Towards Circularity in Alberta Plastic Waste Management: New Recycling Technologies and Design for Recyclability Gap Review

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EXECUTIVE SUMMARY

A technology gap review of new and emerging technologies that enhance the recycling of traditionally difficult to recycle plastics such as flexible films and e-waste plastics as well as the design of plastics to be recyclable was undertaken.

The main drivers for this gap review are the policies and regulations from both the provincial and federal government levels on creating a plastic circular economy. Provincially, these are the new extended producer responsibility program and boosting advanced chemical and renewable, low-carbon plastics recycling (as outlined in Government of Alberta's "Getting Alberta Back to Work: Natural Gas Vision and Strategy" document). Federally, there are proposed regulations on mandatory minimum thresholds of recycled plastic content in new plastics and a general reduction in plastic usage. InnoTech Alberta conducted a scan of current plastic waste management and recycling practices and ongoing technological innovations in plastic recycling in 2023. This review builds upon that work and focuses on the difficult-to-recycle plastics consisting mainly of flexible films – and referred to as flexible plastic packaging in this report. Flexible plastic packaging makes up almost half of the plastic produced in Canada, yet the recycling rate of all plastics in 2022 was only 16%. While data on the amounts of films and flexible material that is actually recycled is lacking, it is assumed that for these types of plastics the rates are extremely low. This is because flexible plastic packaging is often contaminated with different polymers, organics (e.g., food, agricultural residue), and multilayers of different materials which makes recycling them into high-quality post-consumer recycled material nearly impossible. A recent study conducted in Europe determined that there is and will continue to be a great shortage of high-quality post-consumer material to meet plastic recycled content requirements unless recycling rates are not increased even further.

Fortunately, there are many technologies, ranging from bench to pre-commercial stages, that tackle the barriers to recycling flexible plastic packaging to create high quality recyclates. These can be broadly categorized as decontamination processes that remove incompatible polymers and additives, volatile organic carbons that cause unpleasant odors, and inks that cause discoloration of final recylate products. Limitations to some of these processes are the use of hazardous solvents that must be disposed of and the specificity towards certain polymers so that there is no one process that will decontaminate all the myriad types of plastics generated. Cost and being able to integrate seamlessly into current recycling facilities are other important factors in the development of decontamination technologies. Novel sustainable processes that are in development include supercritical CO_2 deinking and metal-organic frameworks (MOFs) for deodourization.

Many flexible plastics packaging is comprised of multiple layers of different materials. Technology development on delaminating multilayered plastics has focused on dissolution-reprecipitation processes. Current limitations are the choice of solvent and antisolvent and their ratios can profoundly affect the efficacy of polymers separation and recovery. There is a great need for optimization and scaling up of processes. There are alternative technologies being developed that use advanced "green" separation methods. These include using steam, microwaves, ultrasound, supercritical fluids, and hydrophobic deep eutectic solvents. These technologies can not only reduce the volumes of solvents used but can also shorten residence times allowing for higher volume processing. Further testing, optimization and validation are required.

Design for recyclability refers to a series of design ideas and methods that fully consider the end of life of a product or packaging to improve its recycling rate. This can encompass the removal of problematic elements from packaging, providing alternatives (e.g., no polyvinyl chloride, polystyrene and oxo-degradable components), using monomaterials and non-hazardous products or producing transparent and uncolored products.

A critical issue with designing monomaterial-based packaging is ensuring that functionality and properties such as moisture and oxygen barriers are not compromised. Research and development into incorporating coatings and barrier performance enhancers that are easily recycled or degraded are being conducted. Likewise, designing inks that are degradable or easily removed from films are being developed and opportunities for collaborative work in this area may be available.

An emerging area in designing new plastics with enhanced recyclability or degradability is the use of chemistry and artificial intelligence (AI) to create polymers with desired specifications for a variety of applications. Chemical reactions such as recyclable ring-opening polymerization are being incorporated into polymers so that they can degrade and separate easily upon addition of stimuli like ultraviolet light or heat. These designer polymers are best suited for plastic products that need to be single use and readily degraded such as medical and pharmaceutical plastic products and devices.

A final area that was investigated for this technology gap review was the recycling of plastics from electronic waste (e-waste). Even though the average size of plastic components used in electronics continues to shrink and wall thicknesses are reduced due to advancements in polymer processability and end-use performance, the usage of plastics in electronics is rising. The main impediments to recycling e-waste plastic are the presence of toxic and hazardous flame retardants and different types of polymers bonded together. While innovative recycling technologies such as pyrolysis, supercritical fluid extraction and dissolution-precipitation separation are being tested, the cost-benefits and economics are low. There may be a greater opportunity in upcycling the plastic into construction materials including concrete as well as redesigning electronic plastics with detachable adhesives.

In summary, recent legislation, policies and recommendations are driving the need for greater research and development in enhancing plastics recycling, whether its for currently produced plastic or future, redesigned plastics. There are many novel opportunities for research groups to champion and help move society towards a world where plastic waste is not a detriment but a value-added product.

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Funding for this review was provided by Alberta Innovates.

GLOSSARY

Dual Stream Recycling – Dual Stream Recycling refers to when users need to separate recyclable items into subcategories – like mixed paper and commingled containers (plastic, glass, and metal).

Ionomers – An ionomer is a polymer composed of repeat units of both electrically neutral repeating units and ionized units covalently bonded to the polymer backbone as pendant group moieties. Usually no more than 15 mole percent are ionized. The ionized units are often carboxylic acid groups (Ionomer - Wikipedia).

Polyamides – A polyamide is a polymer with repeating units linked by amide bonds (https://en.wikipedia.org/wiki/Polyamide). Polyamides occur both naturally and artificially (Polyamide - Wikipedia).

Polyesters – Polyester is a category of polymers that contain one or two ester linkages in every repeat unit of their main chain (https://en.wikipedia.org/wiki/Polyester). As a specific material, it most commonly refers to a type called polyethylene terephthalate (PET) (Polyester - Wikipedia).

Polyolefins – A polyolefin is a type of polymer with the general formula $(CH_2CHR)_n$ where R is an alkyl group. They are usually derived from a small set of simple olefins (alkenes). Examples are polyethylene and polypropylene (Polyolefin - Wikipedia).

Polyurethanes – Polyurethane (often abbreviated PUR and PU) is a class of polymers composed of organic units joined by carbamate (urethane) links (Polyurethane - Wikipedia).

Single Stream Recycling – Single Stream Recycling refers to when all recyclable items are placed into one bin for collection. Users do not need to further separate items into any subcategories.

ACRONYMS

BFR	Brominated flame retardants
CAGR	Compound annual growth rate
CEFLEX	Circular Economy for Flexible Packaging
CTAB	Cetyl trimethylammonium bromide.
D4ACE	Design for a Circular Economy
EPR	Extended producer responsibility
EXPRA	European Extended Producer Responsibility Alliance
FF	Flexible film
FFP	Flexible film packaging
HDPE	High density polyethylene
IAS	Intentionally added substances
ICI	Industrial, Commercial &Institutional
LDPE	Low density polyethylene
LCA	Life cycle analysis
LLDPE	Linear low density polyethylene
MAE	Microwave assisted extraction
MRF	Material recovery facility
NIAS	Non-intentionally added substances
NIR	Near-Infrared
OPEX	Operating expenditures
PA	Polyamide
PCE	Plastics Circular Economy
PCR	Post-consumer recyclate
PE	Polyethylene
PEG	Polyethylene glycol
PET	Poly(ethylene terephthalate)
POPs	Persistent organic pollutants
PP	Polypropylene
PRO	Producer responsibility organization
PS	Polystyrene
PU	Polyurethane
PVC	Poly(vinyl chloride)
VOC	Volatile organic component
w/w	Weight per weight
Wt%	Weight percent

1.0 INTRODUCTION

Alberta (and indeed Canada and many other countries) is moving towards implementing a circular economy or CE. A large focus of the CE is on plastic waste and the creation of a plastics circular economy (PCE). An initiative that supports greater sustainability and a move towards a PCE is Alberta's Extended Producer Responsibility (EPR) regulation[1]. The aim of the regulation is to transfer the responsibility for paper and plastic waste generated back to the producers and manufacturers, and to free municipal waste management services from having to bear the costs of end-of-life disposal and or recycling. It is believed the EPR framework will drive changes at the producer level to reduce plastic usage and encourage the development of materials and or packaging that are easy to recycle.

Another PCE initiative is the Government of Alberta's plan for enhancing plastic recycling in Alberta, as described in their 2019 "Getting Alberta Back to Work: Natural Gas Vision and Strategy" document[2]. It outlines a goal of establishing a Centre of Excellence for Plastics Diversion and Recycling for Western Canada by 2030 which focuses on advanced chemical and renewable, low-carbon plastics recycling research and deployment.

On the federal side, the Government of Canada published in 2023 proposed labelling measures for recyclability and compostability for all consumer facing plastics. It also proposed mandatory minimum thresholds of recycled plastic in various categories of plastic packaging, and the development of a national plastics registry. Under these new measures, most plastics are required to have a minimum of 30 to 60% recycled content by 2030[3]. Given these shifts in how Alberta and Canada as well as industry use and manage plastic products and related waste, there is a pressing and continuing need to develop innovative solutions to support a PCE.

In 2022-2023, InnoTech Alberta conducted a scan of current waste management and recycling practices, and ongoing technological innovations in plastic recycling and circular economy, for Alberta Innovates' Clean Resources (Budwill, Ngo and Mohammed, 2023). The report provided a broad overview of the recycling landscape and recommended further investigations into emerging trends such as designing polymers and plastics for recyclability and tackling traditionally hard to recycle plastics such as flexible films. Flexible films are rarely recycled due to difficulties in separating the different resins and polymers used in multi-material flexible plastic packaging (FPP) as well as the inks used on FPP that can affect the quality of the plastic and harm recyclability. Another overlooked area of plastic waste management is plastic from waste electrical and electronic equipment. These can be technically difficult to recycle and may contain hazardous substances, such as flame retardants, which are problematic for recycling. If such chemicals enter the natural environment, for example, through uncontrolled burning or slow degradation in landfills, they may pose risks to both environmental and human health.

EPR legislation in Alberta and Canada more broadly, is driving the need for a significant increase in collection of FPP, as well as increased use of post-consumer recycled (PCR) content in new film and flexible

[1] Extended Producer Responsibility | Alberta.ca

[2] https://open.alberta.ca/dataset/988ed6c1-1f17-40b4-ac15-ce5460ba19e2/resource/a7846ac0-a43b-465a-99a5-a5db172286ae/download/energy-getting-alberta-back-to-work-natural-gas-vision-and-strategy-2020.pdf

[3] https://gowlingwlg.com/en-ca/insights-resources/articles/2023/canada-proposes-significant-regulation-of-plastics

packaging. For example, under Canada's EPR regulations[4], 40% of film and flexible packaging must be recycled in Quebec by 2027, and 25% in Ontario by 2026. The recycling rate of FPP is currently estimated at only 4%[5].

The objectives of this report were to conduct a technology gap review in emerging recycling technologies of difficult to recycle plastics, material design for enhanced recyclability, and recycling of plastic from electronic waste. Detailed searches through publicly available reports, news items, conference proceedings and electronic journals were conducted to find literature related to the themes of plastic recycling (see Appendix 1 for details on search methodologies). The overall goal is to obtain an up-to-date overview of plastic waste management technologies and to recommend areas for future research and innovation.

[4] Environment and Climate Change Canada (ECCC)

[5] https://www.packworld.com/sustainable-packaging/recycling/article/22892299/scaling-solutions-for-film-and-flexible-packaging-recycling

2.0 PLASTICS RECYCLING OVERVIEW: PRODUCTION, RECYCLING RATES, CHALLENGES, AND GLOBAL PERSPECTIVES

This section provides an overview of plastic production and recycling rates and gaps, market trends and drivers, and global recycling perspectives.

2.1 PLASTIC PRODUCTION AND MARKETS

Global plastic production has increased 11.8% from 2018 to 2023[6], with 413.8 million metric tons produced in 2023. Approximately 90% of plastic is derived from fossil fuels (Figure 1). In contrast, plastic recovered and reused from mechanical recycling increased by 20.7% during the same period (2018-2023) but made up a small percentage (8.7%) of the total plastic produced in 2023. Bio-based/bio-attributed plastics or plastics from chemical recycling comprised less than 1% of total plastic production in 2023 (Figure 1).

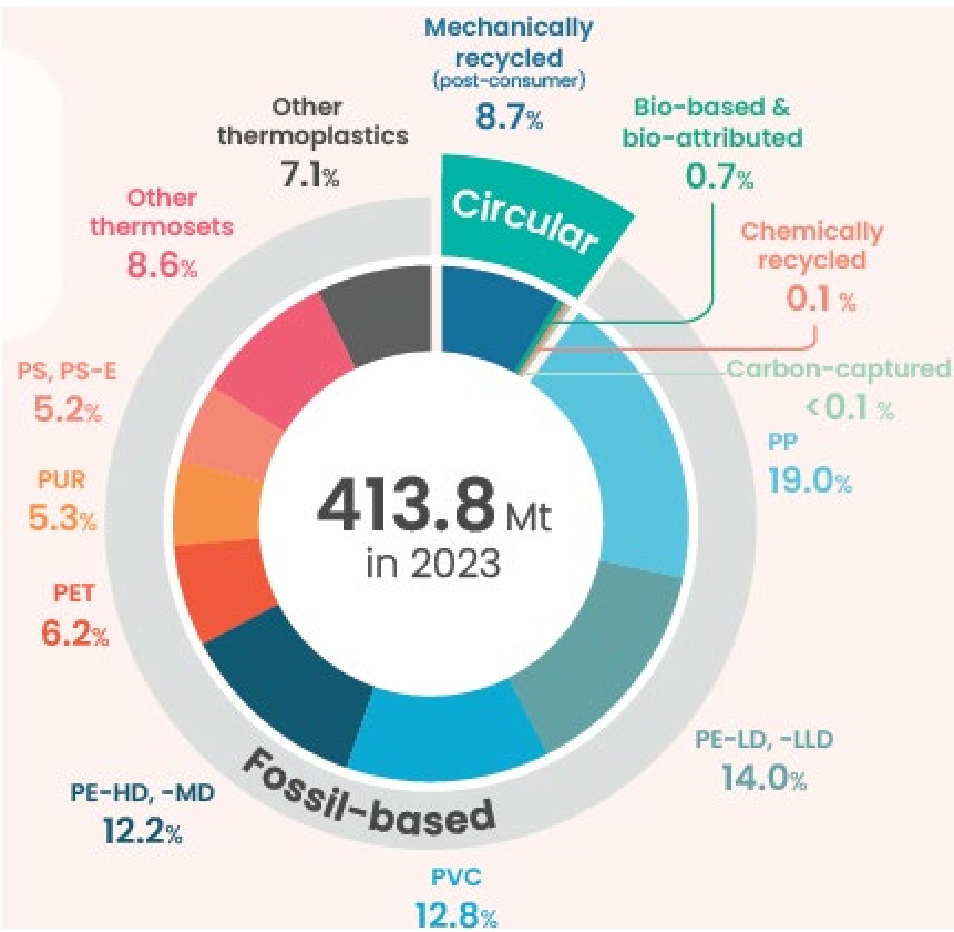

Figure 1. Composition of plastic production in 2023[6].

