this study examines the role that advanced sorting technologies could play in increasing circularity in plastic packaging. Key conclusions are the following:

For rigid plastic packaging:

- Advanced sorting will not increase overall recycling rates to a significant degree;
- Advanced sorting is only necessary for a limited set of rigid applications and polymers, namely contact sensitive applications in HDPE and PP; and
- The most cost-effective method of addressing HDPE and PP contact sensitive recycling would be to use OR when compared to marker technologies.

For flexible plastic packaging:

- Advanced sorting will not increase overall recycling rates to a significant degree;
- Advanced sorting is likely not necessary to produce recyclate grades but might be necessary to produce contact sensitive grades and recyclate specifications via mechanical recycling;
- There is insufficient evidence to determine performance and cost projections for advanced sorting in flexibles; and
- There could be reasons to assume that the cost and performance between the technologies could be a similar order of results as the rigid plastic findings – i.e., OR could provide an important and more cost-effective solution, but further trials of all the technologies across a full range of flexible plastic applications and polymers would be necessary to reach a clear conclusion.

The analysis found that the most cost-effective method of addressing HDPE and PP contact sensitive recycling would be to use OR when compared to marker technologies.

For traceability:

All advanced sorting technologies could offer increased traceability, though it is reasonable to conclude that this would be greater with digital markers than with OR. However, traceability would require significantly more investment than is needed to achieve greater circularity and in the case of markers would require far more packages being marked. Whether there is a willingness to pay for increased traceability remains uncertain.

Implementation:

It seems highly likely that OR can be (and arguably is being) adopted far more quickly than marker technologies.

Overall:

It seems likely that there will be continued adoption of OR technologies and these may offer a more cost-effective solution for circularity. Both the plastics industry and policy developers should consider whether the additional cost burden that the use of markers would bring offers sufficient additional benefit to warrant the complex implementation process that would be needed to use specific markers as a mass market solution.

Contents

Glossary and Abbreviations

Term	Definition
Advanced Sorting	Sorting technologies that either employ marking technology or OR technologies
AI	Artificial intelligence
CEAP	Circular Economy Action Plan
Contact-sensitive	Packaging containing food contact (food and beverages), medical, cosmetic, and pharmaceutical products
C&I	Commercial and industrial
EOL	End-of-Life
EPR	Extended Producer Responsibility
EVOH	Ethylene-vinyl alcohol
DfR	Design for Recycling – the processes where packages are designed or re-designed with a focus on recycling outcomes
DRS	Deposit Return System
Ejector	Used in this report to describe a component of sorting technologies which uses compressed air which is directed through fine nozzles in order to select items
Food-contact	Packaging containing food and beverage products
HDPE	High-density polyethylene
Jazz	Mixed-coloured material
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MFI	Melt-flow index
Metallised /Metal foil	Metallised is used to describe packages with a very thin layer of aluminium and when layered on a mono resin are considered in this report to be mono material. These differ from metal foil plastic packaging where the metal element is significantly higher proportion of the package weight.
Mixed polyolefin structures	These are structures that contain more than one polyolefin polymer – e.g., PE and PP blended or as an MMML (without layers of polymers that are not polyolefin)

MMML	Multi Material Multi Layer – flexible packaging structures are any structure that has multiple layers within it that are made of different materials (excludes metallised).
MRF	Materials Recovery Facility
NIR	Near-infrared
OR	Object recognition
PCR	Post-consumer recyclate
PET	Polyethylene terephthalate
POM	Placed on the Market
PP	Polypropylene
PPWD	Packaging and Packaging Waste Directive
PPWR	Packaging and Packaging Waste Regulation
PRF	Plastics Recovery Facility
RFID	Radio frequency identification
rPET	Recycled PET
Skin-contact	Packaging containing items intended to come into contact with human skin
SKU	Stock Keeping Unit – a 12-digit alphanumeric code that identifies certain attributes of a product
SUPD	Single-Use Plastics Directive
UV	Ultra-violet

1.0 Introduction

1.1 Background & Objectives

The plastic packaging industry is experiencing a growing call for increased sustainability. The emphasis is on increasing recycled content and fostering a circular plastic economy, where plastic packaging is efficiently recycled back into packaging. The amount of pressure from the public and governments varies across Europe. However, there is a notable trend towards demanding greater environmental responsibility from the plastic industry. In response, brand owners have voluntarily taken up commitments to sustainable practices. At the same time, European Union (EU) legislation sets specific targets for recycled content and there is potential for these targets to increase in scope and ambition if the Packaging and Packaging Waste Directive (PPWR) is accepted in its current state.

Increasing plastic packaging circularity is not without its challenges. Plastic packaging placed on the market (POM) has diverse visual appearances and material properties. This diverse packaging needs to be sorted at end-of-life (EOL) to be recycled so that recycled content is made available and can be reused, and eventually recycled again, i.e. a "circular" recycling model. Sorting such a diverse range of different packaging for circular recycling demands substantial investment and often further advancements in both sorting and recycling technologies. Currently, this process is technically complex and costly.

Addressing this issue requires a multifaceted approach. Designing for recyclability will alleviate some of the challenges in sorting post-consumer plastic. However, it is essential to recognise the diverse functional requirements of different packaging applications that necessitate different material properties.

For example, flexible packaging can comprise multiple layers, oxygen barriers, foils, and various polymers, depending on whether it is used to extend the shelf life of a chocolate bar or retain moisture in wet wipes.

Rigid packaging also varies considerably depending on its intended use. Containers for household chemicals, such as bleach bottles, require packaging with high stress-crack resistance. Beverage containers might require additives to create oxygen barriers.

Another challenge is that the origin of packaging is often unknown to recyclers. This makes it challenging to identify potential contaminants from packaging contents. To ensure safety, recycled packaging for contact sensitive applications should predominantly be sourced from packaging that was previously used for contact sensitive applications.

To realise a truly circular plastics economy, it is imperative to enhance both the quality and quantity of available recycled plastic material. This starts with the collection of waste plastics, but it is clear that sorting, i.e., the sorting of post-consumer packaging using efficient high-volume, high-speed processes, plays a pivotal role in achieving this goal. This is because the output of sorting facilities directly impacts the quality and quantity of plastic material available for processing in circular recycling processes. Therefore, optimising sorting practices is of paramount importance.

In addition, traceability for packaging materials can be useful for safety in packaging-to-packaging recycling because the original application of the packaging is known. Traceability also enables better monitoring of plastic waste flow and helps facilitate extended producer responsibility (EPR) by enabling identification of the original packaging producer.

This report focuses on the role of sorting in achieving plastic packaging circularity. This report acknowledges that existing sorting technologies are sufficient for most packaging applications. It aims to:

- Identify the specific flexible and rigid packaging applications that require advanced sorting using packaging markers or other new technology to achieve circularity;
- Consider the different packaging advanced sorting technologies and evaluate their potential as possible solutions to the identified problem packaging types; and
- Analyse the costs and benefits of applying these technologies in practice.

It also explores the role of traceability in packaging circularity and assesses if the benefits traceability brings are worth the additional time, cost, international coordination and associated administrative and bureaucratic burden.

1.2 Scope

The scope of this study is researching how sorting and in particular advanced sorting technology can contribute to circularity and traceability in plastic packaging recycling. Within this broad scope, the study focuses on plastic packaging that becomes waste in waste streams that are "household like" (i.e., municipal waste in a European context).

This study focuses on sorting solutions required to provide a suitable feedstock for mechanical recycling processes producing material suitable for packaging manufacturer. This project focus is due to the underlying assumption that the potential for circular recycling using mechanical processes should be explored before defaulting to the assumption that chemical recycling processes would be used to process the relevant material.

The study does not directly examine problem sets for existing sorting that may exist for sorting for chemical recycling processes. It is reasonable to conclude that if this had been examined these problem sets would differ and there would be a lower number of them overall. Nonetheless, it should also not be assumed that there would be no problems with existing sorting technologies for chemical recycling.

The geographic scope of this report is the plastic packaging market of the EU, Norway, Switzerland and the United Kingdom. This regional emphasis shapes the study's policy context, the identification of specific problems, and the nuances of the cost and performance modelling.

1.3 Approach

1.3.1 Identifying the Packaging Problem Set

The first step in this study was to determine which polymer and packaging material formats are not adequately sorted to achieve circularity by existing sorting technologies.

For the purpose of this analysis, "adequate" or "sufficient" sorting is defined as the ability to segregate packaging into bales of material that possess similar characteristics in terms of polymer type, colour, mechanical properties, material properties, and by whether or not the material was previously used to package contact-sensitive items or not. More detail on the importance of each of these factors is described in the Appendix (Table A).

In defining the 'problem set', a longlist of the plastics packaging types with the largest tonnages placed on the market based on their polymer type and format was identified. These packaging types were assessed on how well current technology can sort them to enable a high degree of circularity via mechanical recycling. Packaging types that are not sufficiently sorted by current technology were identified as part of the 'problem set'.

The polymers and packaging formats that were evaluated are described in Table 1-1. The final problem set included:

- HDPE ("Jazz" – meaning all colours except natural) Containers;
- PP Containers; and
- PE, PP and multi-material flexibles (including mixed polyolefin structures).

From this problem set, HDPE ("Jazz") containers and PP containers were both taken forward for modelling. PE, PP, and multi-material flexibles were not taken forward for modelling due to the uncertainties in the applicability of advanced sorting technology to flexible materials, as well as uncertainty about the degree to which the required levels of separation of food contact materials for mechanical recycling can be achieved. Flexible packaging is therefore discussed in detail in Section 3.4 and Section 4.4, but is not considered in the sections where costs of implementation were modelled.

Table 1-1: A description of whether technology currently exists to enable circularity for various types of polymers and formats.

Polymer/Format	**Technology for Contact Sensitive Circularity**	**Taken Forward for Modelling?**
PET Bottles	Existing	No – existing tech
PET Thermoforms	Existing	No – existing tech
HDPE (Natural) Containers	Existing[1]	No – existing tech
HDPE ("Jazz") Containers	Advanced	Yes
PP Containers	Advanced	Yes
PE, PP and multi-material flexibles	Potential for Advanced	No – uncertainty too great*
**See Section 3.4 for details*		

[1] Albeit for the limited number of markets in the EU that use this packaging in significant quantities for food contact packaging.

1.3.2 Identifying Advanced Sorting Technologies

The next step in this study was to identify and evaluate new technologies that have been developed and could enable advanced classification and sorting of post-consumer plastic packaging. In particular, advanced sorting technologies that could better sort the identified problematic packaging types were evaluated. Thus, solving the circularity problem set.

A longlist of twenty-one new sensor- and marker-based sorting technologies was identified. All have been developed and tested and in some cases are used in a limited number of plants; none are currently widely used.

These technologies were evaluated based on elements such as technology readiness level, effectiveness, technical feasibility, limitations in application or scope, and benefits beyond the sorting stage (such as enhanced product traceability).

After evaluation, a shortlist of three technologies was selected for subsequent cost and performance modelling.

1.3.3 Cost and Performance Modelling

For the three shortlisted advanced sorting technologies, the following was modelled:

- Sorting performance/efficiency to sort two packaging types from the packaging problem set: HDPE (“Jazz”) containers and PP containers; and

- Implementation costs.

For the three technologies modelled, technology providers were requested to input key parameters to the modelling work. This included evaluating their technology’s performance in areas including 1) sorting, classification and selection, 2) the cost implications of adapting production and sorting lines for their technology, and 3) their proposed licensing framework for supply chain usage.

Final cost assessments were modelled using Eunomia’s projected Europe-wide material flow for 2030, which assumes that the 55% plastic packaging rate is met and is based on a number of sources including Plastics Recyclers Europe’s market reports for specific polymers. In line with this projection, cost modelling anticipated that the collection rates of plastics disposed of for recycling would increase to meet EU packaging targets. Since plastic waste that is collected is expected to be sorted at a Materials Recovery Facility (MRF), material tonnages used in the modelling were based on the output tonnages of the ‘problem set’ materials. Using throughput data provided by technology providers, the number of machines required to sort this tonnage across Europe was then calculated, providing the basis for modelling the cost of advanced sorting.

1.4 Important Terminology

Specific terminology is used throughout this report, particularly in relation to the sections on sorting. This terminology is explained below. A full glossary of terms is included at the start of this report.

Positive selection is not 100% efficient, since neither the classification nor sorting mechanisms are perfect in practice. For example, an item of plastic packaging might be obscured by another, resulting in it reaching the end of the conveyor belt without being identified by the sensor. Furthermore, even for items that are identified, positive selection depends on the selection unit accurately predicting the item's position. Packaging items may shift as they travel from the sensor unit to the selection unit, leading to potential misses. The following elements are important to consider when evaluating the efficiency of advanced sorting technologies in performing particular tasks:

- **Classification Rate** – the rate at which the sensor accurately detects and identifies the desired item;
- **Selection Rate** – the rate at which the identified item is accurately selected for separation;
- **Recovery Rate** – combines the classification and selection rate; and
- **Purity** – calculated by comparing the weight of items that are targeted for positive selection with the actual weight of material that has been captured by the positive selection stream. For example, if the positive selection stream contains 8 tonnes of clear bottles that were targeted, but also contains 0.2 tonnes of yellow bottles that were not targeted, then the purity would be around 97.6% (calculated from 8.0/8.2*100).

2.0 Current Sorting Landscape

2.1 Policy Context

The EU has and is progressing with requirements for member states that place an onus on increased plastic packaging circularity. These requirements are detailed in regulatory frameworks such as the Packaging and Packaging Waste Directive (PPWD). The PPWD sets specific recovery and recycling targets for packaging waste in the EU. These targets vary based on the type of material and are calculated based on the weight of the packaging waste generated. For plastic packaging specifically, the following targets have been set for 2025:

- 65% by weight of all packaging waste (not exclusive to plastics) is to be recycled; and
- For plastic packaging waste in particular, a recycling rate of 50% as a minimum must be achieved.