[6] Plastics – the fast Facts 2024 • Plastics Europe

Canada generated 1.96 million metric tons of plastic packaging in 2022, nearly 3.6% more than it did in 2019[7]. Part of this increase is due to the inclusion of Industrial, Commercial & Institutional (ICI)-generated plastics by the Canada Plastics Pact's audit. Flexible plastic packaging (FPP) accounted for nearly half (47%) of the plastic packaging placed on the Canadian market in 2022[8].

FPP is a high-volume stream of consumer packaging. The main qualities of FPP are its light weight and superior performance in reducing food spoilage[9]. Furthermore, only small quantities of raw material are needed in its production. Examples of FPP include sleeves, pouches, bags, and shrink films (see Appendix 2 for an extensive list of different types of FPP currently used in the market). Canada's FPP market size was estimated at 2.09 billion USD (United States Dollar) in 2024 and is expected to reach 2.86 billion USD by 2029, growing at a compound annual growth rate (CAGR) of 6.52% during the forecast period (2024-2029)[10]. In 2024, Canada produced approximately 0.87 million tons of flexible plastic packaging, with projections indicating an increase to 1.12 million tons by 2029, reflecting a compound annual growth rate (CAGR) of 5.26%[11].

2.2 Recycling and Recyclate Markets

The global market for plastic recycling was valued at 41.9 billion USD in 2023 and is projected to reach 57.9 billion USD by the end of 2029[12]. The plastic recycling market is expected to grow at a CAGR of 6.4% globally and at 7.0% for Canada from 2024 to 2029. Increasing the use of plastic in the manufacturing of lightweight components utilized in many different industries, such as automotive, electrical and electronics, and other industries, are the key market drivers enhancing the market growth[12].

Polyethylene (PE) recyclates accounts for over 26% of the global revenue in 2023 due to its extensive use in packaging applications. Indeed, the packaging sector itself represented over 37% of the global market share due to the growing demand for sustainable food and beverage containers, personal care products, and industrial packaging. On the other hand, polyethylene terephthalate (PET) plastic bottles are the dominant source of recycled plastics, contributing over 74% of global revenue in 2023 due to their broad applications across industries, including food, beverages, and pharmaceuticals.

As for the Canadian perspective, only 16% of plastic waste in Canada was recycled in 2022[13]. The rest ended up in landfills, waste-to-energy facilities, or stayed in the environment. As can be seen from Figure 2, PET, mostly in the form of PET bottles, are the key type of plastic recycled in Canada. FPP can be comprised from high density polyethylene (HDPE), low density polyethylene (LDPE) and linear low-density polyethylene (LLDPE), but these are likely to more rigid plastics (e.g., shampoo bottles, tubs, etc.). As stated in a report released in 2024 by the Canada Plastics Pact, there was a 17% increase in rigid plastic waste but a 6% decrease in flexible plastic waste produced between 2019 and 2024[14]. Conversely, there

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7 Canada-wide Plastic Packaging Flows: A 2024 Progress Report - Working together for a Canada without plastic waste or pollution..

8 Canada Plastics Pact Unveils 5-Year Roadmap to Drive Circular Economy for Flexible Plastic Packaging - Working together for a Canada without plastic waste or pollution.

9 https://www.thepkglab.com/blog/61/packaging-film-types

10 https://www.researchandmarkets.com/reports/5986278/canada-flexible-plastic-packaging-market-share#

11 Canada Flexible Plastic Packaging Market Size, Share, Growth & Analysis

12 https://www.marketresearchfuture.com/reports/recycled-plastic-market-11993

13 Recycling Statistics in Canada for 2025 | Made in CA

14 https://plasticspact.ca/canada-wide-plastic-packaging-flows-a-progress-report/

was a 2% decrease in rigid plastic recycling and a 13% increase in flexible plastic recycling in that same time frame.

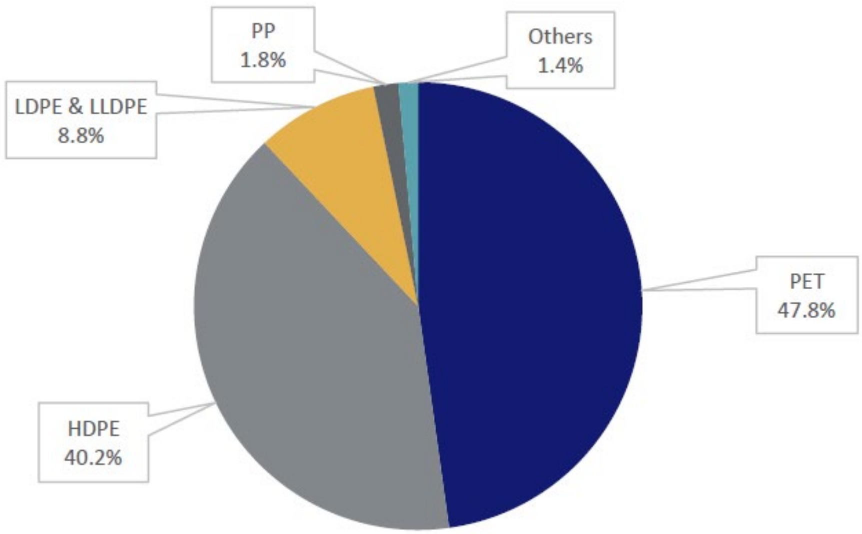

Figure 2. Pie graph depicting the percent Canadian market shares of plastic recycling, by type in 2023[15].

Recycling rates must be increased to meet the demand for PCR material (i.e., recyclates) and new PCR content regulations put forth by the Canadian government[16]. Indeed, a recent study[17] analyzed the current availability of PCR and forecasts demand up to 2030 in the European Union (EU). The results show that despite expected improvements in recycling infrastructure, significant PCR supply shortages are expected. In 2022, approximately 32.3 million tons of plastic waste were collected in the EU, of which only 16.4 million tons were recycled (an approximate 51% recycling rate). This resulted in a current recyclate output of 7.7 million tons (24% recyclate production rate), with 6.7 million tons of recyclate remaining within the EU. By 2030, however, a total demand for 13 million tons of PCR is anticipated. Under a conservative "business-as-usual" scenario, this results in a supply shortfall of 5.3 million tons of PCR material in the EU. Even an ambitious "advanced scenario," which accounts for significant investments in mechanical and chemical recycling, would still leave a 788,000-ton gap. This gap in recyclate production is illustrated graphically in Figure 3, although here the focus is on FPP only.

15

16 https://gowlingwlg.com/en-ca/insights-resources/articles/2023/canada-proposes-significant-regulation-of-plastics

17 Plastic Recycling: The future of recycled material availability: Challenges and opportunities to 2030 | WMW

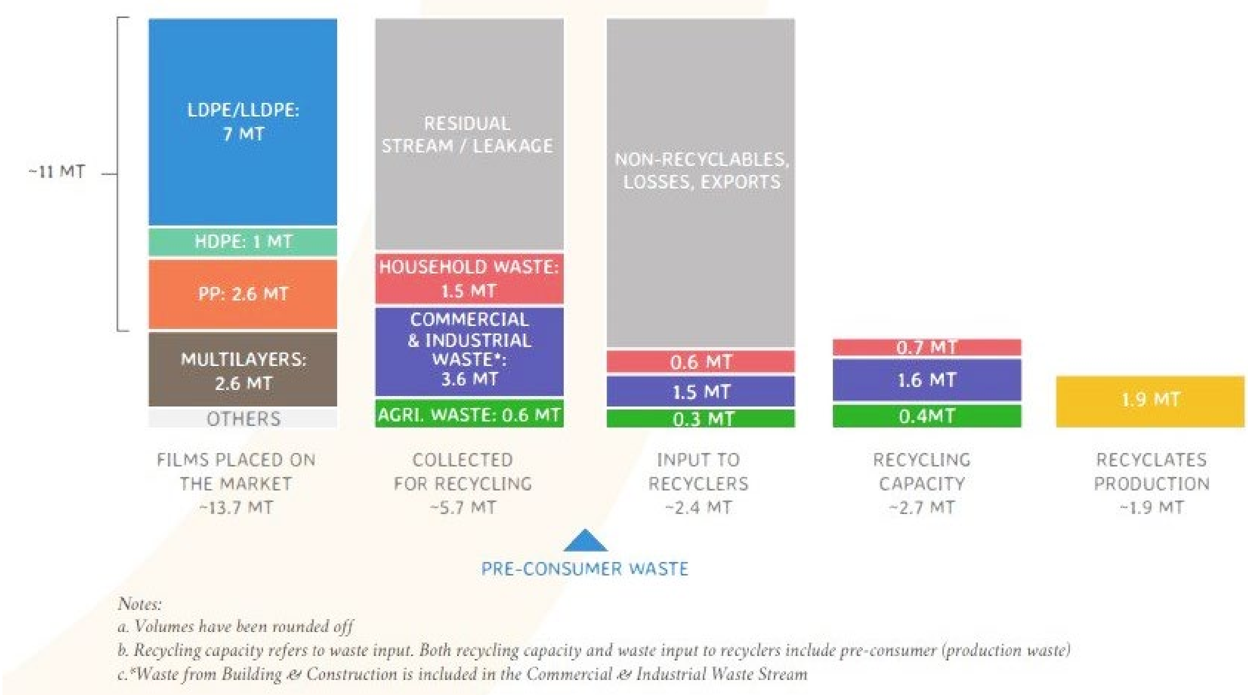

Figure 3. European flexible films volume flow across the recycling value chain, 2020 data[18].

As Figure 3 depicts, a total of 13.7 million tonnes of flexible films were placed on the EU market in 2020, comprising of 11 million tons from PE and PP streams and the rest from multi-layers and others. It is estimated that only 40% of these films (dominated by PE flexible films) were collected for recycling. Following sorting to remove contamination from non-recyclables (including compostable waste, moisture and non-recyclable plastics), only 2.4 million tonnes of flexible films were used as input for recyclers in the region in 2020. This represents a recycling rate of 18% in relation to the films placed on the market. Approximately 80% of this FPP recycled was converted into recyclates. If it is assumed that 13.7 (or 42%) of the 32.2 million tons total plastic waste is FPP, then 5.5 million tons of FPP (42%) of the 30 million tons of recyclate demand by 2030 would be needed. The current recycling rate and recyclate production yields would need to increase by 87% to make up the shortfall (approximately 3.6 million tons) in FPP-derived PCR.

In Canada, there is insufficient data to measure progress on recycling film and flexible material. Basic data that is available for other materials, like PET and HDPE bottles, does not exist for film and flexible packaging. Reliable data and consistent metrics are necessary to track performance against recovery goals established by individual companies as well as by collaborative initiatives like the U.S. and Canada Plastics Pacts. Basic metrics such as capture rate studies to collect more information on the generation of films and flexibles, as well as recovery of FPP when that is available to consumers will help create standardized ways to assess generation and composition of FPP allowing for more consistent comparisons from one study to another.

[18] van Rossen, 2023

2.3 POLICIES, PROPOSALS, AND SUPPORT FOR ENHANCING PLASTICS RECYCLING

2.3.1 European Perspectives

Europe is generally seen as the forerunner in implementing a PCE as shown by the different action plans, directives and strategies listed in Table 1.

Table 1. European policies and legislations for plastic recycling (van Rossem, 2023).

Policy	Year Established	Overall Goal/Details
EU Action Plan for a Circular Economy	2015	• Ensure all plastic packaging is recyclable by 2030.
Packaging and Packaging Waste Directive (PPWD)	2018	• Increases recycling targets for plastic packaging from the current 22.5% to 50% by 2025 and 55% by 2030.
EU Strategy for Plastics in a Circular Economy	2018	• Initiated the Circular Plastics Alliance (CPA) • Help plastics value chains boost the EU market for recycled plastics to 10 million tonnes by 2025 (80% of the increase in recycled plastics should come from packaging).
Packaging and Packaging Waste Regulation (PPWR)	2022	• Proposal to repeal the PPWD and aim to ensure that all packaging placed on the European market is either reusable or recyclable by 2030 and to reduce packaging, over-packaging and therefore packaging waste.

A major collaborative European initiative called CEFLEX (The Circular Economy for Flexible Packaging) with over 190 stakeholders representing all parts of the European FPP value chain aims to collect 100% of flexible packaging for recycling and/or 80% of the packaging for upcycling into valuable new markets and applications. To enable this initiative, CEFLEX targets an established collection, sorting and reprocessing infrastructure and economy for post-consumer flexible packaging across Europe by 2025. CEFLEX is supported by EXPRA (European Extended Producer Responsibility Alliance). This EPR alliance provides guidance on design for recycling, collection, sorting, and end markets.

One of the recent outputs from CEFLEX are their "D4ACE" or "Design for a Circular Economy" guidelines on the key elements of the structures of polyolefin-based flexible packaging, including thresholds for mono-PE and mono-PP used, functional barriers, size and shape, density, adhesives, pigments, additives and fillers printing inks, and labels.

Another initiative to enhance plastics packaging recyclability is RecyClass. RecyClass aims to establish a harmonized approach towards recycled content calculation and its traceability in Europe. Activities within RecyClass include the development of recyclability evaluation protocols and scientific testing methods for innovative materials which serve as the base for the "Design for Recycling Guidelines" and the "Recycling Online Tool"[19]. RecyClass offers Recyclability Certifications for plastic packaging (Figure 4) and Recycled Content Traceability Certification for plastic products.

[19] Design for Recycling Guidelines - RecyClass

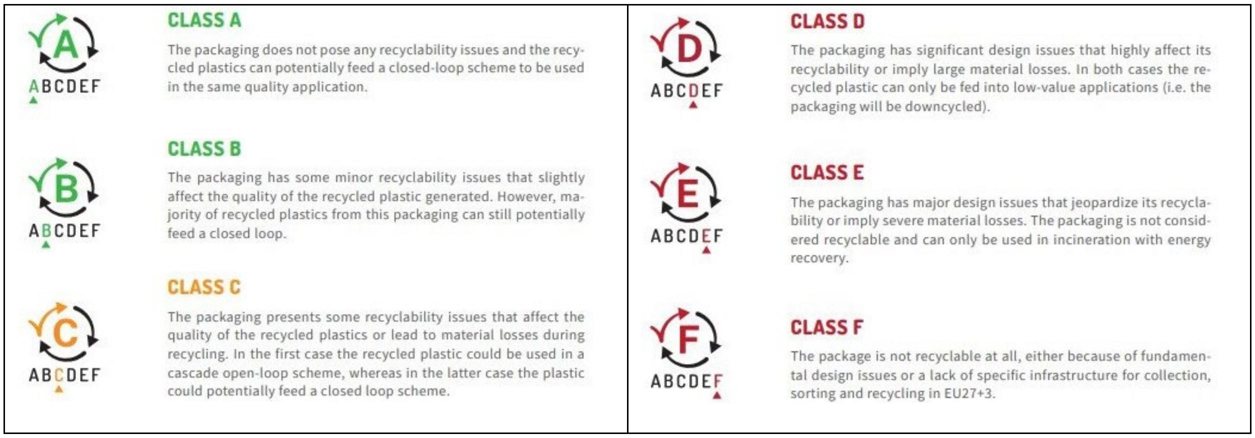

Figure 4. RecyClass classification system for plastic packaging recyclability[20].

Germany has emerged as a European hub for plastic recycling due to a favorable regulatory environment and investments. Germany uses a dual system for collecting, sorting, and recycling of plastic packaging items[21]. A dual recycling system is one in which the consumer separates their recyclables into separate bins or bags before they are picked up by the recycling operation. There are currently 10 dual systems that inform customers about the correct collection of used packaging. They use a yellow bag or bin for collecting packaging that is not made from paper, cardboard, carbon or glass. Examples of items that can go in the yellow bin range from lids of all materials, plastic food containers, plastic bottles, bubble wrap, to toothpaste tubes. Customers are also expected (or encouraged) to separate different plastic parts from a multi-component package. Thus, pre-sorting by the customer ensures the material recovery facilities (MRFs) can efficiently identify, sort, and recycle different plastics.

In early 2022, a sorting facility was commissioned in southern Germany (Eitting, Bavaria) that can process up to 120,000 tonnes/year of lightweight packaging collected from German households, including plastic packaging (both rigid and flexible), aluminum and steel containers, and aseptic and gable-top cartons. The collected packaging material is sorted into a total of 18 different fractions. This includes polypropylene (PP), PET, PE, and polystyrene (PS) plastics. The facility uses the latest technology in the sorting process, including:

- 38 Near-infrared (NIR) spectroscopy optical sorters, almost twice the amount installed compared to other facilities.
- Screens located in the upfront sorting trommel screens to remove all materials less than 20 mm (typical screen size in sorting plants remove materials that are less than 40-50 mm).
- Black scanners to identify black plastics that are difficult to sort in conventional plants.
- The latest generation of sorting robots to support employees in quality control and re-sorting.
- Further sorting of the fractions by color.

2.3.2 Canadian Perspectives

The Canada Plastics Pact, CPP, is a multi-stakeholder, industry-led collaboration platform to tackle plastic packaging waste. They recently published a "Roadmap for Flexible Plastic Packaging in Canada" which

[20] Design for Recycling Guidelines - RecyClass
[21] Waste separation works | Mülltrennung wirkt! (muelltrennung-wirkt.de)

outlines a 5-year strategic roadmap to reduce the environmental impact of flexible plastics[22]. The strategy has 4 main goals:

1. Design for circularity by making FPP easier to recycle by ensuring it meets certain design criteria.
2. Increase collection and recycling by improving infrastructure and systems so more FPP is collected and recycled.
3. Increase the use of recycled content by encouraging companies to use more recycled materials in their packaging.
4. Drive innovation by supporting new technologies and business models for reuse, recycling, and composting.

The aim is to have 100% of plastic packaging to be reusable, recyclable, or compostable, 50% of packaging to be effectively recycled or composted and 30% recycled content in plastic packaging by 2025. The CPP claims this will be achieved by developing design guidelines for flexible packaging that make it recyclable in Canadian systems, creating a list of recyclable vs. non-recyclable materials to help companies make better packaging choices, standardizing labeling to inform consumers on how to properly dispose of packaging and conducting pilot programs for collection and recycling of FPP across Canada.

A key action item for the CPP is to build end markets for recycled FPP to ensure economic viability. To this end, they created the PRFLEX Initiative[23] in 2023. It is a collaborative effort among Canadian organizations—including the CPP, Chemistry Industry Association of Canada, Circular Materials, Circular Plastics Taskforce, Éco Entreprises Québec, Recycle BC, and The Film and Flexibles Recycling Coalition of The Recycling Partnership—to enhance the recycling system for FPP in Canada. They plan to do this by:

- Conducting a baseline assessment of the current collection and recycling rates of FPP across provinces, categorized by format and type.
- Conducting an infrastructure gap analysis to Identify deficiencies in existing sorting and recycling facilities that hinder effective processing of flexible plastics
- Propose and implement new technologies and processes to increase capture rates, improve sorting accuracy, and produce higher-quality post-consumer recycled resins.
- Install and evaluate the performance of optimized equipment and processes in select partner facilities to validate improvements.

2.4 Plastic Markets Summary: Drivers and Innovation Needs

The increasing demand for durable flexible and lightweight packaging in e-commerce, high-barrier materials for food preservation, and customization through advancements in digital printing technologies are changing and driving the packaging industry. Indeed, manufacturers are seeking new polymer blends and composites that enhance the functionality of packaging, such as improved barrier properties and extended shelf life for perishable goods. They are also investing in the development of monomaterial packaging due to increasing societal demand for enhanced recyclability of their products. In parallel, government regulations on increased recycled content in packaging materials is occurring.

[22] 5-Year Roadmap - Working together for a Canada without plastic waste or pollution.

[23] PRFLEX: Perfecting the Recycling System for Flexible Plastic Packaging in Canada - Working together for a Canada without plastic waste or pollution.

In Canada, almost half of the plastic production in 2022 was in the form of FPP. Although, there is a lack of data on the exact numbers and types of plastic recycled, it is estimated that only 16% of the total plastics produced in 2022 was recycled. Thus, given the low recycling rates with changes in the packaging landscape for more recycled content and enhanced recyclability, innovation is imperative to address these drivers. Due to the complexity and wide variety of FPP available as well as the great demand for FPP, multiple research and development prongs will be required such as:

- Innovations in sorting and cleaning technologies to produce high-quality recycled resins.
- Advancements in chemical recycling technologies to complement mechanical recycling for processing hard-to-recycle plastics.
- Improved data and tracking on the complete life cycle of FPP to understand the scope of production and recycling rates.
- Designing FPP and other plastics to be readily recyclable.

3.0 RECYCLING OF FLEXIBLE PLASTIC PACKAGING: GAPS AND OPPORTUNITIES

This section investigates the major gaps in recycling of FPP and identifies possible solutions and opportunities to enhance their recycling rates and quality of recyclates.

3.1 FPP RECYCLING BARRIERS AND LIMITATIONS

Most FPP can theoretically be recycled if they are efficiently sorted at the MRF, either physically by using wind shifters and ballistic separators, or optically by Fourier Transform Near Infrared Spectroscopy (FT-NIR) (Guo et al., 2022). The use of digital labeling technologies (e.g., Digital Watermarks HolyGrail 2.0[24]) can greatly improve the collection and sorting of packaging waste. However, many factors still impede the widespread recycling of FPP such as:

- Difficulties in sorting and separating FPP containing multiple layers of different types of plastics and other materials.
- Issues in processing polymer blends and/or multilayered plastics to generate PCR materials due to differences in physicochemical properties such as PE and PET. Similarly, in thermochemical recycling processes, heterogeneous polymers such as PET, polyamide (PA), polycarbonate (PC) can contaminate polyolefinic plastic waste (Schyns et al., 2020, Kol et al. 2021).
- High contamination levels of ICI FPP waste.

Solutions to mitigate flexible film waste in the environment and to encourage recycling can be divided into two categories: 1) material redesign for recyclability and 2) preprocessing existing FPP to enhance recyclability. Material redesign will be discussed in the Section 4. In this section, processes to enhance the recycling of FPP, namely decontamination and multilayer separation processes, to improve recyclate quality will be discussed.

3.2 DECONTAMINATION AND CLEANING OF FPP

Contamination in and on FPP is a major issue as highlighted by a study that detected 134 different substances in post-consumer HDPE and LDPE samples. More than 50% of the substances in recycled LDPE were reported to be contamination arising from the recycling process, typically from the packaging content (Horodytska et al., 2020). The contamination found in FPP is often classified as being from intentionally added substances (IAS) or from non-intentionally added substances (NIAS). Examples of IAS are additives (e.g., flame retardants), processing agents, printing ink, and adhesions (i.e., solvent-based polyurethane (PU) in multilayer packaging) (Cabanes and Fullana, 2021). Examples of NIAS include the degradation of products of IAS, impurities from IAS, side reaction products, and contaminations from recycling processes. If not removed, IAS such as brominated flame retardants (BFRs) and phthalates can be blended in the recyclates during mechanical recycling, posing a potential health risk for consumers, especially in food contact materials and childrens' toys (Roosen et al., 2020). Some additives can also have a direct impact on the recyclability of the plastics and even lead to their degradation. This is the case for metal-containing additives, such as metals salts or oxides like Fe_2O_3, Cu_xO and ZnO, that will form pro-oxidants and photo-oxidation catalysts, promoting the degradation of the plastics during the reprocessing

[24] Pioneering Digital Watermarks | Holy Grail 2.0.

phases in mechanical recycling (Hahladakis et al., 2018). This makes it difficult for recyclers to offer reclaimers a pure, high-quality product.

Current pre-treatment technologies including sorting, washing, float-sink and grinding have been found to be ineffective in removing all contaminants in PCR material especially those embedded in the polymer structure (Roosen et al., 2020). Even when sodium hydroxide or a detergent are added to water as washing additives in order to reduce surface contamination such as dirt, labels and glue (Welle, 2011), a 100% efficient removal of the heterogeneous contaminants cannot be achieved. There are new approaches using solvents to enhance the washing steps. An example of a piloted or commercially available decontamination process is the CreaSolv® technology[25], patented by the Fraunhofer Institute IVV, which consists of a dissolution-precipitation technique (described further in 3.3.2.1) that can remove additives, such as plasticizers from different polymers including polyolefins, PS and PET in scrap packaging. Likewise, PureCycle Technologies (based in Florida, USA) uses a form of solvent dissolution to remove contaminants and purify PP[26]. The technology consists of six main process stages from an initial melting and filtering out contaminants in the PP feedstock to several solvent purification steps. Additives that the process removed during the final extrusion are added back in. During the final production stage, the polymer is cut into pellets and dried. UpSolv, formerly Polystyvert[27], developed a dissolution process for recycling all types of PS. In this process, the solvent is an essential oil that rapidly dissolves the PS. The oil is non-hazardous and can easily be reused to recycle more material. The dissolved PS is then separated from the essential oil. During this step, hexabromocyclododecane, the BFR, although now banned but is still found in some types of PS, can be removed. UpSolv has also developed a solution to eliminate fine particles and contaminants that remain in the solution, such as ink, pigments, and different types of additives. This low-temperature chemical process, for which a patent application has been filed, avoids using filters that are costly and have to be replaced frequently. UpSolv is aiming to build its very first commercial plant in Québec, dedicated to recycling highly contaminated PS waste.

Technologies that target specific contaminants such as odorous volatile organic components (VOCs) and inks are being developed to be integrated before, during or after the extrusion step to provide recyclates with a higher purity as described in the following sections (Kol et al., 2021).

3.2.1 Deodourization

A recent study detected 400 volatile organic components (VOCs) that remained on plastic molecules after washing as shown in Figure 5 (Cabanes et al., 2020). Esters and alkanes were two of the main VOC functional groups found on the plastics. However, since their physicochemical properties are fundamentally different it makes efficient deodorization very challenging, as water-based washing media have been shown to be insufficient to produce recyclates with an acceptable odor threshold (Kol et al., 2021).

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[25] The CreaSolv® Process - CreaSolv

[26] Our Process | PureCycle | Polypropylene Plastic Recycling

[27] Home - Polystyvert

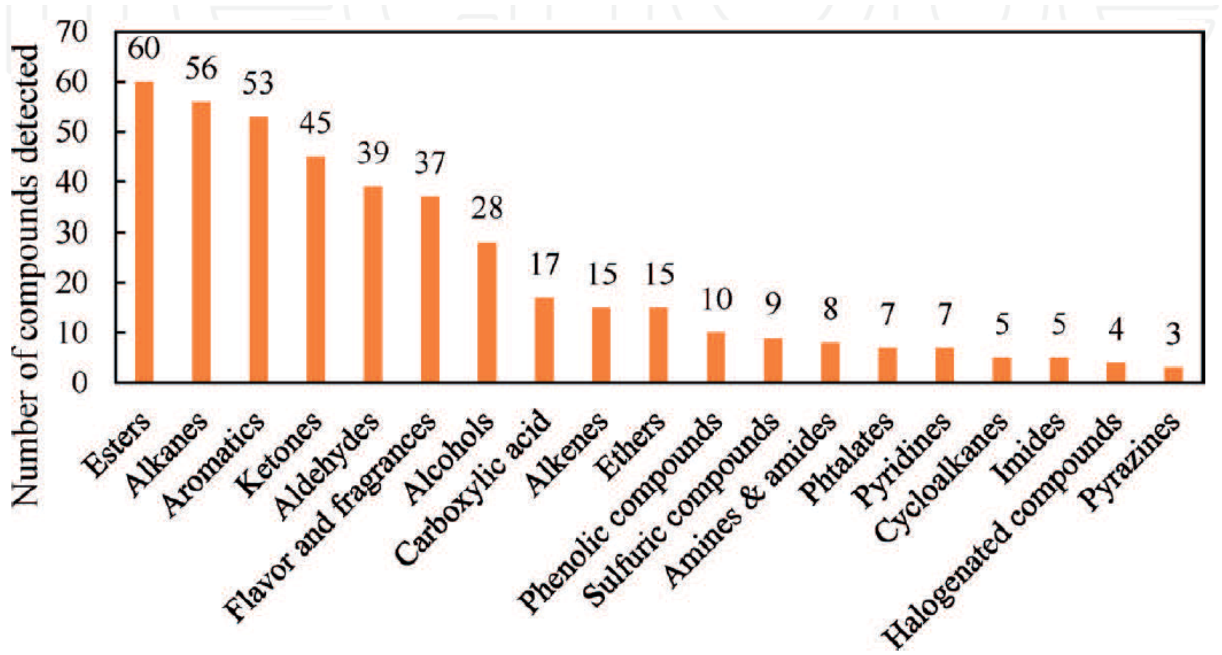

Figure 5. Number of VOCs (divided into subcategories based on their chemical structure) detected on plastic materials after washing. (Kol et al., 2021).