The PPWD will be replaced by the Packaging and Packaging Waste Regulation (PPWR), which is in the final stages of the EU legislative process and will apply from 18 months after the date it is published in the *Official Journal of the European Union* (likely to be later in 2024). The agreed text[2] of the PPWR sets the following recycled content targets (Table 2-1).

Table 2-1: Proposed Recycling Targets contained in the Packaging and Packaging Waste Regulation

January 2030 Target	January 2040 Target
30% for PET contact sensitive packaging except single use beverage bottles	50% for PET contact sensitive packaging except single use beverage bottles
10% for contact sensitive packaging made from plastic materials other than PET, except single use beverage bottles	25% for contact sensitive packaging made from plastic materials other than PET, except single use beverage bottles
30% for single use beverage bottles	65% for single use beverage bottles
35% for plastic packaging other than those above	65% for plastic packaging other than those above

[2] Based on the text agreed between the European Council and European Parliament and passed by the Parliament on 24th April 2024, accessible at https://www.europarl.europa.eu/doceo/document/TA-9-2024-0318_EN.html#title2

When these targets become law, their significance in enhancing plastic packaging circularity in the EU will be considerable. Although the exact method of applying these targets is still to be determined, it is anticipated that meeting the targets will likely involve using resin derived from recycling post-consumer plastics, applicable to specific packaging types.

Consequently, the recycling supply chain must provide adequate recycled content to meet the target for each plastic packaging type, precluding the possibility of averaging recycled content across different packaging types. Currently, the average recycled content for most plastic packaging formats in the EU falls significantly short of the 2025 targets, indicating a low level of circular plastics use. This situation poses significant challenges for the recycling supply chain. A rapid shift towards more circular recycling methods is needed. In addition to increased collection and recycling processes, effective sorting processes are an essential part of this.

The challenge of circularity is particularly pronounced in contact-sensitive applications. EU Regulation (EU) 2023/1442[3] sets out requirements for the use of mechanically recycled plastics in contact with food. It provides a reasonable framework for considering recycled content for a broader range of contact sensitive applications. It does not detail the sources of plastic recyclates for use in food contact applications (excluding PET), but it does establish a procedure for new processes and technologies to receive approvals as 'novel technologies'. Additionally, it ratifies the previous regulatory situation for PET: that at least 95% of the feedstock scrap must have been used in food contact applications. Insights from mechanical recyclers suggest that similar standards are expected for novel technology applications involving plastics other than PET. This implies that sorting processes must effectively separate waste packaging into streams for food contact (or other contact-sensitive applications) distinct from other plastic packaging.

2.2 Current Common Sorting Technologies

Plants that sort post-consumer plastic packaging utilise a range of technologies and processes to sort materials for recycling. These sorting technologies are generally divided into two categories:

- **Mechanical processes**: These perform the initial bulk sorting, separating out larger items and dividing the waste based on its physical properties (such as size, shape, density, and weight).
- **Sensor-based processes:** Theses further refine the sorting process, dealing with more complex tasks such as differentiating between plastic types based on colour and chemical composition.

A comparison of these technologies is provided in Table 2-2 below.

Table 2-2: A comparison of mechanical and sensor-based technologies that are currently commonly employed in post-consumer plastic waste sorting facilities

Type	Function	Examples of current technology
Mechanical Technology	Sorts according to physical properties, such as size, shape, density, weight.	• Screening (separation by size). • Ballistic separation (weight and flexibility). • Density Separation (using gravity techniques).

[3] Commission Regulation (EU) 2023/1442 'amending Annex I to Regulation (EU) No 10/2011 on plastic materials and articles intended to come into contact with food as regards changes to substance authorisations and addition of new substances' (July 2023) *Official Journal* L177/45, available at: link.

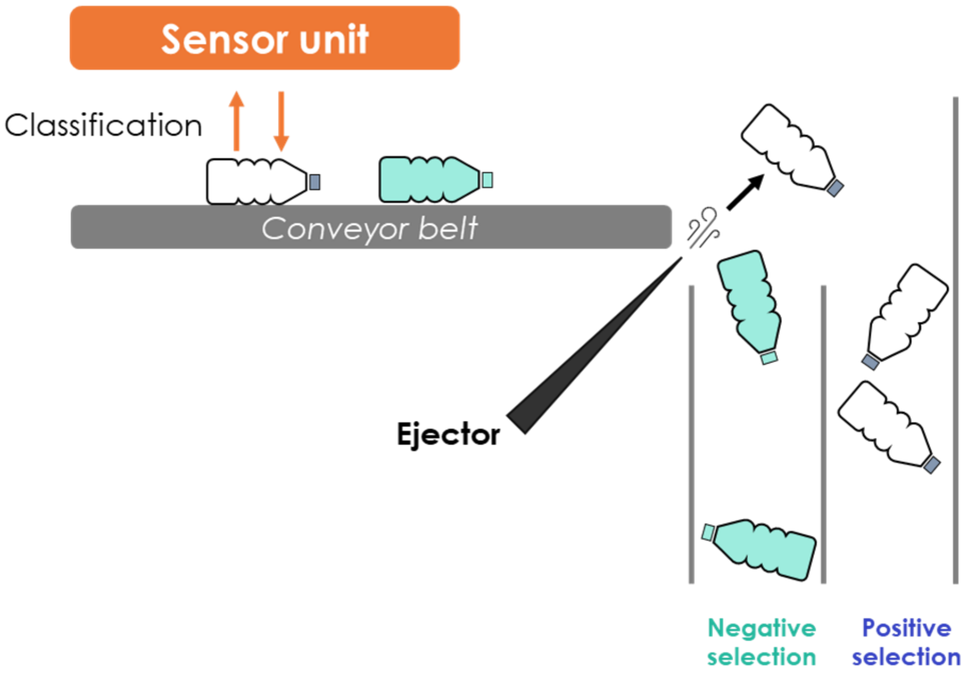
Sensor-based technology	Sorts in conjunction with ejectors according to materials by chemical composition and colour.	• Near-infrared (NIR) sensors. • X-ray fluorescence (XRF). • Visual spectrum sensors.

Typically, sensor-based sorting technologies work by making use of a machine that passes post-consumer plastic packaging on a conveyor belt below a sensor unit. The sensor unit uses a light source to irradiate the material, predominantly using a near-infrared light (NIR) source. Following irradiation, specific characteristics are detected that determine key features of the item, enabling the machine to be programmed to select or ignore items with specific characteristics. To carry out this selection process, packaging items are passed along the conveyor belt from the sensor unit to a separate unit where positive selection is typically carried out.

By far the most common selection method is ejector technology, whereby the sensor identifies an item to be selected, and the processing unit of the ejector calculates the time at which the item will pass beneath it and shoots a compressed air jet such that the package is knocked from the conveyor to the appropriate pathway in the plant. For items that are not selected, the air jet is not fired. Although ejectors are the most common selection technology, other selection technologies such as robotic arms can also be used.

The combination of sensor-based classification and selection with air knives is shown in Figure 2-1.

Figure 2-1: A schematic of bottles passing on a conveyor belt beneath a sensor unit, and subsequently being positively or negatively selected (i.e., not selected) using the ejector.



Current sensor-based technology enables the segregation of plastics by polymer type and colour, but its capacity to distinguish between certain packages on aspects such as the exact resins used remains problematic. For example, differentiating between low-density polyethylene (LDPE) and linear low-density polyethylene (LLDPE) remains challenging. This hinders the potential to achieve high-purity streams of these materials.

Recently, several new advanced sensor-based sorting technologies have emerged. This report evaluates how these advanced sensor-based methods may be used to enhance or replace existing sensor-based technologies in sorting facilities to help sort specific packaging types inadequately sorted by current sorting technologies. The focus is on sensor-based technologies; it is assumed that mechanical sorting processes would remain the same and continue to function as they currently do in sorting facilities.

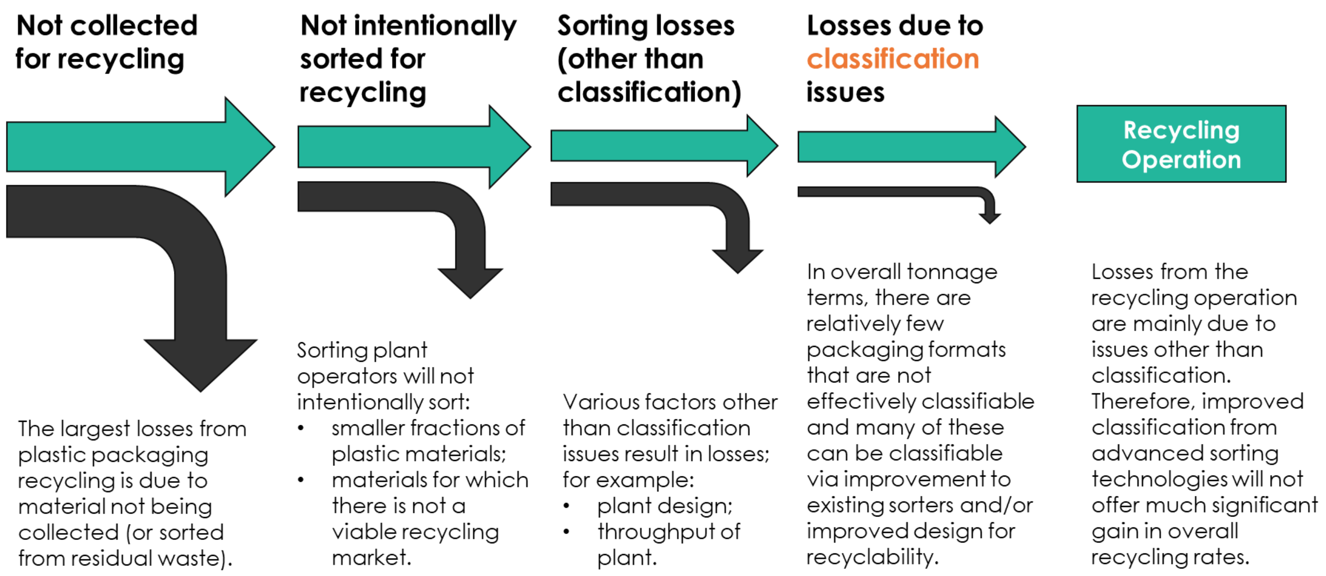
3.0 Circularity Problem Set Identification

3.1 Recycling Rates as a Problem Set

A key aspect of the circularity issue is determining whether the volume of post-consumer plastics entering recycling operations is adequate to meet the established recycling and recycled content targets. If current volumes are insufficient, advanced sorting technologies may provide solutions to increase the quantities of plastics being recycled.

To explore this issue, it is important to identify where losses in the recycling supply chain occur, and to assess whether these are linked to limitations of existing technologies that could potentially be addressed by advanced technologies. Advanced sorting technologies change the classification method of plastic items. The selection methods used by sensor-based sorters, such as air ejection or robotics, remain unchanged. Similarly, all other aspects of the sorting process, including mechanical screens and trommels, remain unchanged. Figure 3-1 illustrates where material losses currently occur in the recycling process.

Figure 3-1 Illustration of losses throughout plastics collection and sorting processes



The majority of losses are attributed to plastics that enter and remain in residual waste treatment instead of recycling streams, either due to non-collection or failure to separate from general waste.

Next in terms of scale are plastics that remain unsorted for recycling because there is no functional or economic market for them once sorted and because in the vast majority of plants' losses occur due to 'sizing' issues, where non-economically viable smaller fractions are screened out.

Other losses occur where plastics which are targeted by sorting are nonetheless missed during the sorting process. Although sorting plants are designed to specific performance standards, achieving higher efficiency often may incur prohibitive costs and the plant will be run for optimum financial performance which may not always be at the lowest loss rate possible.

Finally, a small fraction of plastics is lost in the recycling process due to current technologies failing to classify certain materials, such as some carbon black formats, extremely thin and transparent flexible plastics, or perhaps highly soiled or scratched materials. These items were not quantified as part of this study; however, these unclassifiable materials account for a low proportion of plastics. Therefore, while the integration of advanced sorting technologies could potentially improve the classification and recovery of these materials, such enhancements are unlikely to produce a significant increase in overall recycling rates. Furthermore, many of the existing classification issues can be addressed with existing sorting technology with arguably simpler and more cost-effective solutions such as improving the spectral libraries for existing sorting machines or alternative solutions such as the elimination of carbon black (when used as predominate colouration of packaging) or the inclusion of detectable additives.

In summary, for the provision of sufficient quantities of recycled materials, improved collection methods are required alongside the generation of new markets for recycled plastics. Generating new recycling markets might involve producing the right quality of plastics for sorting. The potential advantages of advanced sorting techniques in improving quality are discussed in the following sub-sections. Further potential for increased recycling rates could stem from improved consumer participation in separating plastics for recycling. The draft PPWR addresses this with requirements for on-pack labelling, an initiative that is independent of whether advanced sorting and tracking technologies are adopted.

KEY FINDING: The key to increasing the quantity and quality of plastic packaging recycled and thereby increasing the plastic packaging recycling rates is not to modify classification machines with advanced sorting techniques, but to increase the amount of plastic packaging collected and optimisation of existing sorting technology. The amount of material not recycled because it cannot be classified with existing technologies represents a small proportion of packaging placed on the market and this can be reduced further by improvements to existing sensor sorters and some design for recycling changes. In any case, because the currently unclassifiable plastic fractions represent a small proportion of plastics, by improving classification this will represent a relatively small increase in overall plastic packaging rates.

Improving classification using advanced sorting technologies will be important in increasing circularity in certain categories of plastic packaging such as contact sensitive or food sensitive applications.

3.2 Recycled Content Problem Set – Rigid Plastic Applications

As outlined in Section 2.1, EU policy will drive the need to incorporate increased amounts of recycled content in packaging, sourced from post-consumer packaging waste. To maintain the quality and functionality of packaging, mechanically recycled plastics, "recyclate" will need to meet key specifications to be fit for purpose.

While existing technology suffices for certain specifications, it falls short in other areas. For example, existing technology can accurately segregate major polymer types like PET from HDPE and can also effectively separate most colours. However, existing technology cannot reliably distinguish aspects such as whether the packaging was used in contact-sensitive applications.