Different approaches to removing odours from waste plastics such as solvents, air/steam and degassing, and adsorbents are described below.

Solvents

Solvents such as ethyl acetate have been tested as an alternate to water to clean polyolefin-based packaging products. Results indicated that with a batch-wise extraction using ethyl acetate at 65°C could, on average, remove 90% of analyzed odor components (Kol et al., 2021). Another solvent that has been tested to remove odorous constituents from a HDPE waste stream is polyethylene glycol (PEG). PEG is considered a relatively eco-friendly solvent due to its low volatility and toxicity compared to conventional solvents, and its higher miscibility with organic compounds compared to water (Cabanes and Fullana, 2021). A batch lab-scale extraction with PEG has shown that the quantity of VOCs was reduced with 74% after PEG extraction at 100°C (Kol et al., 2021).

Air/Steam and Degassing

The application of air can also remove volatile odorous constituents. A commercially available example is the ReFresher technology with the INTAREMA® TVEplus® machine[28]. This equipment applies heated air directly to the extruded pellets to flush out volatile contaminants and simultaneously remove the air via a degassing unit. Applying a hot air stream during a few hours was found to significantly reduce the overall odor intensity of recycled HDPE pellets with an efficiency varying between 51 and 99% (Strangl et al., 2019). A disadvantage of this technique is the relatively long contact time that is needed to achieve the maximum feasible removal efficiencies, typically between 4 and 7 hours. Depending on its size, the

[28] EREMA Engineering Recycling Maschinen und Anlagen Ges.m.b.H., Ansfelden, Germany INTAREMA TVEplus

ReFresher has a capacity between 350 kg/h and 4000 kg/h (Kol et al., 2021). Steam on its own can be applied to remove VOCs from plastic materials. A study has shown that an increased VOC reduction is achieved via steam stripping compared to hot air stripping (Cabanes and Fullana, 2021). A study using post-consumer HDPE measured an overall reduction of volatile components above 70% when the plastic was treated in a lab-scale distillation unit for 2 hours (Kol et al., 2021).

Different devolatilization methods using vacuum and thermal degassing or degassing with the help of ultrasound have been tested. A study on the removal of VOCs from plastics via a vacuum degassing system showed that the odor concentration was reduced by 37% after three degassing steps. The disadvantages of these devolatilization processes are that it is complex as temperature and shear profiles, screw configuration and placement of venting equipment all influence the removal efficiencies of VOCs. For instance, a higher temperature and pressure during extrusion can increase the volatility of the moisture content and permit water and/or other volatile materials to be released (Alshahrani et al., 2015).

Adsorbents

Highly specific surface adsorbents added during the extrusion process can remove VOCs through adsorption from the plastic waste (Strangl et al., 2020). They are added to a polymer in melting phase and the VOCs adsorb on the adsorbing agents' surfaces. Adding 0.30 wt% of a certain adsorbent such as zeolite or activated silicate, can significantly reduce the concentration of VOCs by approximately 80% coming from post-consumer HDPE (Kol et al., 2021). While there a great variety of adsorbents available on the market (e.g., BYK Additives[29]), there are emerging technologies that are enhancing the effectiveness of them.

One such emerging deodourization technology is the development of reactive additives that undergo chemical reactions with the functional groups of odor-causing substances converting them into non-volatile components (Pfaendner, 2015). An example of such a commercially available additive is zinc ricinoleate, manufactured as TEGO® Sorb PY 88 TQ by the company Evonik[30]. Zinc ricinoleate is the zinc salt of ricinoleic acid, a major fatty acid found in castor oil. Evonik claims their product has excellent odour absorbing properties and is suitable for the effective control of odours evolving from products like hydrogen sulfide, mercaptane, thioether, isovaleric acid, amines and ammonia. The product exhibits good heat stability in the compounding process. It is especially suitable for polyolefins (e. g., LDPE, PP), rubber compounds (e. g, vulcanized thermoplastic elastomers or ethylene propylene diene monomer) and recycled material (e.g., polyamides (PA), polyolefins and rubber).

Another emerging deodourization technology are Metal-Organic Frameworks (MOFs). MOFs are a class of porous polymers consisting of metal clusters coordinated to organic ligands. The company Numat Technologies[31] develops MOFs for a variety of applications, including the removal of hazardous gases and odourants. One advantage of using MOFs is that they can be designed, atom-by-atom, to capture and separate target hazardous chemicals. While promising, more scientific studies are needed to quantify and optimize the effectiveness of such additives (Kol et al., 2021).

[29] Supplier of additives – BYK

[30] Tego Sorb PY 88; Evonik Industries AG, Essen, Germany Evonik

[31] Home - Numat

3.2.2 Deinking and Decolorization

Although inks are a necessary component of plastic packaging, they are a significant source of contamination in plastic recycling. If printed plastic films are processed together, a low quality brownish, grayish, or black recyclate is obtained, making it only suitable for downcycled products (Gabriel and Maulana, 2018). The presence of ink also causes recycled films to be less stiff, weaker, and denser compared to the original material. Furthermore, during the processing or reprocessing, residual ink can also decompose and produce gases causing rancid odor formation and decrease the physical properties of a raw material (Horodytska et al., 2018). Inks are complex, tailor-made chemical products added to the surface or inner layer of packaging products (Kol et al., 2021). The main constituents of printing inks are resins, solvents, colorants and additives as shown in Table 2

Table 2. Characteristics of components of inks used in FPP manufacturing (Kol et al., 2021).

Component	Composition of ink (%wt)	Examples	Function/Details
Resins	15 to 50	Acrylics, polyurethanes, polyvinylbutyral, nitrocellulose	• Binder for colorant stabilization • Type of binder affects viscosity, scratch resistance, flexibility, and gloss
Solvents	Up to 66	Ethanol and isopropanol, ethyl acetate, acetone, and methyl ethyl ketone	• Dissolves resins and keeps the ink liquid for supporting ink transfer
Colorants	5–30	Pigments, dyes, lacquers or overprint varnishes	• Gives desired color to plastic packaging. • Pigments are insoluble solid fine particles which are dispersed in the binder, while dyes are substances that are completely soluble in the binder • Lacquers or overprint varnishes are uncoloured forms of printing inks, which can be used to provide gloss and protective properties to the print
Additives	Up to 10	Plasticizer citrate esters dispersants and surfactants	• Improves physicochemical properties of inks (e.g., adhesion, slip and scratch resistance). • Enhances the compatibility between pigments and the ink medium, as well as pigment dispersion during ink application and lifetime.

Deinking technologies are aimed at removing inks and coatings from the surface of plastic materials. Washing the plastic flakes with water and 1–2 wt% caustic soda (NaOH) at a high temperature (70–80°C) has been shown to partly remove the printing ink (Gabriel and Maulana, 2018, Horodytska et al., 2018, Strangl et al., 2020). An example of a commercially available de-inking technology is KEYCYCLE deinking[32]. It is a water-based process that eliminates printed ink and other contaminants in plastics (e.g., paper stickers, glue, dust) to obtain high quality, virgin-like recycled plastics. During the deinking process, the ink is dissolved from the surface of the shredded film or regrind material. The company claims their deinking process can increase the circularity of plastics two-fold. The process also incorporates a water-treatment system to reuse the same water for several months.

[32] KEYCYCLE Deinking | keycycle.at

Different surfactants have been tested on water-based and solvent-based ink systems with different colors. Surfactant removal of ink occurs in four main steps as illustrated in Figure 6: 1) adsorption of the surfactant on plastic surfaces, 2) solubilization of the binder in the surfactant aggregates into so called micelles, 3) detachment of ink particles from the surface, and 4) stabilization of the detached ink particles (Chotipong et al., 2007). Studies have shown that cationic surfactants such as cetyl trimethylammonium bromide (CTAB) were more effective to remove both water- and solvent-based inks than other surfactants. Critical micelle concentrations, pH of the medium, temperature and stirring all have an effect on deinking efficiency (Chotipong et al., 2007).

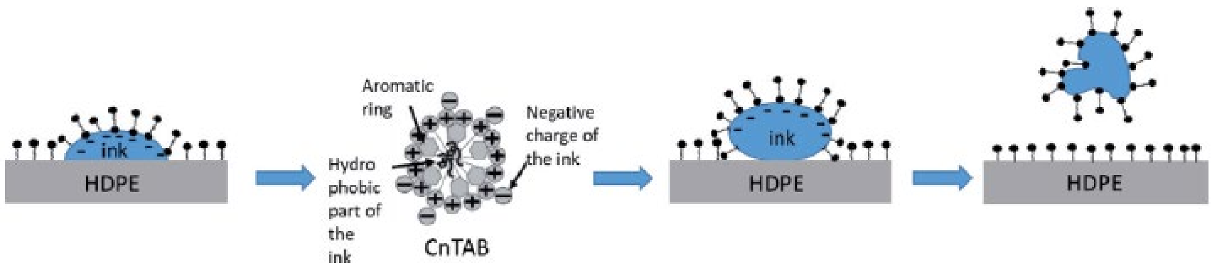

Figure 6. Four-step mechanism for the removal of solvent-based ink from an HDPE surface (Kol et al., 2021).

Table 3 summarizes different deinking processes tested or under development. Each deinking technology has its own set of advantages and limitations, and the choice of technology often depends on the type of ink, the polymer used in the packaging, and the intended recycling process. Flexibility, cost, and environmental impact are key considerations when selecting a de-inking method. As well, possible side reaction products should be systematically investigated in the future (Guo et al., 2022).

Table 3. Summary of deinking technologies.

Technology	Process	Advantages	Challenges	TRL	Companies/Research Groups
Mechanical Deinking (Scraping or Abrasive Techniques)	• Involves physically scraping or abrading the ink layer off the plastic surface. • The printed plastic surface is treated with mechanical methods such as brushes, rollers, or abrasive media that physically remove the ink layer.	• Simple and low-cost approach. • Requires no chemicals or complex equipment. • Inline compatible. • Best for labels removal.	• May cause wear and tear on the plastic, limiting its reuse or reducing the material quality for recycling. • Only surface level deinking, cannot remove embedded ink. • Not effective for UV-cured, high-adhesion or chemical-resistant inks.	High (>7), commercially available	• Sorema • Erema • Herbold Meckesheim
Thermal Deinking (Heat Treatment)	• Involves applying heat to the printed plastic to loosen or melt the ink.	• Can be effective for heat-sensitive inks and when combined with other processes like washing. • No water required.	• May require careful temperature control to avoid deforming or degrading the plastic. • High energy use • Colour smearing may occur.	High (7-9), commercially available	• APK GA (Germany) • Sorema • Erema
Solvent-Based Deinking	• Printed packaging is immersed in or treated with a solvent solution that dissolves the ink. • The solvent breaks down the ink's bond with the plastic, allowing it to be removed.	• Effective at removing a wide range of inks, especially solvent-based and UV-cured inks. • Best for soluble inks and rigid plastics	• Requires careful handling of solvents due to environmental and health concerns. • May also lead to residual solvent traces in the recycled plastic	High (7 – 9)	• Cadel Deinking Technology (Spain)
Electrostatic Separation	• A process where electrostatic forces are used to separate ink particles from the plastic surface. • The printed plastic is charged, and then an electric field is used to attract or repel ink particles, causing them to detach from the plastic.	• No chemicals or solvents required, environmentally friendly. • Energy efficient. • Selective separation • Scalable for flake sorting. • Best for post-wash sorting and black ink removal.	• Effective only for certain types of inks and requires precise control of electrostatic parameters. • Works better with rigid flakes and flexible films.	High (7-9)	• EU Research projects: CREAToR and Multicycle • TOMRA • Hamos
Plasma Treatment	• Uses low-pressure plasma (ionized gas) to modify the surface of the plastic and remove ink. • The plastic is exposed to a plasma field, which generates reactive species that interact with the ink and degrade it, making it easier to remove.	• Eco-friendly, no solvents or water involved, and suitable for a variety of ink types. • Low-temperature, non-destructive to polymers such as PE, PP. • Best for inline cleaning and high purity reuse.	• High setup and operational costs, typically suited for small batches or high-value applications. • Not effective for deeply adsorbed or UV-cured inks. • Slow throughput compared to wet methods.	Medium (5-7)	• Fraunhofer IST and IVV • Plasma Treat GmbH
Ultrasound-Assisted Deinking	• Utilizes high-frequency sound waves (ultrasound) to break up the ink particles from the plastic surface.	• Low chemical usage, eco-friendly, and effective in breaking the ink adhesion. • Best for printed films	• Can be energy-intensive and requires specialized equipment. • Not all ink types are equally responsive (UV-cured and high-	Low (3 to 5), at bench or pilot scale.	• Fraunhofer Institute IVV • Technical University of Munich

Technology	Process	Advantages	Challenges	TRL	Companies/Research Groups
	• Sound waves create microscopic bubbles that implode near the ink particles, causing them to detach from the substrate. • Process is often combined with water or a mild detergent.		adhesion inks may resist ultrasound-based removal). • Requires careful control of frequency, power, and exposure time to avoid damaging the polymer.		
Supercritical CO_2 Deinking	• Uses supercritical carbon dioxide (CO_2) as a solvent to remove ink. • CO_2 is used under high pressure and temperature to create a supercritical state, which has properties between liquid and gas. • In this state, CO_2 can act as a solvent and effectively break the ink's bond with the plastic surface.	• Non-toxic, environmentally friendly, and efficient at removing a variety of inks. • Very low substrate damage. • No water required.	• Requires specialized equipment and energy for maintaining supercritical conditions. • Limited ink solubility in pure CO2, often requires co-solvents. Process parameters must be finely tuned per ink/polymer type.	Low (<3), experimental	• Fraunhofer Institute IVV • Japanese Research Institutions
Laser Ablation	• Involves the use of laser light to directly remove ink from plastic films. • The laser light targets the ink layer, which absorbs the energy and evaporates or flakes off without damaging the underlying plastic.	• Highly selective and precise, with minimal chemical use. • Minimal physical wear. • Dry and clean, integrates well with automated systems. • Best for spot cleaning and high value reuse.	• Expensive technology, typically used for high-end applications, and may require significant energy input. Selective ink compatibility	Low (<3), experimental	• Technical University of Dresden • Siegwerk • Flint group
Biological Deinking	• Involves using enzymes or microbes to break down or degrade the ink. • Certain microorganisms or enzymes can break down the chemical components of the ink, rendering it easier to remove.	• Environmentally friendly and chemical-free. • Targeted action. • Adaptable to different ink types.	• Slow process, and not yet widely applicable or commercially viable for large-scale operations. • Enzymes can be expensive.	Low (<3), emerging	• University of Boras (Sweden) • Fraunhofer IVV

In addition to these individual technologies, there are also hybrid methods being developed that combine multiple techniques, such as solvent and ultrasound, or plasma and washing. This can increase efficiency and reduce costs as well as negative environmental impacts.