For certain packaging formats, such as PET bottles, both the design and application of the packaging is highly uniform. Since existing technology can effectively separate PET bottles from other material streams, advanced sorting technologies are not necessary. However, for other packaging formats that are more variable, existing sorting technology is often inadequate at providing a homogeneous material stream, and advanced sorting would be beneficial.

Two key characteristics need examining to assess whether advanced sorting technologies would be required for a given packaging format:

1. **Contact Sensitive**. As mentioned in Section 2.1, recyclate for contact-sensitive applications must be sourced from post-consumer recyclate (PCR) that contains a high proportion (at least as high if not higher than previously established for PET i.e., ≥95%) of packaging previously used for such purposes. Therefore, for each packaging format, this study focuses on the predominant type of contact sensitive application that the packaging is used for. For example, for PP containers, the majority of contact sensitive applications are food-contact, whereas for HDPE "Jazz" containers, a high proportion of contact sensitive applications are skin-contact.

2. **Recycled Content Requirements**. Various types of plastic packaging require resin that meets stringent mechanical specifications, aligning with both the conversion technology and the end product's requirements. This issue has partially been addressed in a previous report[4] that describes the required characteristics of recyclate for three types of packaging formats. As the demand for recycled content rises, the recyclate must increasingly conform to precise mechanical specifications, prompting crucial questions regarding the granularity of sorting necessary to produce specific grades of recyclate. Notably, for many plastic packaging types, this issue is complex, as it involves not only sorting but also other mechanical recycling techniques and technologies. Additionally, due to the scarcity of established circular uses for these materials, these considerations are somewhat hypothetical.

3.2.1 Rigid Packaging Types

The most common types of rigid plastic packaging placed on the market, along with their typical applications, are detailed in Table 3-1 below. While most rigid plastic packaging is made from either PET, PE or PP, other smaller fractions of other polymers such as polystyrene also exist. While these other materials were not considered in this work, findings are likely to be applicable.

[4] Eunomia (2023), *Defining Recyclate Quality Target Specifications to Improve Plastic Packaging Circularity*. Available online at: https://www.eunomia.co.uk/reports-tools/defining-recyclate-quality-target-specifications-to-improve-plastic-packaging-circularity/

Table 3-1: A summary of plastic types and their typical original applications

Polymer	Format	Colour	Typical original application
PET	Beverage bottles	All colours	Food-contact
	Other rigids (e.g., trays)	All colours	Food-contact and skin-contact
HDPE	Containers (pots, tubs, etc.)	Natural	Food-contact
		Other mixed colours (also known as "Jazz")	Highly variable
PP	Containers (pots, tubs, etc.)	All colours	Highly variable

3.2.2 PET Bottles

More than 89% of PET bottles are used for beverages and are therefore food contact. PET bottle recycling is arguably the most advanced mechanical recycling in Europe in terms of packaging circularity. Research shows an average of only 17% recycled content in PET bottles across Europe[5], which is short of the PPWR targets. However, there are examples of essentially closed loop systems (Deposit Return Systems (DRS) with a fairly closed loop) which are achieving more than 50% recycled content when averaged across the whole system. In addition, experimental work has demonstrated that DRS collected material, without advanced sorting techniques, is likely to be able to achieve 75% recycled content[6], which exceeds the 65% PPWR 2040 recycled content target.

There is still a relatively small amount of packaging placed on the market that is problematic for circularity. The vast majority of these are because of losses of the packaging from the supply chain, such as full-sleeved bottles. This issue can be addressed by producers adhering to existing Design for Recycling (DfR) guidance.

Contact Sensitive

Food contact PET bottle grade recyclate is being manufactured in Europe without advanced sorting techniques. DRS collect beverage-only PET and therefore easily produce more than 95% previously food contact packaging. Separate collection systems (that are not DRS) also appear to be supplying sufficient material into food contact recycling without advanced sorting techniques. Therefore, it seems unlikely that advanced sorting is necessary to achieve food contact circularity in PET bottles, although there may still be benefits that can be achieved by applying advanced sorting technologies to these streams, and there are previous examples of advanced sorting technologies being tested on PET bottles.

[5] PET Market in Europe: State of Play 2022, Plastics Recyclers Europe, Eunomia, 2022, https://www.plasticsrecyclers.eu/publications/

[6] How Circular is PET, Eunomia, 2022, https://zerowasteeurope.eu/library/how-circular-is-pet/

Recycled Content Specifications

PET beverage bottles are all made with the same conversion technologies and are made from a relatively consistent resin. There appears to be a high degree of evidence that existing sorting technology is sufficient to achieve more than the 65% recycled content requirements.

KEY FINDING: Advanced sorting is not necessary to achieve PPWR recycled content targets for PET bottles.

3.2.3 Other PET

Other PET rigids, such as thermoforms, are used in relatively high proportions for food contact use. Historically, PET thermoforms had a relatively high recycled content, but this was derived from PET bottle recycling, and it would seem reasonable to assume that higher proportions of recycled content into thermoforms will need to be derived from the same forms of packaging to meet PPWR targets. It should also be noted that "tray-to-tray" mechanical recycling processes are still in their infancy in Europe. Within this group of materials, both mono material packages and multi material multi layered (MMML) versions of thermoforms exist. There are also examples of A-PET structures and C-PET structures. The majority of existing PET thermoform mechanical recyclers are focused on recycling clear, mono A-PET trays and use existing sorting techniques to separate coloured trays and MMML trays into separate streams for other recycling processes.

Contact Sensitive

Although the existing scale of recycling is relatively low, recyclers are reporting being able to meet food contact requirements with existing sorting technology.

Recycled Content Specifications

By sorting for colour and MMML, existing sorting technologies can produce reasonably circular grades of mono material. There are also emerging mechanical recycling processes reporting the ability to recycle MMML material to produce circular grades of rPET, again relying on existing sorting technologies.

A question still remains about the effective separation of C-PET from A-Pet, which may well be necessary for circular solutions. However, it appears that existing colour sorting and MMML sorting is resulting in C-PET quantities that are not problematic in A-PET recycling processes.

KEY FINDING: Advanced sorting does not appear necessary to achieve PPWR recycled content targets for 'Other PET'. However, the evidence is not as definitive as for PET bottles. Therefore, whilst it is does not appear necessary, there may well be some advantages in applying advanced sorting techniques.

3.2.4 Natural HDPE Containers

Natural HDPE containers refer to containers that are partially opaque and white/clear colouring. Their usage in European markets varies from country to country, but in virtually all markets high proportions are used in food contact applications. In markets where there are high proportions of natural HDPE in the overall rigid HDPE stream, this material is often separated into a high value natural HDPE stream using existing sorting techniques.

Contact Sensitive

For several years, there has been an effective natural HDPE and fresh milk bottles recycling market in the UK, despite no official European approval of HDPE for use in food contact material existing. Natural HDPE is easily sorted from other colours, and, in the UK market and probably in other countries, separation by colour characteristics is sufficient to produce food contact material.

Recycled Content Requirements

Natural HDPE resin is very uniform in nature and can be effectively separated from Jazz material.

KEY FINDING: Advanced sorting is not necessary to achieve PPWR recycled content targets for HDPE natural containers.

3.2.5 Jazz HDPE Containers

Jazz HDPE containers are HDPE containers that are not naturally coloured and tend to be manufactured in a wide range of colours. Jazz HDPE containers are used for a wide range of applications, including both contact-sensitive and non-contact-sensitive packaging. Therefore, the material properties and design of Jazz HDPE containers varies widely, and current sorting technologies cannot identify and separate the material further with sufficient accuracy. Advances in sorting technology may therefore be required to enable circularity. Advanced sorting technologies would enable the classification and separation of Jazz HDPE containers with different resin characteristics, and according to whether the material was used in food-contact, skin-contact, or non-contact sensitive applications. Further colour sorting is also then possible using existing technology where quantities are sufficient for economic viability.

Contact Sensitive

The diversity in Jazz HDPE containers makes it difficult for current sorting systems to distinguish those used in food-contact or skin-contact applications from those in non-contact-sensitive uses. While there is no official European approval of HDPE use in food contact materials, this distinction is likely to be crucial for ensuring that materials recycled for contact-sensitive purposes meet health and safety standards.

Recycled Content Requirements

Jazz HDPE resin is highly variable in nature. Advancements in sorting technology are needed to improve the segregation of Jazz HDPE containers based on resin characteristics.

KEY FINDING: Advanced sorting is necessary to achieve PPWR recycled content targets for Jazz HDPE containers.

3.2.6 PP Containers

PP containers are used for a wide range of applications, including both contact-sensitive and non-contact-sensitive packaging. In addition, there is potential for PP containers to contain a variety of other polymers and co-polymers. Both the material properties and the design of PP containers are therefore highly variable, and existing sorting technology cannot identify and separate PP material further with sufficient accuracy. Given the potential for PP containers to comprise a variety of polymers and co-polymers, it is likely that recycling predominantly results in the destabilisation of material properties.

Advanced sorting technology is likely to be required to enable the circularity of PP packaging, to ensure the classification and separation of PP packaging containing different polymers and co-polymers, with different resin characteristics, and with different original packaging applications.

Contact Sensitive

As PP is used for a wide range of applications, the composition of PP is approximately 60% food contact packaging with the remainder being PP used for other applications. Existing sorting technology is not capable of detecting the difference between these applications. For food contact approvals in Europe, it is likely that mechanical recyclers will need to ensure that their feedstock is at least 95% previously food contact material and therefore there is almost certainly a need for advanced sorting for circularity in PP food contact materials.

Recycled Content Requirements

The high variability in the composition of PP resin poses a significant barrier to achieving circularity in PP packaging. Advanced sorting technologies could enable more precise classification and separation of PP packaging based on different polymers, co-polymers, and resin characteristics. This precision is likely to be vital to maintain the integrity of recycled materials and meet the increasing demands for specific recycled content in packaging.

KEY FINDING: Advanced sorting is necessary to achieve PPWR recycled content targets for PP containers using mechanical recycling techniques.

3.3 Problem Set Findings in Rigid Plastic Applications

Two categories of rigid plastic packaging were found to require advanced sorting to achieve PPWR recycled content targets:

- HDPE containers – Jazz coloured (all colours other than clear and natural); and
- PP containers – all colours.

According to research estimates, contact-sensitive material in Jazz coloured HDPE containers and PP containers accounts for about 11% of the overall rigid plastic packaging stream placed on the market in Europe. This is based on a total tonnage of Jazz HDPE containers of 1,895kt of which 60% are contact-sensitive (1,137kt total), plus a total of 1,775kt of PP containers of which 75% (1,243kt) are contact-sensitive. This total of 2,379kt of contact-sensitive material accounts for 11% of the plastic packaging placed on the market. Once losses through (lack of) collection and initial sorting are accounted for, the total amount of contact-sensitive Jazz HDPE and PP currently available for advanced sorting is calculated at 1,353kt. This means that the amount of problem set material which reaches the stage of advanced sorting amounts to **6.6%** of overall rigid plastic packaging placed on the market.

As such, it is reasonable to assume that further sorting would only be required to be carried out on a small subset of all rigid packaging to ensure circularity. While advanced sorting could provide benefits to all rigid forms of plastic packaging, it is only likely to be necessary to enable circularity for PP containers and HDPE containers.

KEY FINDING: Existing technology can provide for circularity for most rigid applications and polymers and therefore advanced sorting technologies are not necessary. Advanced sorting technologies are necessary for contact sensitive separations in PP and HDPE. These contact sensitive materials account for a relatively small proportion of the rigid tonnage, being around 11% of the overall stream. Therefore**,** it is reasonable to conclude that advanced sorting is only necessary for circularity in a small subset of rigid applications. That is not to say that advanced sorting would add no benefit to the other polymers or applications, it probably would and there are examples of OR in some of these applications, but advanced sorting is not necessary in these groups.

3.4 Problem Set Findings in Flexible Plastic Applications

The evolution of circularity in flexible plastic applications is arguably considerably behind the evolution of circularity in rigid applications. There are challenges to be overcome in various stages of the flexible plastic packaging supply chain, including sorting, for there to be improved circularity.

Relatively large quantities of commercial and industrial (C&I) post-consumer material are successfully recycled back into flexible plastics and was not deemed a problem set for this study.

Most European municipal waste recycling collection systems are relatively limited in scope. They either do not allow for the collection of the full range of flexible plastics, or, if they do, sorting plants only sort a limited scope of flexible plastics for recycling. Except for a few relatively new examples, most sorting plants in Europe sort a grade of flexible plastics similar to the DSD-310 specification and this study uses this grade as an example. This grade has evolved as a means of producing a relatively pure grade of PE flexibles and has a minimum sheet size as approximately an "A4" equivalent. This results in most flexibles that are not mono-PE being excluded. However, significant quantities of flexibles that are municipal waste will not be included within the DSD-310 specification but will be included in the DSD-323 specification. This will include all flexibles above a relatively small size (this size is not defined by the specification) and will include all flexibles that are not DSD-310. It therefore includes:

- Mono PE;
- Mono PP; and
- MMML (including metal foil laminates, paper laminates, and PE/PP laminates).

Metallised packages that are otherwise a mono material are considered to be mono grades[7]. Where mechanical recycling for materials from DSD-323 materials exists, at present there are very few if any examples of circularity at scale. Instead, some examples exist of inclusion of PE elements into waste

[7] As per CEFLEX D4ACE Guidelines

containment and shopping bags. Any remaining components might be recycled into items such as wood substitute materials.

Furthermore, at the time of considering these issues, the likely composition of DSD-323 was unknown. Research determined that reasonable estimates of the proportions of mono and multi-material components could be approximated. Some approximate estimates of the proportion of contact sensitive material as a whole were available, but it was not clear how contact sensitive was distributed amongst the various mono and multi-material components.

Eunomia consulted with industry experts to develop a working composition for the DSD-323 stream by polymer and colour. The different estimates of composition developed through this process, as well as the specification for DSD-323, are shown in Table 3-2. It should be noted that Ceflex have recently conducted further composition work in some EU markets that was not available at the stage of the study where this could be considered.

Table 3-2: DSD-323 Composition

Packaging Type	Estimate 1	Estimate 2	DSD-323 Specification
PE film	37%	33%	Minimum 90% of target materials
Of which metallised	*0.6%*	*0.4%*	
PP film	14%	16%	
Of which metallised	*1.6%*	*2.3%*	
PE-PP film	2%	0%	
PE-PET film	0%	0%	
PE rigid	3%	1%	
PP rigid	9%	11%	
Other Multilayer film	4%	2%	
Other Plastics	13%	4%	
Foam	0%	2%	Maximum 0.5%
Beverage carton	0%	0%	Maximum 15%
Paper & Board	0%	4%	
Other	18%	28%	Maximum 3%
	100%	100%	

The reliability of this composition is difficult to ascertain. There was close consensus between different estimates on the levels of PP and PE films in the composition and relatively similar estimates of the amount of PP and PE rigids. However, the breakdown of non-target materials is both inconsistent between estimates and out of line with the published specification for DSD-323. Both estimates have target materials well under the specified 90% mark, and residues far more than the allowed 3%. Furthermore, there is very limited information on the levels of contact sensitive material within this composition. Finally, future policy changes may mean that this composition changes in the future, especially for materials which are not currently recyclable given the likely requirements for recyclable packaging of new legislation such as the PPWR.

At earlier stages of the project, a hypothesis was determined for flexibles as follows:

Existing technology cannot adequately detect MMML to the extent that producing relatively pure mono grades from DSD-323 is not possible.

At the time there were several technical reasons behind this hypothesis which can be broadly classified into the following problems:

- NIR classification can in some cases only detect the facing layer and will determine that the item is mono according to the facing layer; and
- The presence of metallised laminates and paper laminates can cause reflection and absorption issues which are detrimental to classification.

Further investigation of these issues was undertaken with project partners and through consultation with Ceflex. These investigations indicated that the initial hypothesis was likely incorrect. Optimisation of existing technology which would mainly involve a relatively straightforward update of spectral libraries and some design for recycling changes could result in DSD-323 type grades being adequately sorted into mono material grades and MMML grades, excepting a small number of cases that can be considered marginal issues which are unlikely to cause circularity issues.

Some examples of remaining issues are the ability to classify EVOH (ethylene-vinyl alcohol) layers, metallised packages where the metallisation is on the outside of the package or facing the sensor or metallisation behind purely white plastics. In general, with some probability, industry-acceptable design for recycling modifications to packaging and further optimisation of existing technologies, it would appear that mono materials (including most forms of metallisation) and MMML structures will be classifiable and therefore can be sorted from each other.

KEY FINDING: Existing technology, with further optimisation and some minor design for recycling improvements to the supply chain, will be able to sort material to produce mono PP and mono PE, and potentially more than one grade if required. However, recycled content targets as set by the PPWR are unlikely to be achieved for all categories of flexible packaging with only existing sorting technology and mechanical recycling.

Contact Sensitive

Significant proportions of flexible packaging will be used in contact sensitive packaging. However, this study found no reliable estimates of how much of this material is used in contact sensitive applications, and the proportions distributed across the key four output fractions (see Figure 3-2) remains uncertain. This makes it challenging to determine how to apply advanced sorting techniques and the associated costs and benefits.

Another challenge is the lack of clarity around whether mechanical recycling processes for flexible packaging are likely to be able to achieve contact sensitive approvals, even if high quantities of materials previously used in contact sensitive applications could be sorted.

Recycled Content Requirements

Circular use of recycled content in flexibles is arguably in its infancy. Very few markets within Europe have sorted material from household-like sources for recycling at scale other than large fraction[8] PE and some

[8] Typically, a large fraction would be larger than “A4” or approximately 300mm x 300mm.

PP and mixed PO fractions to non-packaging or rigid packaging markets. Even with large fraction PE, most material is recycled into non-packaging applications and the recyclate used in packaging applications tending to be used in low recycled content applications and/or blended with recycled content from other more homogenised sources such as from agricultural films or C&I sources. This is likely to be because PE films from PE sources have a relatively high degree of mechanical characteristic variability.

Existing sorting technology cannot accurately classify LDPE from LLDPE.

To achieve circularity in PE flexible films, advanced sorting technologies are currently necessary, particularly for sufficient quantities of recycled content to be supplied from mechanical recycling techniques.

Mechanical and circular recycling processes for mono PP flexibles are being developed in Europe and there is likely to be plant-scale capacities for this recycling route in the near future, though not likely for contact sensitive applications. There are interesting and important research and development projects proceeding in this area, but it is too early to conclude that more granular or indeed advanced sorting is necessary.

KEY FINDING: Advanced sorting technologies might be necessary for mechanical circular recycling for flexible plastic packaging. However, considerable uncertainty exists around:

- what grades advanced sorting would need to obtain;
- what quantities of materials would need sorting with advanced sorting techniques; and
- whether mechanical recycling techniques are sufficiently developed at present to be certain that this type of granular sorting is in fact necessary.

4.0 Advanced Sorting Options

4.1 Deciding Which Advanced Sorting Technologies to Model

This section identifies new technologies that have been developed and could enable advanced classification and sorting of post-consumer plastic packaging.

Overall, 21 different sorting technologies were assessed for inclusion in the modelling work. Each sorting technology was evaluated based on elements including technical feasibility, limitations in application or scope, or benefits beyond the sorting stage (such as enhanced product traceability).

Table 4-1 shows each of the technologies evaluated, the data storage they provide, sorting utility and examples of technology providers. Table A-7-1 in Appendix 1 shows the list of all identified technology providers, along with more detailed analysis on their utility and factors driving their selection (or otherwise) for further modelling.

Table 4-1: Advanced Technologies Grouped in Typologies

Technology Group	Data Contained	Use in Advanced Sorting	Examples
Barcode (1 dimensional)	Stock Keeping Unit (SKU)	Not usable	Reuse.id
Barcode (2 dimensional)	Potential to serialise down to the individual unit	Not usable	QR Code
Radio frequency identification (RFID)	Potential to serialise down to the individual unit	Not usable in packaging	PragmaticIC Thinfilm Electronics Germark Interactional
Chemical additives. (a traceable additive in the resin of the plastic)	Unknown – probably far less than resolution than SKU	Not usable	Security Matters
Digital Watermarks	Marker is thought to have capacity to serialise to the individual unit[9]	Usable	Digimarc
Embossed codes	Are a subset of other technologies- Can be to a watermark level of granularity	Usable	CurvCode/FiliGrade Axion consulting
Chemical Markers (a chemical printed on outer layer of packaging)	Ranges from a simple set of binary markers (e.g. contact sensitive yes/no) to use of markers sterilisable to the unit	Usable	Nextloopp Polymark Ergismark MaReK
Object Recognition	n/a	Usable	Grey Parrot

[9] The marker has capacity to contain this data, but the sorting and tracing machinery has not been tested at anywhere near this level of data granularity.

Technology Group	Data Contained	Use in Advanced Sorting	Examples
			AMP GAINnext™
Blockchain Technology	Require marker technology to work alongside	Supporting technology	Circulor/Project Trackcycle Circularise

A small number of solutions combined elements of more than one of these technologies. For example, blockchain solutions need to work in tandem with a marker technology. Some technologies had multiple providers offering solutions, whilst other solutions were linked to a single service provider. The technologies investigated were also in different stages of development: a limited number of providers have operational technology currently in use in sorting plants, others are undergoing trials to demonstrate the performance of their technologies, and some are still untested.

Some of the solutions evaluated had issues or limitations which rendered them unsuitable for the type of application being considered in this study. These were not taken forward for modelling. For example, radio frequency identification (RFID) technologies. These work by applying relatively expensive 'tags' to packaging or labels. Whilst this has the advantage of eliminating the need for line-of-sight for sorting, the expense of the tags means that the technology is impractical for single-use products. Furthermore, there were concerns that multiple tags could not be read concurrently, for example if not adequately spaced out on a sorting conveyor.

Three technologies were chosen for further analysis due to a combination of their suitability and technology readiness level:

1. Object recognition;
2. Chemical markers; and
3. Digital markers.

Each of these three technologies:

- either replace or work alongside NIR sensors, meaning that they can work alongside existing selection processes; and
- have available data on their performance in terms of classification rate and sorting efficiency – either from operational trials or, in some instances, from existing commercial applications.

These criteria mean that the chosen technologies occupy the same place in the existing sorting process and have performance and cost data available. This means that a direct comparison of the likely cost and performance of introducing such processes to existing sorting facilities can be made.

More detail on these three technologies is outlined in the following sub-sections.

Object Recognition

Several object recognition (OR) technologies employ artificial intelligence (AI) to identify and sort post-consumer waste. It has been proven to enable the classification and sorting of food-contact, skin-contact, and non-contact sensitive items.

Image recognition is achieved using algorithms like convolutional neural networks. These can be trained on large datasets of images to recognise different objects and materials.

Once recognised, objects on a conveyor belt or sorting line can be separated using an ejector, mechanical sorters or robotic arms. Sorting errors can be fed back to the OR system, allowing it to improve over time. Several companies offer OR sorting technologies, including Grey Parrot, AMP, and TOMRA. Some of these technologies operate commercially already.

Chemical Markers

Chemical markers are an emerging technology that embed a chemical barcode or fingerprint in the label of a plastic packaging item. This can later be detected by a sensor during sorting. The chemical marker is typically invisible to the human eye and emits and absorbs light during classification either in the NIR range, or in the ultra-violet (UV) range. As such, an NIR or UV sensor is required during sorting. Chemical markers can provide information regarding plastic type and plastic origin (i.e., whether the packaging was used in food-contact, skin-contact, or non-contact sensitive applications).

As they are applied to labels, chemical markers benefit from being identifiable irrespective of packaging design. However, depending on the orientation of the packaging as it moves through the conveyor belt of the sorting facility, chemical markers may not always be readable by the sensor. In addition, the ability to use chemical markers is somewhat limited to rigid packaging formats, since films and flexibles are often unlabelled.

Chemical marking is also limited in terms of enabling traceability, as it does not provide information on the retailer from which the item was purchased, or the brand responsible for its production. To enable traceability, the technology would have to be combined with a 2D barcode that could also be read by a sensor.

Providers of chemical marker technologies include Polytag and Nextloopp. The technology is currently in the laboratory testing phase of development.

Digital Markers

Digital watermarking embeds a digital code across the entire packaging unit that is invisible to the human eye. The code contains information on polymer type, format, packaging application, and can also provide detail on the producer of the packaging. This provides traceability throughout the recycling supply chain. Image recognition software can be used to detect and decode the digital watermark, reading the encoded data. High resolution cameras can detect the watermarks at a rate of 3 m/s, thereby increasing both the accuracy and speed of sorting plastic packaging.

Since digital watermarks cover the entirety of a plastic packaging item, the packaging information can be identified irrespective of whether a package passes through the sensor as a whole item or in pieces, and irrespective of the package design and its orientation as long as any of the printed side of the packaging is on display to the camera.

As well as offering producer traceability, consumers can engage with some marker systems by scanning the item with their smartphone. This allows consumers to trace details such as where the package has come from, how much recycled content it contains, and how to correctly dispose of the item.

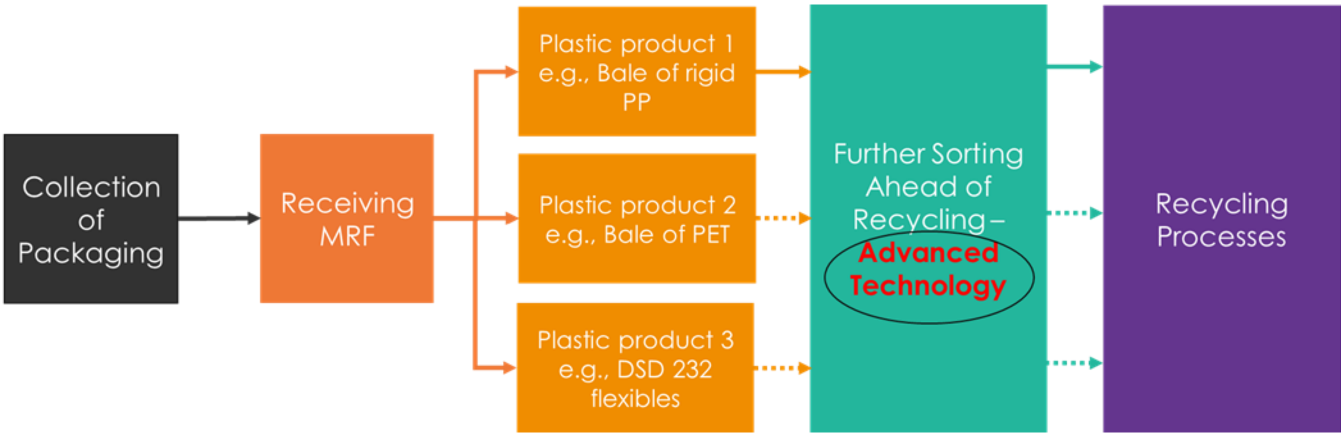
The main provider of digital marker systems covered by this study is Digimarc. This technology is at the stage of undergoing trial testing in real-word conditions.

4.2 Where to Deploy Advanced Sorting

The advanced sorting technologies described in Section 4.1 can theoretically be deployed anywhere along the recycling supply chain. However, to install the minimum possible number of technologies with maximum effectiveness, it would make economic sense for the technology to be deployed at the sorting stages immediately preceding recycling, and not at the receiving packaging MRFs. In this way, bales of sorted material can be further sorted to facilitate circular recycling ahead of entering the recycling plant.

The model presented in Figure 4-1 is used in costing assumptions. This model of deployment is likely to be the most financially efficient and substantially easier to implement than trying to apply a technology in the many receiving MRFs where all the existing plants would require substantial modification.