Siegwerk[33], one of the world's leading providers of printing inks for packaging applications and labels, and APK AG (recently acquired by LyondellBasell[34]), a specialist in the production of high-quality plastic recyclate from packaging waste, successfully completed deinking trials of twofold printed LDPE-films. In spring of 2020 the Research and Development unit of APK AG tested several LDPE-film samples, which had been printed twofold with yellow, red, black and blue inks produced by Siegwerk. The test series aimed to establish whether APK AG's solvent-based recycling technology Newcycling® (section 3.3.2.1) could fully remove Siegwerk's inks from the polymer matrix. The film samples were treated with the Newcycling® solvent and dissolved. The obtained polymer solution still contained printing ink-components. The dispersed inks were then removed with a filter unit explicitly designed for the process step of deinking, featuring a very high selectivity level. The deinking tests of the red, black and blue samples produced a 'near-virgin' transparency. The film printed with yellow ink had marginal yellowness remaining after the treatment.

Like deinking, clarity of recyclates is of importance to the recycling industry. Alpla Werke Alwin Lehner GmbH & Co. KG, of Austria, received a patent for a method of reclaiming thermoplastic materials for recycling that overcomes PET becoming more yellow, cloudy or gray in appearance over progressive cycles of recycling (Siegl 2023). In their process, prepared thermoplastic flakes are exposed to an oxidative fluid and heat, ranging from 160°C to 240°C and 5 minutes to 10 hours. Contaminants and agglomerates formed during the process can be taken up by the oxidative fluid and separated from the reaction vessel. Further separation of solid contaminants can be performed by sifting technologies, and standard sorting systems can be used to remove discolored solid contaminants or contaminants made brittle by the heat and oxidation treatment. The patent states the process works well when used after steps such as washing flakes in alkaline solutions or cold sorting to separate contaminants such as metal or other plastics. The patent claims to enable the polymer chain length to be increased to the level of the original raw material. The method works with thermoplastic materials including PET, PP, polylactide, polyethylene furanoate, polypropylene furanoate and high-density PE.

3.3 SEPARATING MULTILAYER FPP FOR RECYCLING

Many FFP are composed of multiple layers of different compositions as depicted in Figure 7. The different layers provide mechanical stability, oxygen and light barriers, as well as acting as sealants. Many different polymers are used in these layers (Table 4), highlighting the complexity of multilayered FPP.

[33] Siegwerk Druckfarben AG & Co. KGaA

[34] LYB to acquire APK AG recycling technology | LyondellBasell

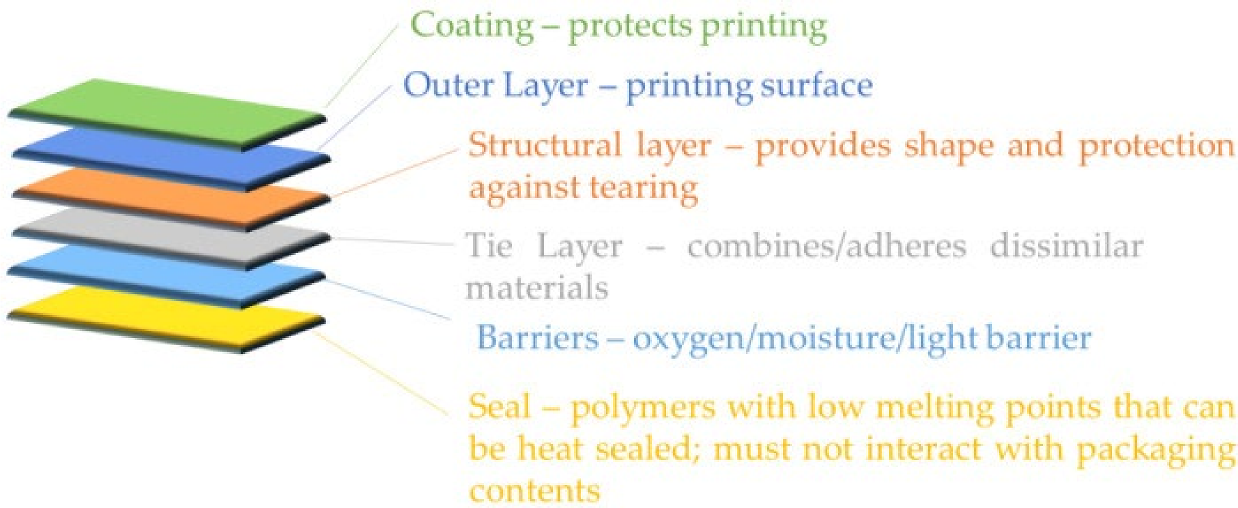

Figure 7. Example of the components of a multilayer FPP structure[35].

Table 4. Overview of components of different functional layers in multilayered FPP[36].

Property	Examples of Polymers and Materials
Mechanical Stability	HDPE, PP, OPP, OPET, PS, Pape
Oxygen Barrier	EVOH, PVDC, Polyamides (nylon, BOPA), Polyesters, OPET, Coatings (SiOx, Al_2O_3, PVOH, nanoparticles, Aluminum
Moisture Barrier	PE (LD, LLD, HD), PP, OPP, EVA, ionomers, PVDC
Light Barrier	Aluminum, TiO2 filled polymers
Tie Layers	Polyurethanes, Acid/anhydride grafted polyolefins
Sealant	LLDPE, LDPE, EVA, Ionomers, PP, OPP, PA, OPA, PET, OPET

BOPA, biaxially oriented polyamide; EVA, polyethylene-vinyl acetate; EVOH, ethylene vinyl alcohol; OPA, oriented polyethylene; OPET, oriented polyethylene terephthalate; OPP, oriented polypropene; PVDC, polyvinylidene chloride; PVOH, polyvinyl alcohol; LD, low-density; LLD, linear low-density; HD, high-density.

Recycling of multilayered FPP is generally difficult due to the presence of immiscible polymer layers (e.g. PET and PE) resulting in recyclates with low mechanical properties (Ügdüler et al., 2021). The release of reactive oxygenated compounds during the chemical recycling of multilayer PET materials can also lead to low quality recyclates. (Kol et al., 2021). Furthermore, the release of hazardous compounds such as halogens during the polymer decomposition can occur and cause corrosion of the process equipment and reactors (Roosen et al., 2020).

Figure 8 illustrates the different options for recycling multilayered FFP. Essentially, the FFP can be recycled without separating the different layers, or extra steps can be taken to separate or delaminate the layers by mechanical or chemical processes into individual components.

[35] Loukodimou et al., 2024

[36] Kol et al., 2021

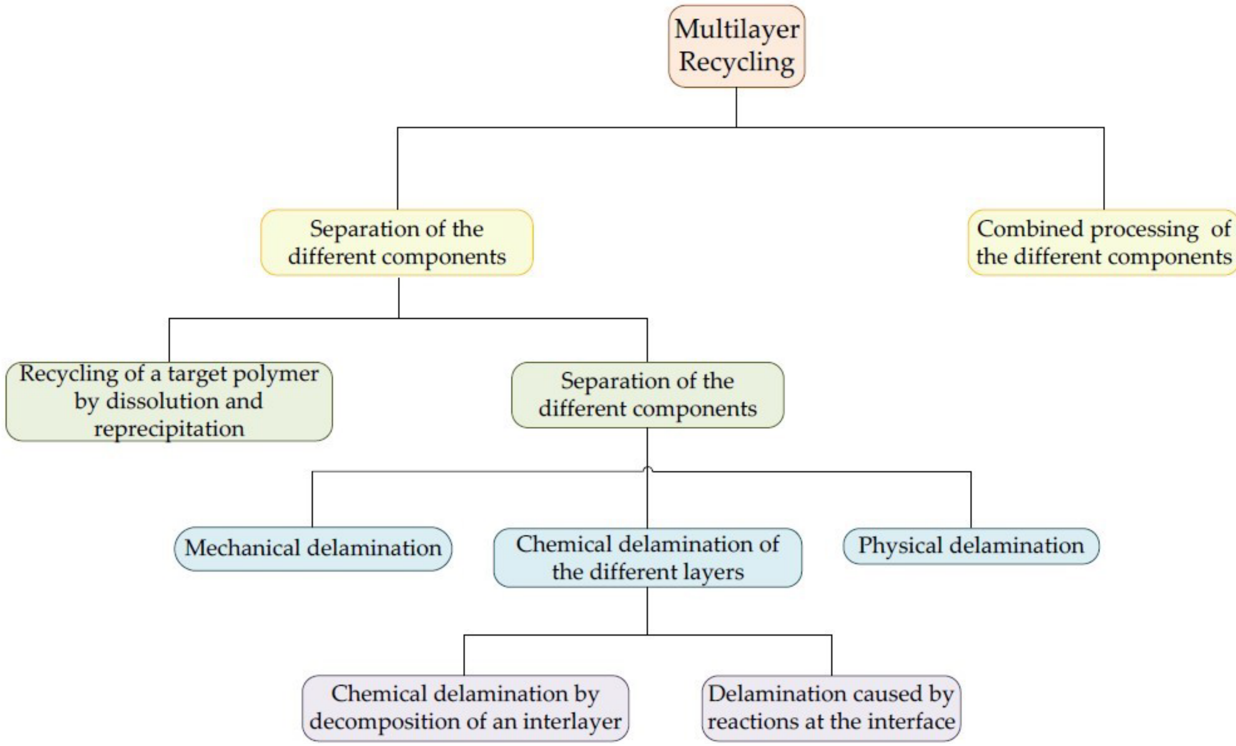

Figure 8. Schematic overview of recycling methods of multilayer packaging[37].

3.3.1 Combined Processing of Different Components of Multilayered FPP

The blending of polymers is an approach to recycling multilayered FPP without the need to separate the components. However, because of insufficient solubility, most blends have poor mechanical properties and unstable morphologies, necessitating the addition of additives in a process called compatibilization. Compatibilization improves a blend's performance by making each component more miscible resulting in the material becoming more macroscopically homogeneous. This is achieved through the addition or in situ generation of a macromolecular species that exhibits interfacial activity in heterogeneous polymer blends. The compatibilized blend thus consists of one component finely dispersed in the other, with good adhesion of the phases and strong resistance to coalescence.

There are limitations or barriers to compatibilization due to fluctuations in the composition of the FPP input or feedstocks that can be unpredictable and thus no constant product quality can be guaranteed. The direct addition of compatibilizer into the FPP system, however, might be a strategy to alleviate these limitations.

3.3.2 Separation of Multilayered FPP

While metal layers, such as aluminum, in multilayered FPP can easily be separated by electrostatic separation, the separation of different polymer/polymer layers is much more difficult. These polymer layers can be separated physically by the dissolution and reprecipitation of macromolecules, and/or by mechanical or chemical delamination of the interlayers or by reactions at the interface.

[37] Kaiser et al., 2018

3.3.2.1 Dissolution-Reprecipitation Processes

In selective dissolution–reprecipitation processes the different polymers of a multilayered FPP are dissolved at a certain temperature one after another, generally in the same solvent. The solution of the first polymer is separated from the remaining solutions or residue by filtration in so-called solid–liquid separation steps. The polymer can then be recovered by rapid evaporation of the solvent or by adding an antisolvent that will cause the polymer to precipitate (Pappa et al., 2001). Drying of the polymer grains and recovery of the solvent and antisolvents are the final steps (Kol et al., 2021). The choice of the solvent and antisolvent is dependent on the solubility of the polymer and/or polymers. The amount of solvent used for dissolution also plays an important role, as a low concentrated solution will lead to low viscous fluids, but will require higher amounts of antisolvent, since normally the added ratio of solvent/antisolvent is 3:1, while concentrated polymer solutions lead to very high viscous fluids, which are hard to process (Papaspyrides et al., 1994). Therefore, typical recommended solvent concentrations are in the range of 5–15 wt% (Kol et al., 2021). The choice of the antisolvent is also important since it influences the form of the precipitated polymer. Some antisolvent may lead to gel-like polymers while other permit the precipitation in the form of powder or grains (Poulakis and Papaspyrides, 2001).

Selective dissolution precipitation techniques at a laboratory scale and pilot-scale for a two-component mixture of LDPE/PP has been investigated (Pappa et al., 2001). The solvent/antisolvent used was xylene/i-propanol in a 3:1 ratio and the dissolution was performed at different temperatures in the range of 85 to 135°C, depending on the polymer. The recovery of the two polymers was greater than 99%. Papaspyrides et al. (1994) studied the dissolution-precipitation technique for LDPE pellets using xylene and toluene as solvents at 85°C. Toluene proved to be the most suitable solvent, as it allowed higher concentrations of polymer (0.30 kg/L) to be achieved while remaining within the limit of viscosity. Acetone was the most successful antisolvent for the LDPE-toluene solution as the polymer was precipitated in the form of powder without forming gelling lumps.

The Chemical Upcycling of Waste Plastics (CUWP) consortium of US researchers[38] developed a dissolution-precipitation process called STRAP (**S**olvent-**T**argeted **R**ecovery **a**nd **P**recipitation), to recover all the constituent polymer layers of multilayer plastic packaging (Walker et al., 2020) as illustrated in Figure 9.

[38] https://cuwp.org/

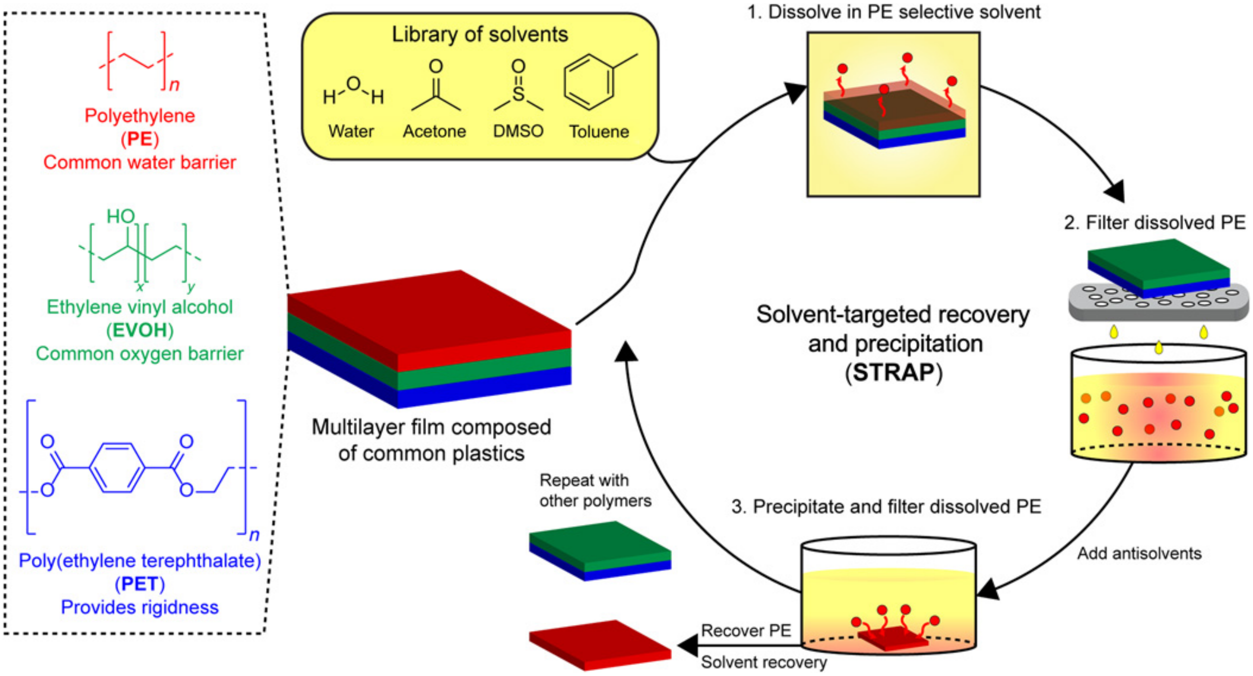

Figure 9. Schematic diagram of the STRAP process to dissolve and precipitate different constituents of a multilayered flexible plastic[39].

The STRAP process has been used to convert commercially available post-industrial rigid multilayer film into its three main polymer components with greater than 99 wt% recovery (Walker et al., 2020). This multilayer film consisted primarily of PE, ethylene vinyl alcohol (EVOH) and PET with various tie layers that included ethylene vinyl acetate (EVA). In the process, the film was dissolved in two different solvents, each of which solubilized an individual polymer. The final resin was then precipitated with the addition of an antisolvent or by cooling the solvent system.

The current limitation of STRAP is that the process only produces small quantities of final material, less than 0.11 kilograms per week. To demonstrate the STRAP technology at a larger scale, a process development unit was designed and tested to produce 25 kilograms per hour of recycled resins from waste flexible and rigid plastics. Figure 10 shows a simplified STRAP diagram featuring the recovery of high purity plastic resins from mixed plastic waste or flexible plastics

[39] Walker et al., 2020

Figure 10. Simplified STRAP process flow diagram[40].

The Newcycling® technology[41] by APK Ag (Germany) is a dissolution-precipitation process that combines mechanical pre-processing steps with solvent-based cleaning and separation processes. This enables the mechanical technology to efficiently recycle complex, flexible packaging waste, such as multilayer films, and to obtain high-quality, single origin recyclates. After first scaling up based on waste from multilayer film production and further testing up to commercial LDPE and PA products, Newcycling was planning on starting construction of a new large-scale plant in Germany in 2024.

3.3.2.2 Delamination Processes

Multilayer packaging can also be separated through dissolution of tie layers, such as polyurethanes (PU), acrylates, and acid anhydrides, which are used as adhesives to laminate dissimilar polymer layers. Currently, only delamination methods suitable for specific types of multilayered plastics exist. For example, Kulkarni et al. (2011) recovered the aluminum layer from multilayer packaging structures by depolymerizing PET and PA in the presence of sub- and supercritical water. In another study, sulfuric acid

40 https://cuwp.org/wp-content/uploads/2023/10/1_STRAP_102023.pdf

41 APK: Restructuring and Newcycling Expansion – KunststoffXtra

was used to degrade PET and recover the PE layer from multilayer plastics (Patel et al., 2016). Although selective degradation of polymer layers is promising in terms of polyolefin recovery, degraded polymers can negatively affect the medium recovery (Kol et al., 2021).

There are several studies focusing on the dissolution of tie layers for separation of polymer-aluminum multilayer packaging by using organic solvent systems (Kirk, 1992). For example, in the patented method of George et al. (2011) the cured composite laminate material was preconditioned to delaminate composite layers by using organic solvents such as water, benzyl alcohol, acetone, methyl ethyl ketone (MEK). As an alternative to solvents, acids are also used dissolve tie layers of a broader range of multilayer structures (Kol et al., 2021) such as polymer, aluminum and/or paper. Protonic carboxylic acids such as acetic acid are used together with organic solvents to increase the solubility of adhesives (Massura et al., 2002). In another study it was proven that the diffusion rate of formic acid is faster compared to other longer chain carboxylic acids such as hexanoic acid and decanoic acid and was thus selected as a superior medium to delaminate different types multilayer packaging (Ügdüler et al., 2021).

3.3.2.3 Advanced "Green" Separation Methods

Alternative techniques like steam extraction, ultrasonic extraction, supercritical fluid extraction, and microwave-assisted extraction have been developed to separate multilayered FPP (Kol et al., 2021). These techniques not only reduce the amount of solvent used but also shorten residence times allowing for higher volume processing (Kol et al., 2021). Most of the processes described in this section are not yet available commercially for separating components of FPP, even though these methods are often applied in other sectors, thus necessitating further research and development specifically geared towards plastics.

Steam Extraction

A recent patent (Garrido Escudero et al., 2024 and awarded to RepetCo Innovations S.L.[42]) describes a system and method for separating multilayered plastics commonly used in agriculture, industry and packaging. The system uses a boiler to introduce superheated steam vapor to a holding vessel containing multilayer plastic fragments. The incoming steam heats the vessel to a temperature between 100 and 191°C and raising its interior pressure to between 1 and 12 bar for 10 to 60 seconds. The fragments are then carried to a discharge tank at a relative pressure between −0.7 and 0.1 bar and at a temperature between 15 and 25°C for up to 5 minutes. The superheated vapor causes heat shock to the plastic layers followed by the mechanical shock (from the sudden pressure change) when the fragments are moved to the discharge tank. Together, these forces weaken and break the chemical bonds between the layers. The multilayer fragments are later transferred to a mechanical separation unit where they are separated into fragments of single-layer plastic. Finally, the fragments progress to a mechanical sorting unit where they are sorted by polymer material.

Microwave Assisted Extraction (MAE)

MAE is an emerging technology for delamination that uses microwave radiation to heat materials rapidly and selectively. It facilitates the breakdown and separation of polymer layers by softening and degrading adhesives or specific polymers. The advantages of MAE are that it can target specific layers (e.g., removing PE or adhesives) without affecting other components, has a lower energy consumption and is faster and

[42] About Us – RepetCo Innovations

uses less solvent than other delamination processes. However, the technology requires complex optimization for each multilayered FPP due to varied layer compositions. In addition there is the risk of thermal degradation of sensitive components.

Researchers at the Center of Plastics Innovation[43] at the University of Delaware have investigated microwave-assisted depolymerization of PET, a common component in multilayered plastics. Their work focuses on the economic and environmental benefits of modular microwave-assisted processes, which could inform strategies for multilayered FPP recycling.

Ultrasound with Nitric Acid Extraction

A method combining nitric acid, heat, stirring, and ultrasound was shown to effectively break down PU adhesive layers, facilitating the separation of polymer layers and aluminum (Šleiniūtė et al., 2023). Ultrasound was found to significantly enhance the delamination process, making it more efficient. This approach successfully recovered three distinct polymers suitable for recycling and allowed for the reuse of aluminum. PU comprises soft and hard segments, and monomers are formed when the polymer is oxidized by acid. These monomers are subsequently removed from the multilayer packaging structure by mixing, breaking down the packaging structure, and separating the polymers. The use of non-concentrated nitric acid further enabled the dissolution of aluminum from the packaging. However, controlling gas emissions remains a significant challenge in the delamination process, warranting further research.

Supercritical Fluids Extraction

Supercritical fluids exhibit liquid-like density and gas-like viscosity and diffusion coefficients which allows them to penetrate easily and deeper into the solid matrix than regular liquids due to negligible surface tension and viscosity. They are suitable as a substitute for organic solvents in a range of industrial and laboratory processes. Advantages of using supercritical fluids for plastic delamination includes shorter extraction times and adjustable solvent strengths. The main disadvantages are high investment costs, and the requirement for high purity extractions and optimizations for polymers.

The MERLIN (**M**ultilay**ER** packaging recyc**LIN**g waste) project[44], funded by the Horizon 2020 program and led by ITENE (a Spanish not-for-profit research institute), is developing a delamination process using supercritical CO_2 combined with co-solvents. This process aims to separate multilayer structures without degrading the main layers, enabling the recovery of high-quality substrates for reuse in new packaging products. The project has two main goals:

1. Development of delamination processes for flexible multilayer packaging by means of selective dissolution processes using green solvents (e.g., ionic liquids, water, supercritical fluids, non-toxic liquid polymers like PEG), and flexible multilayer and adjustable hydrophobicity solvents for metallized flexible packaging.
2. Development of delamination processes for rigid multilayer packaging by depolymerization of the PET layer by solvolysis.

[43] Center for Plastics Innovation |

[44] MERLIN: Increasing the quality and rate of MultilayER packaging recycLINg waste

Hydrophobic Deep Eutectic Solvents (DES)

Hydrophobic deep eutectic solvents (DES) are a new generation of water immiscible solvents synthesized by combining a hydrogen bond acceptor and a hydrogen bond donor. They are considered biocompatible, chemically stable, biodegradable, low volatile, and non-flammable. The physicochemical properties of DES are highly tunable and can be customized to meet the needs of a particular process (Zainal-Abidin et al., 2021).

Researchers have explored the use of DES to delaminate PE/Al/PET laminates. By optimizing variables like temperature, time, and flake size, this method achieved efficient separation of layers with high yields for material and solvent recovery (Loukodimou et al., 2024). The researchers claimed delamination was more efficient when using smaller pieces (10 mm) at lower loading (30 g/L) compared to either larger pieces (up to 50 mm) or higher loadings (up to 50 g/L), or both. The introduction of perforations did not have a significant impact on the rate of delamination for PE, which is evidently dependent on the permeation of solvent through the film. In contrast, the delamination of PET from aluminium was strongly enhanced by perforations.

Thermal analysis of the recovered PE and PET films using differential scanning calorimetry and thermogravimetric analysis demonstrated that the morphology of the films was unaffected by the solvent-based process and that the films retained good thermal stability. A small amount of ~2–3% w/w of residual solvent and moisture was retained within the materials. Further scale-up and evaluation of reprocessed materials is required to assess recycled material properties and performance in detail and validate the overall quality of the products.

Solvent Swelling and Hot Water Treatment

A novel delamination process involves swelling the polymer layers with low-boiling-point solvents, followed by immersion into hot water. This process causes the solvent to release the necessary polymers, facilitating delamination. The German company Saperatec GmbH[45] is developing a procedure that uses a microemulsion containing a surfactant, swelling agents, carboxylic acids, and water to separate the layers of multilayered FPP after the shredding stage (Vagnoni et al., 2023). The process was shown to reduce the interlayer stresses between the materials, allowing for FPP comprised of PE/Aluminum, PP/Aluminum, and PE/PET to delaminate (Ügdüler et al., 2021). Saperatec plans to build a recycling plant with a capacity of approximately 17000 tons per year input.

The Australian company, PVC Separation[46], developed a similar method to delaminate multilayers by swelling the polymer layer with low-boiling point solvent first, followed by inserting it in hot water, which causes the solvent to release the necessary polymers (Vollmer et al., 2020).

3.4 FPP Recycling Summary

FPP is a vital component of commerce and everyday life and makes up almost half of all the plastics produced in Canada. FPP is notoriously difficult to recycle since they are usually contaminated with inks, soil, and organic materials, and composed of multiple polymers that results in poor quality recyclates. As this section demonstrated, there are numerous innovative processes to decontaminate, deodourize,

[45] saperatec
[46] PVC Separation

deink and delaminate. Many of these processes only work well with specific types of polymers. Thus, it is impossible as well unprofitable to employ only one or all of the available processes in a recycling facility to obtain high quality recyclates.

CEFLEX (see section 2.3.1) has developed a recycling process they believe will improve the quality of recycled plastics including flexible films during mechanical recycling as shown in Figure 11. It is integrated into existing mechanical recycling processes at Material Recovery Facilities (MRFs) with four additional steps:

1. An additional NIR-VIS sorting step
2. A hot washing step in addition to standard wet washing
3. An additional filtration step during extrusion (double-filtration)
4. Deodorisation of the finished pellets

A separation step is essential for the quality of the recycled polymer. What must be considered is that, with increasing heterogeneity of the mixture, the complexity of the separation grows. Therefore, the input should be as defined as possible, since a defined input is a prerequisite for a successful separation process later on. This means that a separate recycling stream for delaminable multilayers must be established. This scenario would require the application of new marker-based sorting technologies.

Applying solvent-based technologies for decontamination processes might be quite expensive, considering the extra capital expenditures and operating expenditures that are typically linked to such technologies. This is often not preferable in plastic recycling, given the associated typically low profit margins. Applying chemicals such as solvents and detergents on a relatively highly contaminated waste stream, comprising odorous constituents, glues, paper, inks, additives, degradation products, non-target polymers, etc., should preferably be able to remove a large range or even all of such substances to be economically viable. From this perspective, decontamination and cleaning technologies should be effective over a broad range of polymers, incorporating cleaning, deinking and deodorization in as few steps as possible. One advantage of the dissolution–precipitation method is that the FPP input does not have to run through a complex sorting scheme. The input, thus, can consist of a heterogeneous mixture of different multilayer and non-multilayer packaging systems. Additionally, the precipitated polymer can be expected to be of very high-quality, even competing with the virgin polymer. Because the dissolution–reprecipitation method has been developed for a while and pilot operations are being conduced, this method could be integrated into existing recycling systems quickly.

The biggest drawbacks of this method are the energy-intensive drying of the polymer and the fact that all polymer components that do not dissolve remain as a residue of little value. It has been shown in a study that during selective PET degradation, energy consumption for the solvent and product recovery contributes to a major part of the greenhouse gas emissions of the process (Ügdüler et al., 2020).

Plastic delamination technologies are advancing rapidly to address the recycling challenges posed by multilayered plastics. While no single method currently dominates the commercial recycling of MLPs, hybrid and solvent-assisted approaches show the most promise in terms of scalability and selectivity. Future development is focused on greener solvents, lower energy requirements, and compatibility with diverse MLP types to move these technologies toward widespread industrial adoption. Robust Life Cycle Analyses (LCA) of these new technologies should be carried out to ensure their sustainability.