Figure 4-1: The place for advanced sorting in the recycling supply chain



4.3 Sorting Assessment and Comparison of Technologies

4.3.1 Performance/Efficiency for Rigid Plastic Packaging

The ability and efficiency of the three chosen advanced sorting technologies to sort selected packaging was modelled.

Classification rates used in the modelling were provided by technology providers for each of the chosen technologies: Digimarc for digital markers, Nextek for chemical markers, and TOMRA for object recognition. These classification rates were taken from trial data undertaken in industrial conditions for the marker technologies, and from a combination of trial data and observed data in operational conditions for object recognition.

Selection rates and purity values were taken from data on the existing performance of ejector and robotic selection systems. As the technologies chosen for modelling are all used in conjunction with these existing machines, the selection rate and purity for each technology is the same post-classification.

The following Sections 4.3.1 and 4.3.2 refer only to the application of sorting technologies to the problem sets in rigid plastic packaging. Discussion of the applicability to flexible plastic packaging can be found in Section 4.4.

4.3.1.1 Object Recognition (OR)

The problem sets defined in section 3.0 show the accuracy of TOMRA's OR technology for correctly identifying items and selecting the desired packaging, and the purity of the captured material, as estimated by TOMRA. A recovery rate has also been estimated, which combines the classification and selection rate.

Table 4-2: Classification rate, selection rate, and purity of packaging formats sorted using OR technology

Packaging Format	Classification Rate	Selection Rate	Purity	Recovery Rate
Jazz HDPE Containers	92 - 95%	95 – 96%	96 – 99%	88 – 91%
PP Containers	92 - 95%	95 – 96%	95 – 97%	87 – 90%

The high accuracy in identifying and selecting material of high purity indicates that the use of OR could help in solving the current barriers to achieving circular recycling for problematic packaging formats. In terms of traceability, OR may provide classification of brands supplying Jazz HDPE containers and PP containers at Stock-Keeping Unit (SKU) level through the recognition of brand icons and label text. However, this is likely to be limited for films and flexibles where branding is less prevalent on packaging.

The rates of recognition shown here are achieved after a period of 'training' for the OR technology. Initial recognition rates prior to 'training' would be significantly lower. It is possible that future OR sorting recognition rates could continue to improve due to this training capability.

4.3.1.2 Chemical Markers

The accuracy of chemical markers in identifying items correctly, selecting packaging correctly, and the purity of the captured material have been estimated by TOMRA and are outlined in Table 4-3. For films and flexibles, the use of chemical markers could not accurately be assessed due to the lack of labelling on these packaging formats.

Table 4-3: Classification rate, selection rate, and purity of packaging formats sorted using chemical markers

Packaging Format	Classification Rate	Selection Rate	Purity	Recovery Rate
Jazz HDPE Containers	95.9% - 99.6%	95 – 96%	96 – 99%	92 – 96%

PP Containers	95.9% - 99.6%	95 – 96%	95 – 97%	91 – 95%
PE Film	N/A	N/A	N/A	N/A
PP Film	N/A	N/A	N/A	N/A

Chemical markers have a higher classification rate than OR. This leads to an overall higher recovery rate. However, at this stage there are significant questions about the application of chemical markers to films, which means the technology cannot be used to help sort this waste stream.

4.3.1.3 Digital Watermarking

The accuracy of digital watermarks in identifying items correctly, selecting packaging correctly, and the purity of the captured material have been estimated by TOMRA and are outlined in Table 4-4.

Table 4-4: Classification rate, selection rate, and purity of packaging formats sorted using Digital Markers

Packaging Format	Classification Rate	Selection Rate	Purity	Recovery Rate
Jazz HDPE Containers	95.9 – 99.6%	95 – 96%	96 – 99%	92 – 96%
PP Containers	95.9 – 99.6%	95 – 96%	95 – 97%	91 – 95%
PE Film	95.0 – 97.6%	90 – 92%	88 – 90%	86 – 89%
PP Film	95.0 – 97.6%	90 – 92%	88 – 90%	86 – 89%

Digital markers have the same recognition rate as chemical markers for rigid packaging. This again leads to increased performance compared to OR. For digital markers, this improvement is also seen in the classification of films for sorting. This means that the overall recovery rates of packaging for recycling for digital marker is the highest of the three modelled technologies.

4.3.1.4 Comparison of performance between the technologies

As the three chosen technologies all operate in tandem with the same selection machines, the only differential in performance is generated by the differences in classification rate between the technologies. Classification rates for rigid plastics are broadly similar, which means the overall yield of recovered material for each technology is similar. This is shown in the diagrams in Figure 4-2 and Figure 4-3 which show the tonnage of contact sensitive feedstock recovered for the key material streams using both markers and OR technology. As both marker technologies had the same classification performance for rigid plastics, these are combined into a single waste flow in the diagrams.

Figure 4-2: Modelled Material Flow, HDPE Jazz Rigids

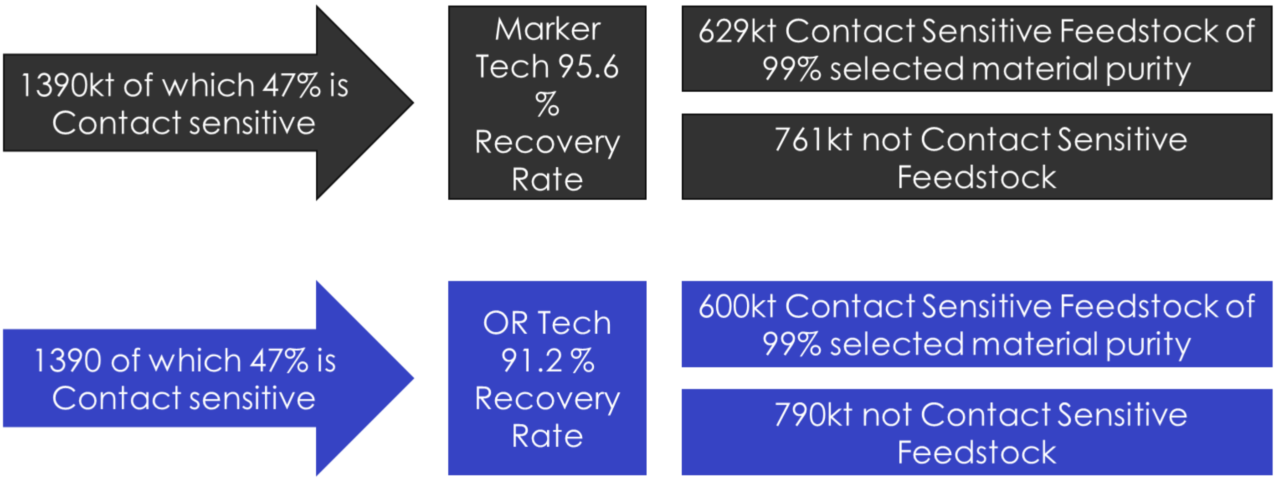
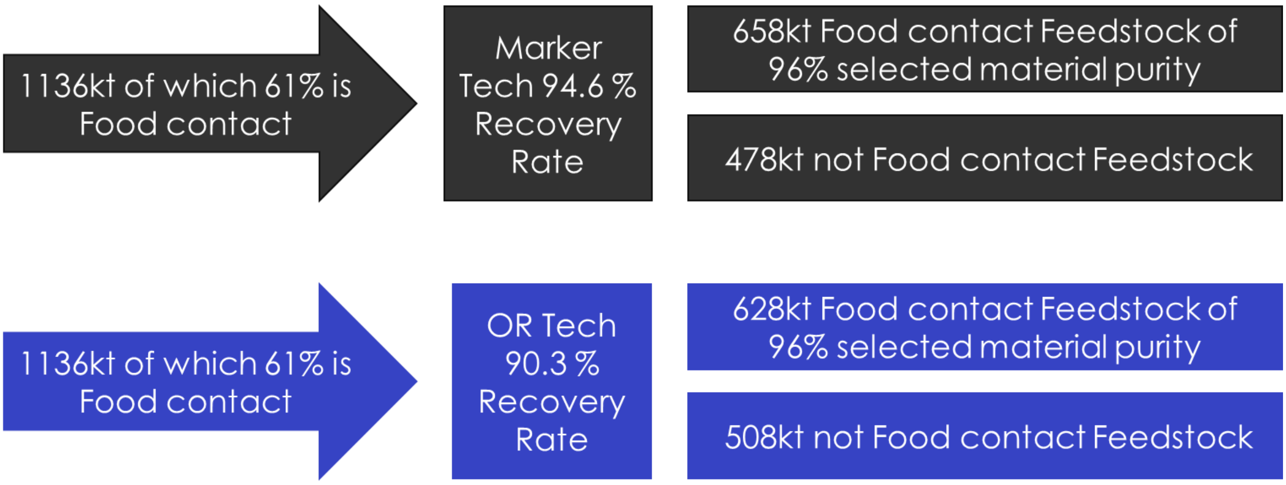


Figure 4-3: Modelled Material Flow, PP Rigids



In addition to the recovery rates of the modelled advanced sorting technologies being similar to each other, the rates achieved are comparable to those seen in NIR sorting and other common current technologies. This is because the classification rates achieved by the modelled technologies are similar to those achieved by common current sorting methods, and once again the selection methodology is unchanged. Because purity rates are a function of the accuracy of selection, these are also similar between all the modelled technologies and common current technologies. Classification rates are similar between all three modelled technologies, and to classification rates achieved by common current technologies.

KEY FINDING: All three of the modelled advanced sorting technologies perform well. Selection rates are the same as for common current technology because they use the same methods. Recovery rates are also in line with those of common current technology, and similar between the modelled advanced sorting technologies. The combination of similar classification rates and the same selection rates leads to purity rates once again being similar between all modelled advanced sorting technologies and common current technologies.

4.3.2 Costs of Implementation for Rigid Plastics

4.3.2.1 Methodology

Circularity of films and flexibles may be achieved through a combination of NIR and induction, which enables separation of metallised, contact sensitive films from non-metallised, non-contact sensitive film. Also, there are uncertainties with the application of the three chosen technologies to film. Therefore, the costs of installing and operating each of the three advanced sorting technologies were assessed for rigid HDPE and PP only.

The costs were assessed based on a projected Europe-wide material flow for 2030. In the modelled scenario, collection rates of plastics for recycling are increased to meet the 55% plastic packaging rate for 2030 as set out in the PPWD. These materials are then sorted in receiving MRFs. The identified PP and HDPE outputs of the MRF sorting were the input tonnages for the cost modelling in this analysis.

The number of machines required to sort this tonnage across Europe was calculated using throughput data provided by technology providers and the tonnage of material requiring sorting in the modelled waste flow. This provides the basis for modelling the cost of this sorting.

Regardless of the type of advanced technology used, the same number of machines would be required, equating to an additional 28 machines across Europe for advanced PP sorting, and 34 machines for advanced HDPE sorting.

Costs were modelled in four broad categories:

- Capital and installation costs were included in the annualised cost of installation of the machinery, setup and integration of the machinery, and an assumed cost for an additional sorting line and bunkering etc. in the sorting facility;
- Operational costs include operational expenses (OpEx) such as electricity costs, maintenance and additional staff costs, as well as the cost of subscription databases (to help identify products);
- Licensing costs cover proprietary costs associated with each technology; and
- Printing costs cover the costs associated with artwork design, cameras, and printing.

The latter two costs are associated only with the marker technologies (AI subscription costs are included in the operational costs) and are approached differently by the service providers who supplied data for this project. As such, comparison is difficult because printing costs for one technology (ink supply) is considered a licensed cost for the other.

The costs modelled are those of a mature 'steady state' system, and as such do not include initial start-up costs or the costs of initially introducing the technologies to market (except where these are annualised into licensing costs).

The costs given are the additional costs implied by each technology. This means that the cost of waste collection, MRF sorting, and any additional plastics recovery facility (PRF) sorting which occurs prior to the new technology is not accounted for in the results shown below. However, the costs do include the additional conveyors, selection equipment and bunkering required to implement an additional sort and a new stream of sorted material.

The modelling does not assume any geographical restrictions, which may in practice lead to a less optimal waste flow and so increased cost. However, this should not impact the relative differences between the technologies. It is assumed that only one stage of sorting is required for each of the new technologies to produce a stream which meets requirements for the relevant food or contact sensitivity requirements. If a second stage of sorting is required, costs would increase.