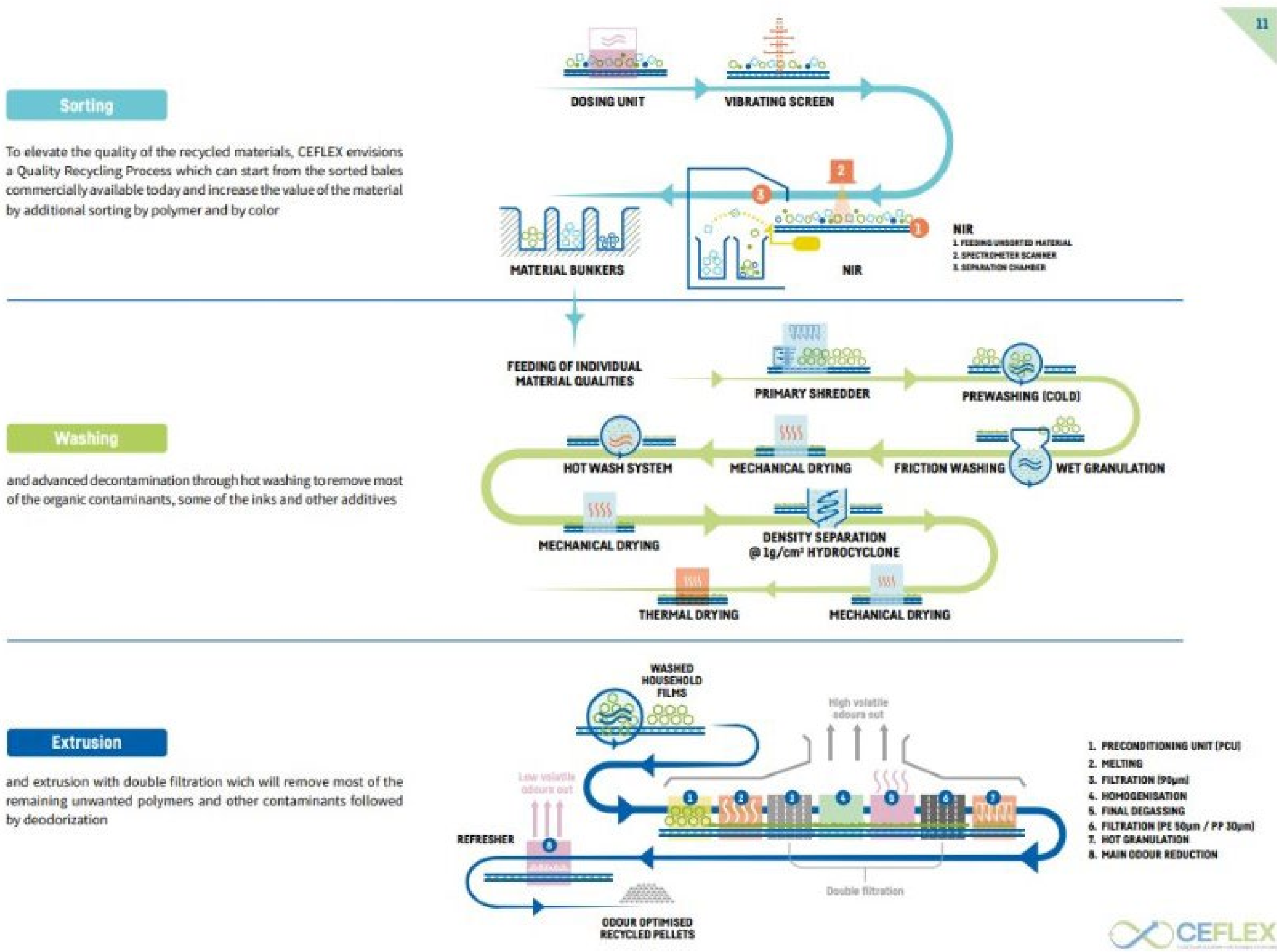

Figure 11. CEFLEX's "Quality Recycling Process"[47].

47 https://ceflex.eu/public_downloads/CEF LEX_QRP_Nov20_PUBLISHED.pdf

4.0 DESIGN FOR RECYCLABILITY: GAPS AND OPPORTUNITIES

Design for recyclability refers to a series of design ideas and methods that fully consider the end of life of a product or packaging to improve its recycling rate. This can encompass the removal of problematic elements from packaging, providing alternatives (e.g., no polyvinyl chloride, PS, and oxo-degradable components), using monomaterials and non-hazardous products or producing transparent and uncolored products. The following sections describe innovative approaches to designing plastics for enhanced recyclability.

4.1 DESIGNING MULTILAYERED PLASTICS FOR ENHANCED RECYCLABILITY

As was discussed in section 3.3, the different layers of a multilayered FPP serve important functions such as oxygen and moisture barriers. While research and development are occurring to replace these with monolayered plastics (see section 4.2), there are approaches being developed to design multilayered plastics to enhance their recyclability. Some of the easiest ways is to simplify the material composition of the FPP is to eliminate substances of concern such as PFAS (per- and polyfluoroalkyl substances)-based process aids by using multilayer coextrusion, and to reduce plastic use through paper integration using high-barrier paper-based solutions.

In multilayered plastic packaging, binders and adhesives are essential components that serve to hold various materials together, ensuring structural integrity, durability, and functionality. They are particularly important in composite materials, coatings, and films used across a wide range of packaging applications. Innovative polymer binders are being developed to enhance recyclability, barrier performance, and sustainability. An example of a commercially available sustainable binder is LOTADER®[48] manufactured by SK Functional Polymer in France. LOTADER® resins are ethylene terpolymers with reactive functions such as maleic anhydride or epoxide (glycidyl methacrylate). It can be processed on traditional extrusion equipment, making them suitable for packaging applications like food wraps. Oxygen permeability results are comparable to traditional ethylene vinyl alcohol (EVOH) high barrier film structures.

Innovations in incorporating debonding mechanisms into multilayered plastics aim to enhance their recyclability. For example, the German company Covestro[49] has developed new debonding technologies for PU-glued multi-material laminates that enable the separation of the layers in flexible packaging. In the process, a special separation agent specifically weakens the bond strength of the PU adhesive. Since the separation agent consists of natural ingredients and water, it is also very sustainable[50].

A couple of European-based research projects have looked at innovative ways to enhance separation and recycling of multilayered FPP. The first project, called TERMINUS (in-built **T**riggered **E**nzymes to **R**ecycle **M**ulti-layers an **IN**novation for **US**es in plastic packaging) used a biological approach by embedding smart enzyme polymers with triggered intrinsic self-biodegradation properties between the polymer layers. These enzyme polymers act as adhesives or tie layers but can be activated in a controlled manner to

[48] LOTADER® reactive terpolymers - SK Functional Polymer

[49] Covestro AG

[50] Debonding PU laminates | Covestro

biodegrade thus enabling the separation of the different layers of the packaging. This allows the different layers to be recycled using conventional recycling methods.

The second European project was the MANDALA project[51]. The project's overall goal was to develop new adhesives with dual functionality (i.e., easy to split and barrier properties) by incorporating thermoreversible covalent bonds and radiation absorbing nanoparticles to enhance critical barrier properties. Different thermoreversible adducts were incorporated into PU, the most widely used commercial adhesive in multilayer plastics. Packaging with this new adhesive can be treated in recycling plants to separate and obtain the different plastic components or layers. In this way, high-quality recycled materials are obtained. The thermoreversible bonds in the adhesives can be formed and broken up to 20 times without significant degradation.

4.2 MONO-MATERIAL PLASTICS

Mono-material films offer a viable solution to enhance recyclability of plastics packaging as they require no extensive and expensive delamination or separation as multilayered films do. In 2020, 21.51 million tons of mono-material flexible polymer packaging were generated with a value of $58.9 billion[52]. Due to the demand for more sustainable solutions to meet brand owner and consumer expectations, it is estimated the mono-material plastics market will grow at a CAGR of 3.8% to reach $70.9 billion in 2025, with a total of 26.03 million tons produced. Fresh food mono-material packaging will also see the most rapid increase in demand across the next five years. Other fast-growing applications for mono-material film packaging include chilled foods, frozen foods, pharmaceuticals, and medical products.

Any shifts from multilayer flexible packaging to mono-material plastics must not compromise product security or shorten its shelf life due to such variables as influx of moisture or air (Marangoni et al., 2019). For instance, several types of candy are susceptible to air and water, which causes them to get stale and lose their crunchiness (Meshram et al., 2024). Innovation is ongoing in addressing the barrier performance of mono-materials. There are currently two types of technical approaches to addressing barrier performance: functional coatings and metallized mono-materials. Functional coatings are water-based or plasma-applied coatings (e.g., barrier lacquers) to enhance oxygen/moisture barriers without the need for multi-material layering. They are also printable and offer sealability, heat resistance, and barrier protection. Metallized mono-materials can be formed by vacuuming metallized coatings onto mono-materials (like PE or PP) to offer improved barrier properties. Some processes use aluminum oxide or silicon oxide coatings as alternatives to full metallization for transparency and oxygen barrier. These coatings are generally suitable for aseptic packaging, which is necessary in the food sector for preservation, protection, and product convenience (Butler and Morris, 2016).

Machine Direction Oriented (MDO) films have been used as mono-material films due to their strength and clarity that mimic multilayer qualities. MDO films are made when a polymer film is heated to a temperature slightly below its melting point and stretched in a particular orientation[53]. Nova Chemicals has developed a new moisture barrier resin using MDO PE for barrier food packaging[54]. The oriented film

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51 Mandala Project – A sustainable Future

52 The Future of Mono-Material Plastic Packaging Film to 2025

53 What is MDO Film? An Overview of the Technology | Polythene UK

54 SURPASS® HPx267-AB Resin | NOVA Chemicals

grades are directly targeted at replacing metallized BOPP (bi-axially orientated PP) or PET-laminate non-recyclable films.

A research group recently investigated embedding nano-clays or graphene oxide into mono-materials to enhance barrier performance while maintaining recyclability (Liu et al., 2023). Nanocomposite films consist of a polymer base (e.g., PE, PP, or polylactic acid (PLA)) reinforced with nanomaterials such as nanoclays (e.g., montmorillonite, organoclays), graphene derivatives (e.g., graphene oxide, graphene nanoplatelets), metal oxides (e.g., nano zinc oxide [ZnO], titanium dioxide [TiO_2]), and cellulose nanocrystals. These nanofillers create a tortuous path that impedes gas and moisture transmission, enhancing the film's barrier properties. The main challenge with this technology is achieving uniform dispersion of nanomaterials within the polymer matrix for consistent performance. Other challenges include cost as nanocomposite films can be more expensive than other composite films to produce, as well as ensuring that nanocomposite materials meet food safety and environmental regulations.

4.3 Designing Inks and Labels for Recyclability

4.3.1 Inks

Since deinking FPP and other plastics waste is very critical for obtaining high quality recyclate, designing new and innovative inks for enhanced recyclability is being targeted. Some best practices[55] regarding ink selection and usage for maximum recyclability include:

- The ink used for printing should be 5% or less of the total weight of the packaging.
- Inks should be composed of ingredients that are unlikely to thermally decompose and create technical problems during recycling such as the generation of corrosive materials or gases and other chemicals that downgrade the quality of the recyclate such as discolouration.
- Inks should be “non-bleeding”, i.e. no noticeable discolouration of washing waters during recycling or of recyclate flakes after drying.
- Use surface printing rather than analogue printing – where an ink layer for the full decoration of the packaging is embedded between two thin layers of the packaging substrate, and which can be very difficult to de-ink. Placing the ink on top of the substrate, i.e., surface printing, using digital printing technologies, increases the likelihood that the ink can be removed, thereby increasing the value of the recycled material.

Examples of novel ink formulations include colorants extracted from algae (Living Ink, US[56]) and vegetable oil-based inks that replace conventional mineral-oil carriers (Domino Printing Sciences, US[57]). The French company Arkema[58] has recently developed a patent pending deinking technology that involves imbedding ink polymers into the plastic product that can then loosen the plastic polymer network upon alkaline washing. Arkema’s Sartomer® hydrolysable acrylate is a low viscosity oligomer containing breakable bonds that allows for better alkaline washing efficiency. It is targeted for use in UV-cured thermosets that are traditionally not recyclable (Figure 12).

[55] https://www.sustainableplastics.com/news/flexible-packaging-and-recyclability-ongoing-challenge

[56] Living Ink Technologies

[57] Industrial Printers, Coders and Markers

[58] Home | Arkema Global

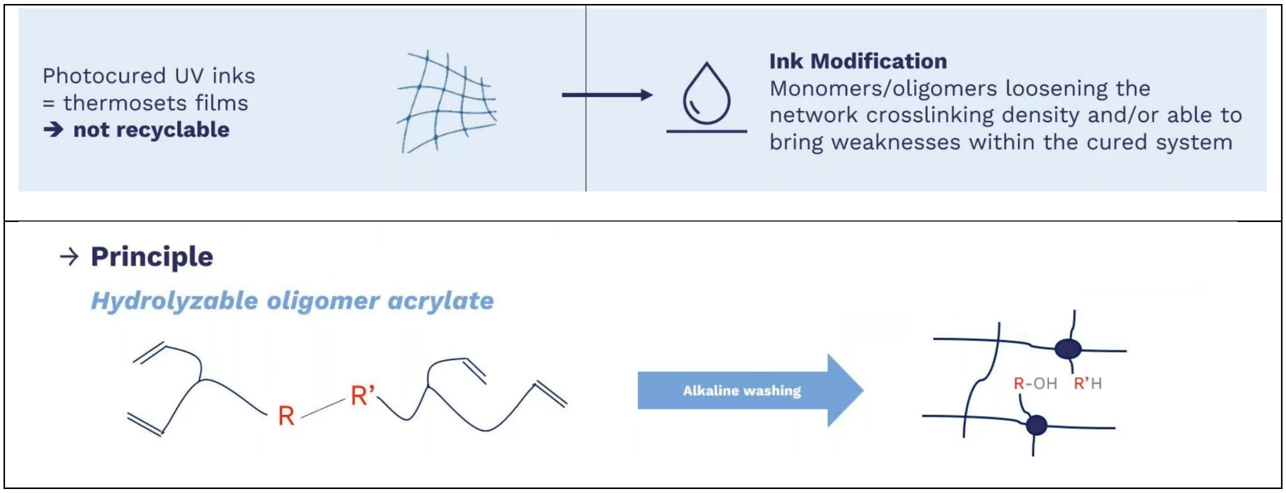


Figure 12. Arkema's Sartomer® hydrolysable acrylate deinking technology[59].