Figure 4-4: Cost range estimations for sorting HDPE and PP rigids using UV markers, digital watermarks, and OR technology

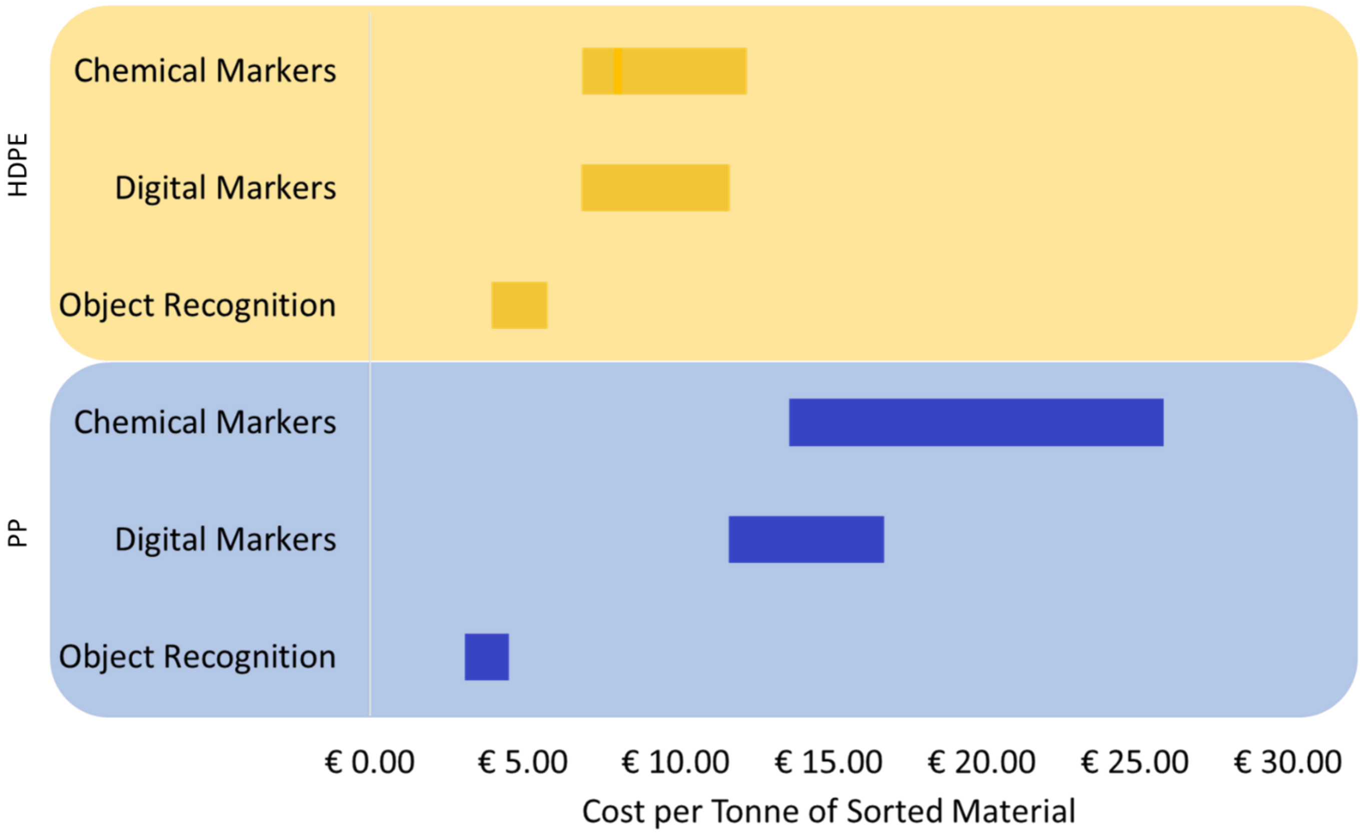


Figure 4-4 shows the headline results of that cost modelling: OR is the lowest cost technology in terms of cost per sorted tonne for both HDPE and PP rigids. This metric is chosen to encapsulate both the cost and the efficiency of the sorting technologies.

The likely cost range of the two different marker technologies overlaps. A large part of the difference between them is due to different licensing systems for each technology. The difference between HDPE and PP in terms of the gap between OR and the marker systems can be explained by the weight of products in each polymer. HDPE products are on average heavier, which means a tonne of sorted material has fewer products or labels associated with it, and so less of these costs which are associated only with the marker technologies. PP products are on average lighter, so there are more labels per tonne of material, which means that the marker costs increase. Conversely, as the modelled PP stream has a higher incidence of target materials than the modelled HDPE stream, OR costs reduce for PP as the same capital and operational costs are divided across a higher yield of target material.

4.3.2.2 Comparison of Technology Cost

Figure 4-5 and Figure 4-6 show the cost breakdown by category for all technologies for HDPE and PP rigids, respectively. The charts show the estimated costs in a 'low' and 'high' scenario, as many assumptions provided were ranges with exact cost information impossible to verify. Even considering these ranges, for both PP and PE, OR was revealed as the most economical technology, and chemical watermarks as the most expensive.

Figure 4-5: Cost Breakdown for All Technologies, HDPE Rigids

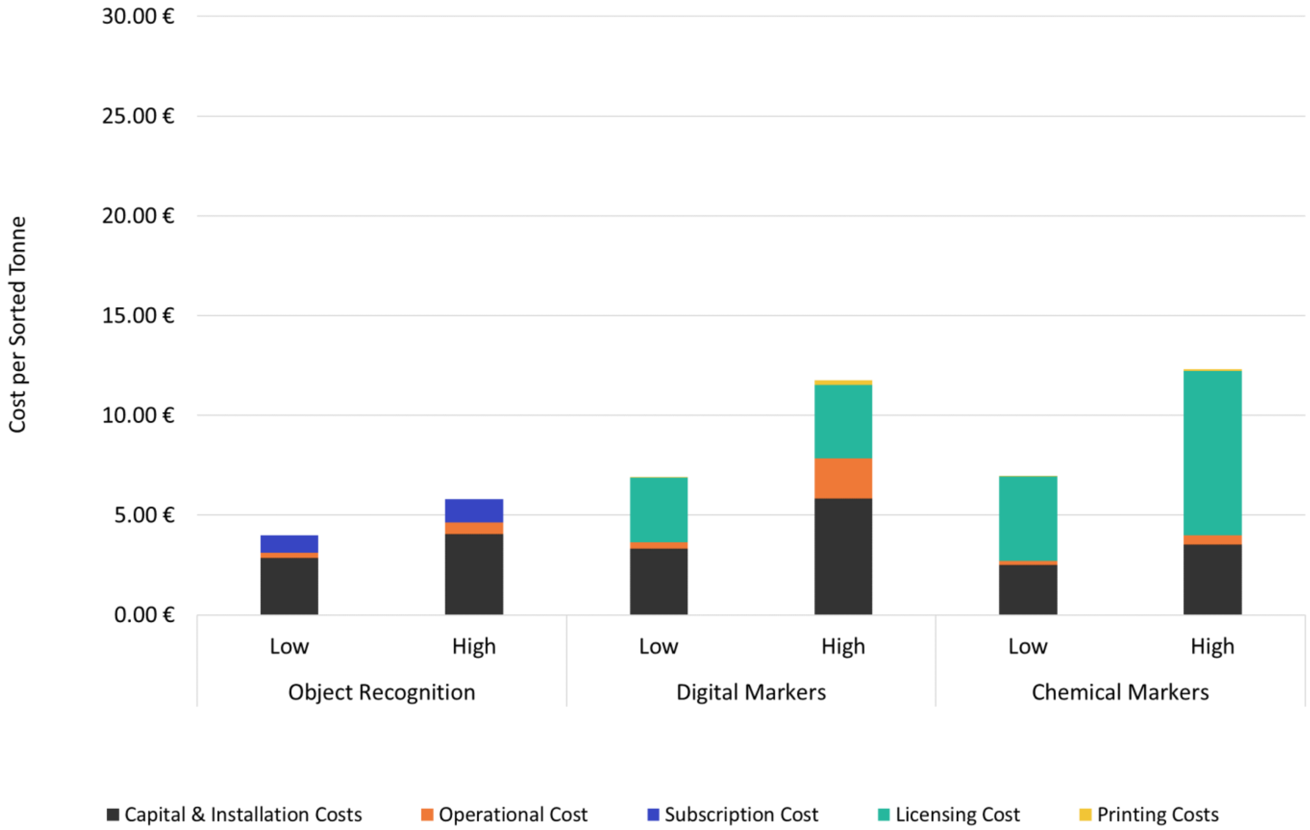
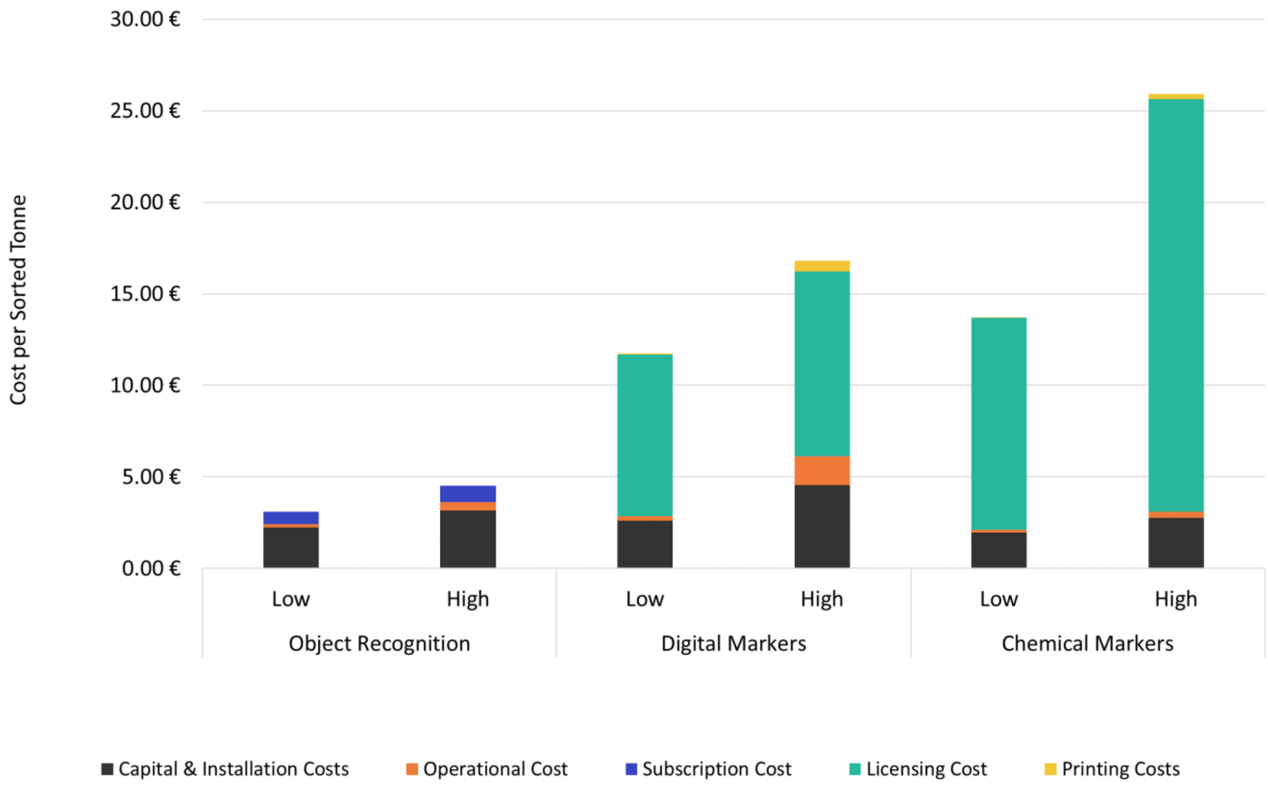


Figure 4-6: Cost Breakdown for All Technologies, PP Rigids



Capital and Installation Costs

Capital and installation costs in these charts refer to the costs for purchasing and installing the machinery to select materials for sorting. There are some variations in the initial capital costs of the technologies, in part due to a relatively high range in estimates of the cost of installation of technology to select via digital watermarks. However, these initial capital costs are depreciated across an 8.5 year period, which means that the overall difference in the contribution to the annual cost of the technology solutions is minimal – in the range of €20k per machine, which at a throughput of 40-50kt per machine per annum results in only a small change in capital and installation cost between technologies when measured using the cost per sorted tonne metric.

Operational Costs

Operational costs in the charts consist of maintenance of the new machinery as well as the additional energy use required. As all the modelled technologies use the same selection method (i.e., ejector selection), the maintenance and energy use of the selection machinery does not change between technologies. This means that the difference between technologies is only that between the classification methods, and accordingly the difference is relatively minor. The one exception to this finding is the potentially much higher energy use in digital watermarking systems required to power the computer used to identify individual watermarks. This is an area of uncertainty, which underpins the difference between the 'low' and 'high' scenario operational costs for digital markers. This additional computing cost is not expected to be required for OR or chemical markers based on Eunomia's research.

Licensing/Subscription Costs

The licensing costs (teal bars in the figures above) considered are those paid to print the relevant marker technology. The OR system does not have these costs as there is no change in labelling for this solution. However, it is likely that sorting operators will be required to take out a subscription to the provider of the OR services to have full access to the sorting database (blue bars in the figures above). The differences between these costs are the key driver of cost differences between the marker technologies and OR.

Costs for licensing the marker technologies modelled were provided by the system operators Digimarc and Nextloopp. An estimate of subscription costs was supplied by TOMRA. All the estimates were provided on different bases. TOMRA provided an annual cost of subscription per machine, although this is subject to change as the technology and market develops. Digimarc supplied a proposed set of tiered licensing and printing costs per SKU and per unit sold, which are all considered to be licencing costs in this analysis as there was a lack of available detail over what is considered in the printing cost. Nextloopp provided a range of potential costs per label printed, a cost which included the UV-active ink required for the system to operate.

Considering the different methodologies used to arrive at the licensing costs for marker technologies, the overall costs arrived at are relatively similar to one another. At the low end of estimates, the licensing costs differ by only €0.02 per 1,000 labels (although the higher end estimates for chemical markers are €0.08 per 1,000 labels higher than the high end of digital marker estimates). It is also clear that licensing for both technologies is considerably more expensive than the estimated cost for subscriptions under an OR model. This means that licensing costs are the key differential between the modelled solutions.

Printing Costs

Printing costs are not expected to significantly change for the modelled marker technologies for most producers, as both can be incorporated into existing print lines. However, it is important to note that for some products and labels there will be a need for redesign to allow for digital watermarks to work effectively. From a producer/brand owner perspective, some of these amends will mean compromising on existing branding and with some portfolios may be a considerable task across many different lines. The potential slightly higher cost for ink needed for the chemical markers system is covered in licensing costs as noted above. The one additional printing cost which is included is that of a camera to verify the printing process, as by design the watermarks cannot be checked by the naked eye. This adds a small cost to the process for the marker technologies, shown by the yellow bar in the chart above.

4.3.2.3 Implementation Costs Summary

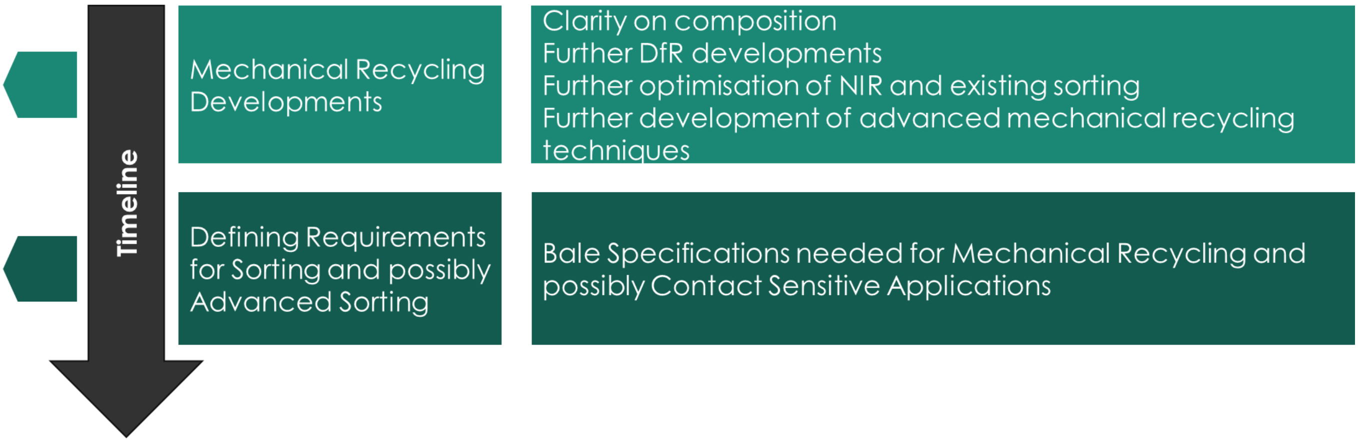
Granular comparison of the technologies is difficult due to the different commercial approaches used. Nevertheless, the key takeaway of the cost modelling exercise is that the installation and operation of sorting machinery is a relatively small fraction of the total cost of producing the desired material stream from the problem sets. By far the larger portion of costs are associated with the application of the markers and licensing of the producer or manufacturer to participate in a given scheme. This is a key area of advantage for OR technology, as there is no need for a marker system and so no need for printing costs, additional monitoring at the production stage, or for licensing of systems to identify the markers. This means that the OR technology has much lower costs on top of the capital and operational costs, despite having marginally lower classification rates than the other technologies. Therefore, OR is the most economical option in terms of cost per yield of target material.

KEY FINDING: The performance, installation and operational costs of each system modelled are broadly similar to each other. However, there is a key advantage for OR in the lack of a marking requirement and so no requirement for additional printing costs nor licensing of a marker system. This means that overall, per tonne of material sorted, OR is the lowest cost solution for the identified problem sets.

4.4 Applicability to Flexible Packaging

Section 3.4 of this report considers the problem set in flexibles and concludes that advanced sorting technologies might be necessary for circularity. However, there are considerable uncertainties that would need further clarification before concluding that advanced sorting technologies are necessary in flexibles and worth the investment. Key questions need to be answered over the next few years before a clear assessment of whether advanced sorting is necessary. There is a clear need for further work clarifying the necessary input specifications to mechanical recycling processes that can achieve circular recyclate grades. There is also a need to further explore the role of mechanical recycling in producing contact sensitive recyclate grades. An aspect of exploring that case is the need to clarify where in the key flexible sorted grades there is sufficient contact sensitive materials for there to be a business case for further sorting to separate this contact sensitive material. Finally, existing sorting technologies should be optimised for sorting flexibles in parallel with the development of any advanced technologies.

Figure 4-7: Timeline of developments to clarify the need for advanced sorting



4.4.1 Likely Performance of Modelled Technologies

There is a need for further exploration and testing of advanced sorting technologies for sorting flexible plastics. In general, it is reasonable to assume that it will be challenging to reach the same recovery rates and purity rates in flexibles that are achieved in rigid formats. It is important to note that flexible packaging comes in a wide range of formats and colours. Some packaging has outer surfaces that are completely printed. Other packaging is completely transparent with just a small, printed label. This wide range of applications, coupled with difficulties in embossing and the potential for packaging to be opened, split apart and potentially showing inside surfaces instead of outside print, all present additional challenges for advanced sorting technologies.

At present, chemical markers are not thought to be suitable for sorting flexibles if there is any use of the recyclate for contact sensitive grades. Furthermore, we are not aware of any testing the efficiency of chemical markers across a wide range of flexible packaging formats.

As a digital marker technology, Holygrail has been tested across a limited range of flexible packaging formats. Further "at scale" testing is believed to be limited to a select range of flexible packaging formats. There are potentially some packages with low print/ low ability to contrast a watermark on which may be challenging to mark and identify.

OR is essentially untested in flexible packaging formats. Using the premise that if a human could identify the packaging type then OR could, there will be several flexible packaging types that OR would struggle to identify because of insufficient print.

4.4.2 Cost Estimation for Flexible Packaging

The costs of printing and licensing of markers for flexible applications will probably be in line with rigid applications as it is driven by the number of units placed on the market and numbers of SKUs. However, the sorting machinery's Capex and Opex will be a higher proportion of the overall costs. This is because the key metric of tonnes per hour for a machine is substantially lower for flexible plastics primarily due to the lower density of flexible packaging. As the proportion of costs that are associated with sorting equipment rise in proportion to the other costs, it reasonable to assume that the gap between OR and marking technologies would close from those that were modelled for rigid PP and HDPE. How far the gap might close and whether markers could represent a lower cost alternative in flexibles will depend on the performance of the technologies and, as described in section 4.4.1, this is far from certain at this point of time.

KEY FINDING: The role of advanced sorting in providing circular solutions for flexible packaging remains unclear. Further research is needed to determine reasonable bale grades for circular mechanical recycling processes; in addition, improved characterisation of collected post-consumer flexible packaging is needed.

Existing sorting technology and some design for recycling improvements are likely to be able to deliver sufficient qualities to improve circularity. However, to what extent advanced sorting is needed to produce further granular sorting to contact sensitive grades and for specific resin specifications needs further investigation. At this point in time, the performance and costs of advanced sorting technologies in providing circular solutions for flexible plastic packaging are far from clear.

However, flexible plastics are a significant tonnage of plastics packaging in Europe and circular solutions will be needed. Further research is required to determine the role of advanced sorting in achieving circularity in flexible plastic packaging.

4.5 Additional Considerations

4.5.1 Consideration of Material Value

Advanced sorting technologies that are sorting into contact or food-sensitive streams will lead to an increased market value of some of the sorted materials with other streams potentially reduced in value. Therefore, the sellers of sorted materials and the recyclers of that material are likely to experience an increased overall material sales value by applying advanced sorting technologies. However, this does not represent a change that should be applied to the costs that producers and associated consumers would experience. Whilst an increase in certain products in the recycling supply chain could potentially reduce EPR fees, those same producers (and consumers) will pay for the increase in value by purchasing the recycled content. As such, the overall costs of implementing advanced sorting technologies should not include any reduction to those costs by applying increases to the value of materials that are only experienced in part of the supply chain.

4.5.2 Potential Risks

Several risks are associated with using advanced sorting technologies like OR, digital watermarking, and chemical watermarking.

The extensive data collection required to train AI and to enable digital watermarking brings concerns around data privacy, surveillance, and appropriate data use policies. Strict governance is needed to ensure data is not misused or exploited. Companies should be transparent about what data is collected and how it is stored, used, and shared.

Additionally, as advanced sensors collect vast amounts of granular data from recycling streams, not all of it may be useful. Thoughtful data management is required to filter and consolidate what is stored to minimize useless data buildup since storage and maintenance of excessive useless data is resource intensive.

Increased use of labels, inks, and coatings to enable classification technologies could contribute to environmental contamination. Water-soluble classification technologies (i.e., inks) risk polluting wastewater, and the carbon footprint of manufacturing, powering, and maintaining data centres should also be considered.

Finally, no sensing technology is perfect and there are always uncertainties and inaccuracies. When automation relies heavily on AI and sensor data, any misidentifications or unforeseen anomalies in the waste stream could lead to downstream issues. Continual auditing and system redundancy is important.

5.0 Traceability

In this context, traceability means the ability to account with reasonable precision where and in what quantities packages of specific formats and sub-formats end up in recycling processes.

5.1 What is the current problem in Traceability?

The current state of play of traceability in Europe is arguably relatively poor. In many member states, other than data from DRS, measurement and reporting is pretty much at a "plastics packaging" level with data being accounted for at a macro level by weighing bales and lorry loads, with sometimes an estimate of the polymer type and maybe the predominant packaging format. In many cases, there is a significant lack of clarity on the following:

- Quantities of specific formats entering recycling operations;
- Which end destinations are receiving specific quantities of packages/ packaging formats;
- Overall recycling rates of certain formats;
- Producers' own recycling rates; and
- Quantities of packages being recycled that are not covered by EPR fee payments.

This lack of clarity may be hampering regulatory procedures and effective regulation.

EPR schemes are required to cover the "necessary costs" of the recycling supply chain (collection, sorting and recycling processes). At present, EPR fees are estimated and modulated for specific plastic polymers and formats on a rudimentary basis. These fees are then applied to producers according to the amounts of material they each place on the market and not the amounts of their own packaging that is entering the recycling supply chain. There is an argument that if there was better traceability in the plastic packaging supply chain then it may be possible to simplify EPR fee systems and calculate or modulate fees on a fairer basis for each producer.

5.2 Implications of the PPWR for traceability

The latest draft of the PPWR (as approved by parliament in April 2024)[10] requires increased data granularity in the measurement and reporting of recyclability and recycling rates for plastic packaging placed on the market by economic operators and Member States respectively.

Member States will need to ensure that quantities of plastics placed on the market, collected, and subsequently recycled, recovered or disposed of are reported according to a fairly basic categorisation detailed in Annex XII, table 3. Although the details of this reporting mechanism will be determined at a later stage, it is unlikely that the categorisation would become more granular and at the current level of granularity there would be no need for using Advanced Technologies to measure the quantities of these categories for most recycling processes. Some recycling processes may include feedstock that covers more than one reporting category (e.g., mixed rigid and flexible polyolefins into a chemical recycling

[10] Based on the text agreed between the European Council and European Parliament and passed by the Parliament on 24th April 2024, accessible at https://www.europarl.europa.eu/doceo/document/TA-9-2024-0318_EN.html

process). In these cases, there is likely to be a need for further accounting of the amounts of each required reporting category.

Article 6 places requirements on economic operators placing plastic packaging on the market to establish that the packaging unit meets design for recyclability criteria and eventually, demonstrating that it is recycled "at scale". Further to that requirement, Annex II, Table 1 details an "indicative list" of the likely level of categorisation of packaging materials, types and formats for which it be necessary to establish recyclability. The feedstock in many mechanical recycling plants is already likely to be delineated sufficiently to allow for reasonable reporting of quantities of specific packaging formats recycled. However, there may be some examples where plants and processes are less delineated, such as PET thermoforms being recycled with PET bottles or PE and PP material being recycled in a mixed polyolefin process, and therefore there would be a need for more detailed accounting and reporting processes in these instances.

The details of the calculation methodologies and reporting requirements to demonstrate compliance with these obligations still remain to be seen but it seems reasonable to interpret that for a limited set of recycling processes there will be a need for more granular accounting than would likely be currently present. However, this does not necessarily mean that advanced technologies would be required or would be the most efficient way of delivering evidence to meet these requirements. For example, relatively simple gravimetric sampling methodologies could be sufficient and could be more cost advantageous.

Annex II, Table 1, PPWR – Relevant Categories for Economic Operators

Cat. No (new)	*Predominant packaging material*	*Packaging type*	*Format (illustrative and non-exhaustive)*	*Colour / Optical transmittance*
8	*Plastic*	*PET – rigid*	*Rigid formats other than bottles and flasks (Includes pots, tubs, jars, cups, mono- and multilayer trays and containers, aerosol cans)*	*Transparent clear / coloured, opaque*
9	*Plastic*	*PET – flexible*	*Films*	*Natural / coloured*
10	*Plastic*	*PE – rigid*	*Containers, bottles, trays, pots and tubes*	*Natural / coloured*
11	*Plastic*	*PE – flexible*	*Films, including multilayer and multi-material packaging*	*Natural / coloured*
12	*Plastic*	*PP – rigid*	*Containers, bottles, trays, pots and tubes*	*Natural / coloured*
13	*Plastic*	*PP – flexible*	*Films, including multilayer and multi-material packaging*	*Natural / coloured*
14	*Plastic*	*HDPE and PP – rigid*	*Crates and pallets, corrugated board plastic*	*Natural / coloured*
15	*Plastic*	*PS and XPS – rigid*	*Rigid formats (includes dairy packaging, trays, cups and other food containers)*	*Natural / coloured*
16	*Plastic*	*EPS – rigid*	*Rigid formats (includes fish boxes / white goods and trays)*	*Natural / coloured*
17	*Plastic*	*Other rigid plastics (e.g. PVC, PC) including multi-materials– rigid*	*Rigid formats, including e.g. intermediate bulk containers, drums*	-

18	*Plastic*	*Other flexible plastics including multi-materials – flexible*	*Pouches, blisters, thermoformed packaging, vacuum packaging, modified atmosphere/modified humidity packaging, including e.g. flexible intermediate bulk containers, bags, stretch films*	-
19	*Plastic*	*Biodegradable plastics[1] - rigid (e.g. PLA, PHB) and flexible (e.g. PLA)*	*Rigid and flexible formats*	-

5.3 How could the different technologies perform?

The advanced sorting technologies modelled in this study could in theory provide an element of increased traceability. The classification method remains essentially the same whether it is connected to a mechanism to select materials or whether it is solely there to record information. What differs between solutions for circularity and solutions for traceability is the amount of data that can be carried in a marker and detected by the advanced technology. In many cases, the data necessary to facilitate circular sorts is quite simple and could be essentially binary in simplicity, e.g., 'Food Contact Material' or 'Not'. Whether some groups of technology can perform at all depends on the level of traceability required.

Table 5-1: Traceability Performance Characteristics of Advanced Technologies

Technology	Granularity of Marker/Image	Evolution of "classification" and data capture
Watermarks	Markers typically have capability to carry well beyond SKU level data.	Classification (sorting) technology has not been trialled and is not yet able to record and transfer mass SKU level data.
Chemical Markers	Varies by technology. Some examples have a relatively small number of identifiers (codes) available. Some such as Polytag could in theory carry data beyond SKU level.	Not investigated in this research. We are unaware of any of these technologies operating at scale or at SKU level.
Object Recognition	Will vary according to packaging type and format. Close to SKU level and probably at least at producer/product type level is achievable where sufficient packaging print allows recognition, although this is also dependent on how open a data platform can be established to help OR systems recognise branding. Format types	There are examples of OR machines being used in plants for recording producer level information from certain rigid plastic packaging applications.

	achievable in rigid applications. Certain packaging formats which are detached from original branding (e.g. PET food trays) could only be recorded at format level not producer level or SKU.	

5.4 Supply Chain Models

A differentiation between sorting for circularity and traceability is the number of packages that would need to be marked or identified. To sort for circularity, only a subset of packaging would need to be marked or identified; typically, this would be the packaging that seeks to be positively selected. For example, in contact sensitive problem sets this study assumed that contact sensitive packaging is marked. However, it is far more likely in a tracing system that all packaging would be marked or would need to be identified.

Another potential differentiation between the concepts of using advanced technologies to sort for circularity and tracing materials is where in the recycling supply chain it would be effective to deploy the classification/sorting machinery. In section 4.2 where advanced sorting technology are to be deployed is described: after receiving MRFs (those receiving material directly from collections) and before recycling operations. If this same model was used for traceability, it would give a reasonable account of materials entering recycling operations with advanced technology and would minimise costs. However, the recycling supply chain is relatively complex in Europe with many examples of PCR packaging being sent to recycling operations in different member states from where it was collected and indeed being exported to countries outside the EU. For this study's proposed model to work for traceability, there would be a need for a common system across the EU supply chain and there would be an outstanding question on how to account for material being exported outside the EU.

The alternative would be to fit equipment early in the supply chain, such as at receiving MRFs. This could be equipment solely accounting for packaging and not sorting. Fitting advanced technologies at receiving MRFS would allow reasonable accounting for collected fractions in the member state from which it is collected. However, it is important to note that this is not accounting for material entering a recycling operation.

5.5 Estimates of Costs for Tracing

A high-level cost estimation for applying the advanced technologies to all plastic packaging once in the recycling supply chain was also made using the methodology described in section 3.4. In producing this estimate there was a high degree of uncertainty; therefore, the Capex for the advanced classification technologies is probably underestimated, and the costs of the whole data architecture are not included. Those costs are shown in Table 5-2.

Table 5-2: Cost estimates per annum for applying advanced technology once in the supply chain

Category	Digital Markers	Object Recognition
Rigids	€135m - €142m	€16m - €17m

Flexibles	€61m - 74m	€31m - €32m
Total	€196m - €217m	€48m - 50m

These cost estimates are relatively substantial and as discussed in previous sections, the performance of these technologies is uncertain, particularly in flexible packaging and for OR. Focusing on just rigid packaging, the modelling showed that providing advanced sorting for circularity in PP and HDPE is necessary to achieve circularity and would cost in the order of €17m for digital markers and €6m per annum for OR. The costs for traceability are therefore likely to be substantially more than those to achieve circularity in rigids. This is probably the case for flexibles as well. Therefore, the key question is if EPR operators can save money through improved tracing, and if producers would be willing to pay for the additional costs to receive more granular data and the potential for fairer fee allocation.

KEY FINDING: Tracing post-consumer plastic packaging throughout the recycling supply chain based on existing technology is not granular and relatively crude. Improving traceability through advanced technologies could improve regulatory processes and could potentially improve the efficiency and fairness of EPR processes.

None of the modelled advanced technologies have been demonstrated to achieve a high level of traceability across all post-consumer plastic packaging formats. However, of the three technologies examined in detail it seems likely that watermarking might offer the most granular tracing solution.

The problem set for traceability is different to that of sorting for circularity. Sorting for circularity may require a smaller amount of sorting technology only applied at certain points of the recycling supply chain. Traceability will require more technology and potentially applied at different points of the recycling supply chain.

Achieving a reasonable degree of traceability will produce substantially more cost than sorting for circularity. The key unanswered question is whether European producers would be willing to pay for better data and potentially improved efficiency and fairness in EPR systems that effective tracing could unlock.

6.0 Implementation of Advanced Technologies

The advanced sorting technologies examined in this report in can be seen as either marking technologies or OR. The anticipated timeline for implementation of these two different technology types is likely to quite different.

6.1 Implementing Marking Technologies

The proposed PPWR draft has wording on the marking of packaging. Most of this wording is focused on consumer facing content and markers. Chapter 11 of the proposed draft has various requirements for marking packaging and essentially reserves many of these matters for the EU to further clarify through subsequent implementing acts. As such, it would seem that the EU's intention is to be able to define pan-European marking systems for packaging.

This indeed makes sense for a marker system for sorting and tracing. From a packaging production and printing perspective, many producers will have production lines orientated to more than one member state and therefore printing markers for only one member state or producing more than one marker of different formats would be inefficient and problematic.

Likewise, there is significant cross border movement of post-consumer plastic packaging for recycling and for efficiency reasons this will continue to be likely. Advanced sorting and tracing machinery would therefore need to be common to all member states.

6.2 Implementing OR

In contrast to marking technology, OR is not reliant on any commonality between member states on makers or where in the recycling supply chain and how advanced sorting and tracing machinery is deployed. Plant operators can already make requirements that are addressed through OR solutions.

OR is already deployed in a number of sorting plants throughout Europe and is already contributing to sorting for circularity and in some cases contributing to increased traceability. However, these are still early days in the implementation of OR. Few databases of learned information are currently shared between plants or across whole markets.

6.3 Implementation Summary

The level of system change required to enable the installation of each technology varies. For both chemical markers and digital watermarks, it is likely that an EU agreement will be required to establish either technology as standard, alongside several other supply chain agreements to arrange the printing and monitoring of watermarks and the storage of associated data. In addition, both marker technologies would require changes in printing lines to accommodate cameras for checks on printing output (as the markers cannot be checked by the naked eye).

Changes to artwork and database management would also be required for digital watermarking; however, these would only be required for chemical marking if 2D barcodes were integrated to enable traceability.

Both chemical markers and digital watermarks have been lab tested, but neither are currently in operation. Since UV markers are less complex to implement than digital watermarks, they could perhaps be implemented at a slightly quicker pace. Either way, securing an agreement for introducing marker technology across Europe could take 5 to 10 years.

In contrast, OR technology would not require EU agreement, or changes to printing lines or artwork. However, database management would be key to enabling its implementation. OR can also already be implemented and is indeed in operation in several plants across Europe.

The main implementation issues for all three modelled advanced sorting technologies are summarised in Table 6-1 below.

Table 6-1: Implementation - levels of change required

Technology	Operational Readiness	EU Level Alignment	Printing Line Changes	Artwork Changes	Database Management	Notes
UV Markers	Lab tested	●	●			If 2D barcodes are integrated, artwork and data base management is required
Digital Watermarking	Lab tested across range of packages – in operational trials	●	●	●	●	
OR	In operation in a number of plants addressing similar problem sets				●	

KEY FINDING: Implementing advanced marker technology is likely to require alignment and harmonisation across Europe**.** This could take a substantial amount of time.

OR can be implemented on a plant-by-plant basis and is currently being deployed to facilitate circular recycling and tracing.

7.0 Conclusion

The insights from this study provide a clear direction for targeted investment and innovation in sorting technologies, emphasising the importance of aligning technological choices with specific recycling objectives and the unique requirements of different packaging types. As the industry moves towards meeting the EU recycling targets, this nuanced understanding will be essential in guiding efforts towards more effective and sustainable plastic packaging recycling practices. In summary, this study examined the role that advanced sorting technologies could play in increasing circularity in plastic packaging and reached the following conclusions.

For rigid plastic packaging:

- Advanced sorting will not increase overall recycling rates to a significant degree;
- Advanced sorting is only necessary for a limited set of rigid applications and polymers, namely contact sensitive applications in HDPE and PP; and
- The most cost-effective method of addressing HDPE and PP contact sensitive recycling would be to use OR when compared to marker technologies.

For flexible plastic packaging:

- Advanced sorting will not increase overall recycling rates to a significant degree;
- Advanced sorting is likely not necessary to produce recyclate grades but might be necessary to produce contact sensitive grades and recyclate specifications via mechanical recycling;
- There is insufficient evidence to determine performance and cost projections for advanced sorting in flexibles; and
- There could be reasons to assume that the cost and performance between the technologies could be a similar order of results as the rigid plastic findings – i.e., OR could provide an important and more cost-effective solution, but further trials of all the technologies across a full range of flexible plastic applications and polymers would be necessary to reach a clear conclusion.

The analysis found that most cost-effective method of addressing HDPE and PP contact sensitive recycling would be to use OR when compared to marker technologies.

For Traceability:

All advanced technologies could offer increased traceability though it is reasonable to conclude that this would be greater with digital markers than with OR. However, traceability would require significantly more investment than is needed to achieve greater circularity and in the case of markers would require far more packages being marked. Whether there is a willingness to pay for increased traceability remains uncertain.

Implementation:

It seems highly likely that OR can be (and arguably is) being adopted far more quickly than the marker technologies.

Overall:

It seems likely that there will be continued adoption of OR technologies and these may offer a more cost-effective solution for circularity. Both the plastics industry and policy developers should consider whether the additional cost burden that the use of markers would bring offers sufficient additional benefits to warrant the complex implementation process that would be needed to use specific markers as a mass market solution.

A.1.0 Appendix 1: Advanced Sorting Technologies

Table A-7-1: Technology Longlist

Technology category	Technology or provider name(s)	General technology description	Maturity (in development/on the market/ETA)	Benefits	Limitations	Modelled?
Barcodes	Reuse.id Polytag	Black and white markings, visible to the naked eye and machine readable.	Widely used Data storage systems in trial use	Widely used Easily applied	Limited data storage in 1D form Single point of view for sorting	No
RFID & Flexible RFID	PragmaticIC Thinfilm Electronics Germark Interacciona	Flexible electronic tag that can be read by specialised readers and mobile phones that provides unique digital ID that enables a container to be tracked.	PragmaticIC is in development. Number of projects currently taking place.	Can be read outside of line of sight Enables actors in supply chain to track economic and environmental benefits. Scan speed of hundreds of items per second Additional Benefits for other supply chain actors (e.g. use as security tags).	Relative cost may mean unsuitable for single use applications Potential slowdown with very high density of tags Limitations in terms of distance signals carry	No
UV Markers	Nextek Polymark Ergismark	Sorting technology for multilayer plastics, applied as a coating material over invisible to naked eye	Research and commercial trials have taken place.	System can be integrated into existing recycling facilities in a straightforward way	Ink and cameras required during printing to place and check markers	Yes

	MaReK	Classification technology added to existing sorting systems to identify		with little capital investment. As marker is not visible, can be printed over labelling for multiple points of detection for classification	Cannot be applied to flexibles	
Embossed code	CurvCode/FiliGrade Axion consulting	Embossed system detectable by cameras and light.	Packaging on market in Netherlands and industrial testing planned.	Does not require label or printing, is applied directly to rigid packaging through embossing the mould. Uses simple/fault tolerant ICT and standard components (monochrome USB cameras and LED lighting).	Intended solely for sorting - not additional tracking data	No
Digital watermark/QR code	Digimarc	Information is stored as a QR or digital watermark code. GS1 standards form the basis of the technology.	Field trials have taken place and results are available for sorting Labelling and tracing in use in meat industry	Can be printed on or over existing labelling 2D/QR codes can contain large amounts of traceability information Labelling and tracking proven utilisation in meat industry	Requires film for invisible watermark or printing of QR code	Yes

Object recognition	TOMRA Grey Parrot	Object recognition uses artificial intelligence systems and machine learning to identify materials for sorting The technology uses algorithms which can be ‘trained’ to recognise any product which is distinguishable by the human eye	In commercial use in a limited number of sorting plants	No printing solution required – can be implemented at the sorting stage independently, with no need for participation of producers or manufacturers – unique amongst the identified solutions	Limited traceability value beyond the point of sorting – not possible to identify the individual label as can be done by many of the marker technologies	Yes
Blockchain	Circulor Project Trackcycle	A blockchain solution to track plastic waste, through the recycling process and on to plastic feedstock. Also used to track raw materials from extraction, through processing, products and disposal/recycling	In development	End to end tracking of plastic - from extraction and production, to through the recycling process. Provides transparency for manufacture and recycling industry.	Needs a marker technology and blockchain infrastructure to work effectively	No
Chemical additive marker	Security Matters ReciChain	Additive for plastic that provides a 'chemical' barcode which connects a physical object to a 'digital twin'.	ReciChain project is a pilot.	No physical mark on product Traceability of key metrics	Little detail known	No

A.2.0 Appendix 2: Approach

Table A-7-2: Key factors in determining whether post-consumer plastic material is sufficiently sorted to enable a high degree of circular mechanical recycling

Factor	Influence
Polymer Type	Different plastics have distinct chemical compositions and properties. Mixing polymer types compromises the quality of the final plastic recyclate, and the consistency of its properties.
Colour	The colour of plastic affects the value of the resulting recycled material. Transparent and natural-coloured plastics are more versatile, valuable, and tend to contain less additives compared with dark and mixed colours.
Mechanical Properties	Mechanical properties like strength, flexibility, and resistance to heat and chemicals vary among plastics. Grouping plastics with similar properties ensures that recycled products retain desired characteristics.
Material Properties	Material properties affect how recycled plastics are processed. Examples include melt-flow index (MFI), and ash-content. A consistent melt-flow index is crucial for ensuring uniformity in the recycling output, as it influences the plastic's viscosity during melting. High ash content can degrade the quality of recycled material and affect its processing.
Contact-Sensitive Applications	Plastics used in contact-sensitive applications have stricter safety standards. Knowing the history of use is vital to meet safety standards for recycled materials that are used in contact-sensitive applications.

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