4.3.2 Labels

Canada's Plastic Pact in collaboration with the Ellen MacArthur Foundation released guidelines[60] for labels used on rigid HDPE and PP packaging to enhance recyclability and reduce waste:

- Ensure material choice, adhesive choice, inks and size are not problematic for recycling
- For closures, ensure material choice, liners and seals are not problematic for recycling
- Phase-out of paper labels and PET, polyethylene terephthalate glycol (PETG), polylactic acid (PLA) and polyvinyl chloride (PVC) labels/sleeves; and non-water soluble/dispersible adhesives.
- Labels/sleeves should not lead to misdetection of the packaging and misdirection to waste. For in-mold labelling use only polyolefins

Examples of recyclable labels include Labelcrafts's Enviroliner[61] which features a 100% recycled paper liner with a proprietary release agent, allowing curbside recycling and eliminating traditional silicone coatings, and Elk Packaging's[62] wash-off pressure-sensitive labels. These labels facilitate the recycling of PET containers by separating cleanly during the recycling process, maintaining both performance and aesthetics. Revolution Label[63] offers labels made from materials that are compostable or biodegradable, catering to various industries seeking sustainable packaging solutions

4.4 ALTERNATE POLYMERS OR MIMICS

Polymer mimics are synthetic polymers engineered to replicate the desirable properties of conventional PE such as flexibility, strength, and crystallinity, but with enhancements broadening their applications from packaging to medical devices. One of the main benefits of polymer mimics in terms of recyclability are that certain PE mimics incorporate biodegradable components, allowing them to decompose more

[59] https://sartomer.arkema.com/en/webzine/post/sartomer/webinars/de-inking-technology/
[60] https://goldendesignrules.plasticspact.ca/rules/increase-recycling-value-in-rigid-hdpe-and-pp/
[61] labelcraft.com+1labelcraft.com+1revolutionlabel.ca+1revolutionlabel.ca+1
[62] elkpackaging.com
[63] revolutionlabel.ca+2revolutionlabel.ca+2revolutionlabel.ca+2

readily in the environment or down to their monomeric forms in controlled recycling processes as briefly described in the following four examples.

Functionalized Polyethylene Mimics via Ring-Opening Metathesis Polymerization and Thiol–Ene Chemistry (Li et al., 2025)

A model system to explore mimics of functionalized HDPE and LDPE using **r**ing-**o**pening **m**etathesis **p**olymerization, or ROMP, combined with thiol–ene click chemistry was developed by researchers at the University of South Carolina and Clemson University. Metathesis reactions occur when two compounds exchange ions whereas the thiol-ene reaction is an organic reaction between a thiol (R−SH) and an alkene ($R_2C=CR_2$) to form a thioether (R−S−R'). Click chemistry is an approach to chemical synthesis that emphasizes efficiency, simplicity, selectivity, and modularity in chemical processes used to join molecular building blocks. It includes both the development and use of "click reactions", a set of simple, biocompatible chemical reactions that meet specific criteria like high yield, fast reaction rates, and minimal byproducts. By adjusting the ester-to-methylene and branch-to-methylene ratios, the researchers achieved tunable mechanical properties and crystallinity. Notably, the PE mimics could be degraded into oligomers and recycled, demonstrating potential for circularity and sustainability.

Long-Chain Polyorthoesters (Haider et al., 2019)

Another research group using the ROMP approach synthesized degradable PE mimics containing ortho ester groups through olefin metathesis polymerization (ortho esters is a functional group containing three alkoxy groups attached to one carbon atom). These materials exhibited semicrystalline structures similar to PE and could be hydrolyzed under ambient conditions over several months. Additionally, non-hydrogenated copolymers with high orthoester content were shown to be biodegraded by microorganisms from activated sludge within several months, indicating potential for environmental degradation. The authors suggested that these materials may find use in applications that require the relatively rapid release of packaging, e.g., in biomedicine or nanomaterials.

Aliphatic Long-Chain Polypyrophosphates (Tee et al., 2019)

Biodegradable aliphatic polypyrophosphate PE mimics have been developed by Tee et al., (2019). These materials exhibited fast hydrolysis rates under mild conditions and could be further degraded by microorganisms in activated sludge. The readily cleavable pyrophosphate groups introduced into the polymer backbone enabled rapid degradation, making them suitable for applications requiring quick dissolution, such as biomedical or packaging uses.

A Closed-Loop Recyclable Low-Density PE (Unger et al., 2024)

Coordinative chain transfer polymerization (Kempe, 2007), or CCTP, a synthesis protocol that permits the controlled and efficient polymerization of ethylene and related monomers (Valente et al., 2013) and very high catalyst economy (Goller et al., 2023), was used to synthesize tailor-made macromonomers to structurally mimic LDPE. The authors used low-pressure (2 bars) and -temperature (70 °C) macromonomer-based synthesis to generate long chain branched PE. The long chain branched PE material had similar key properties as regular LDPE. The introduction of recycle points (ester linkages) permitted grafting and degrafting of the macromonomers via acidic esterification and basic saponification (Figure 13). The two components (backbone and branch) are low molecular weight macromonomers, which are well soluble in a variety of organic solvents for separation from other polymers such as HDPE or PP. The CCTP of ethylene and co-monomers can be used for the synthesis of the functionalized macromonomers permitting a high flexibility of their precise structure and economic or efficient synthesis.

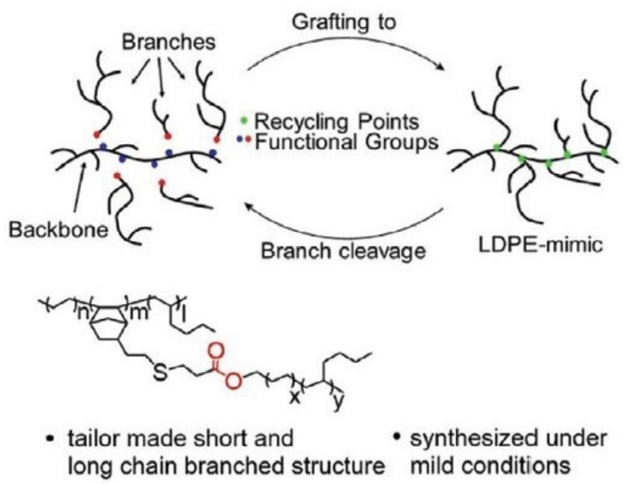


Figure 13. Structural and functional low-density polyethylene (LDPE) mimic with introduced recycling points (Unger et al., 2024).

4.5 ARTIFICIAL INTELLIGENCE (AI)-GENERATED POLYMERS

AI-generated polymers are synthetic materials whose chemical structure, properties, or production methods have been discovered, predicted, or optimized using AI and machine learning (ML) models. These models learn from huge datasets of known polymers and their properties to design new ones that meet desired specifications. Among the numerous benefits of using AI in polymer discovery and development include the prediction of the mechanical, thermal, electrical, and optical properties of polymers before they are synthesized, saving time and money. AI can also assist in running simulations, such as molecular dynamics, faster or more accurately, and for optimizing polymer synthesis routes for scalability or environmental sustainability.

AI is being increasingly used to design biodegradable plastics that decompose more safely in the environment as well as recyclable polymers with easier breakdown or upcycling pathways. There are still regulatory and safety hurdles that need to be addressed with AI-generated polymers. Synthesis and testing still need to be carried out, as in-silico generation and testing does not provide the real-world validation still required for regulations.

Examples of companies using AI and ML to generate novel, circular polymers include:

- **Schrödinger[64] & BASF:** The two companies collaborated to use AI to discover novel polymers for applications in coatings, packaging, and electronics.

[64] Materials science - Schrödinger

- **TNO[65] (Netherlands):** TNO offers a custom platform for polymer design called polySCOUT (Figure 14) that aids in the discovery of sustainable renewable materials. The platform has helped Senbis (Netherlands) develop a biodegradable polyester for textile fibres that also mitigates microplastics production.

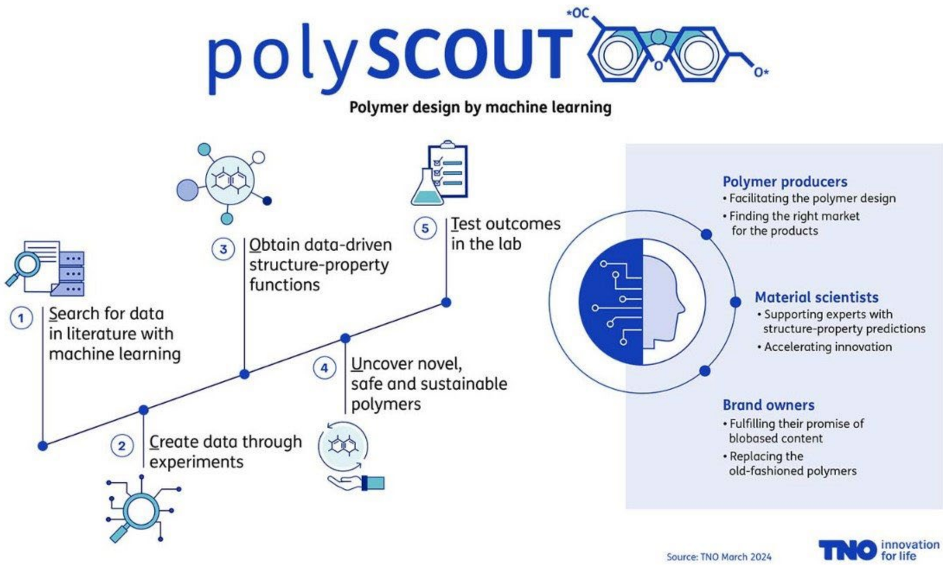


Figure 14. Schematic of PolySCOUT polymer design machine learning by TNO.

- **Matmerize**[66] (USA) developed a material design AI platform called PolymRize™ (Figure 15). South Korean biopolymer producer CJ Biomaterials tested PolymRize™ to optimise their newly designed biobased polymers. Asahi Kasei Corporation aims to use PolymRize™ to accelerate research and development in sustainable polymers, including biodegradable textiles.

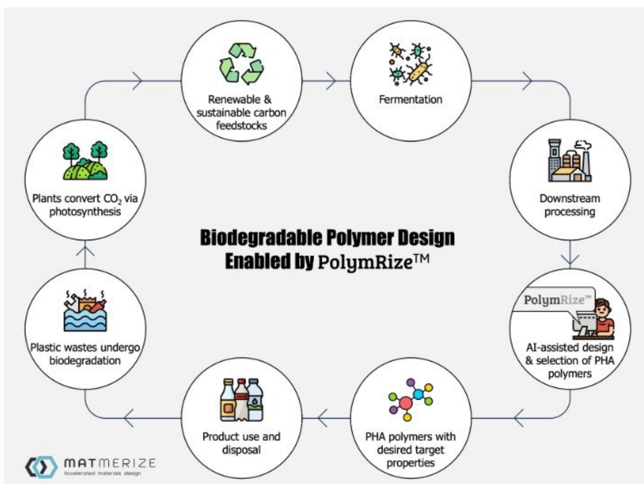


Figure 15. Schematic diagram of the PolymRize™ biodegradable polymer design method developed by Matmerize.

65 PolySCOUT - TNO Ventures

66 Matmerize - Accelerated Polymer Design Powered by AI / Polymer Informatics / Polymer AI Software

An alternative material to PS that could be chemically recycled was recently developed (Atasi et al., 2024). The researchers used an AI-guided approach to design durable and chemically recyclable ring-opening polymerization (ROP) class polymers. ROP polymers have significant potential for chemical recycling into monomers. A genetic algorithm (GA) that designs new monomers and then utilizes virtual forward synthesis was used to generate almost a million ROP polymers (Figure 16). Machine learning models were used to predict thermal, thermodynamic, and mechanical properties helped guide the GA toward designing optimal polymers (Atasi et al., 2024).

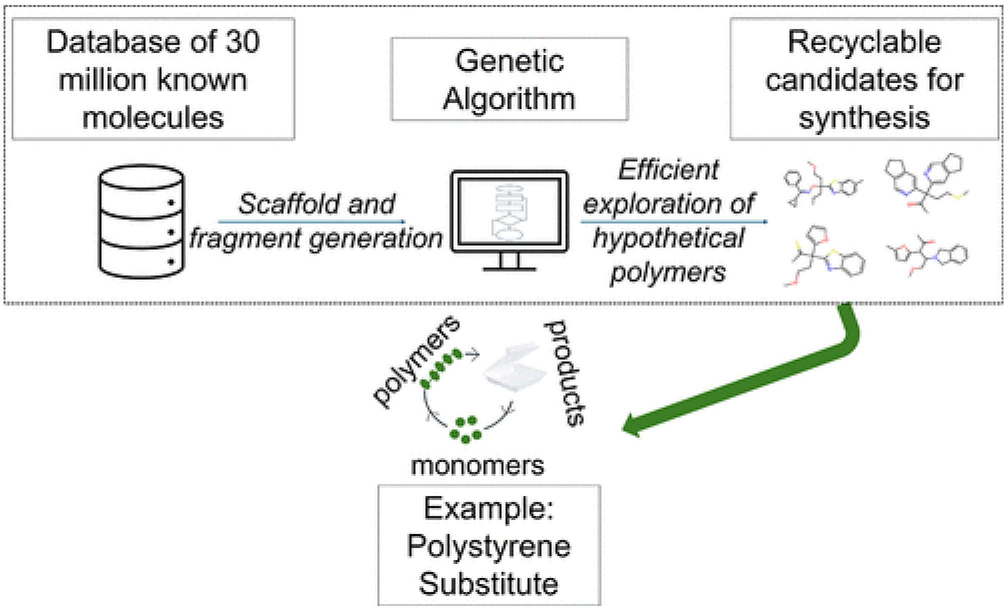


Figure 16. Schematic diagram of using a genetic algorithm to design new recyclable polymers (Atasi, 2024).

Over 7500 potential substitute polymers that exhibited the requisite thermal, mechanical, and thermodynamic properties necessary for serving as recyclable alternatives to PS were identified using the GA and ML. One significant limitation of this method was that while the monomer-to-polymer reaction was well-defined, the monomer synthesis pathway remained unclear. To address this, future efforts will try to leverage retrosynthesis planning tools or integrating established reaction pathways for designing and functionalizing monomers into the GA (Atasi et al., 2024).

Chen et al. (2024) used an integrated workflow that combined robotics and machine learning to accelerate the discovery of all-natural plastic substitutes with programmable optical, thermal and mechanical properties (Figure 17). In this study, an automated pipetting robot was programmed to prepare 286 nanocomposite films with various properties and to train a support-vector machine classifier. Next, through 14 active learning loops with data augmentation, 135 all-natural nanocomposites were fabricated stagewise, establishing an artificial neural network prediction model. The study demonstrated that the prediction model could conduct a two-way design task: (1) predicting the physicochemical properties of an all-natural nanocomposite from its composition and (2) automating the inverse design of biodegradable plastic substitutes that fulfils various user-specific requirements. Several all-natural substitutes, that could replace non-biodegradable counterparts as exhibiting analogous properties were thus prepared.

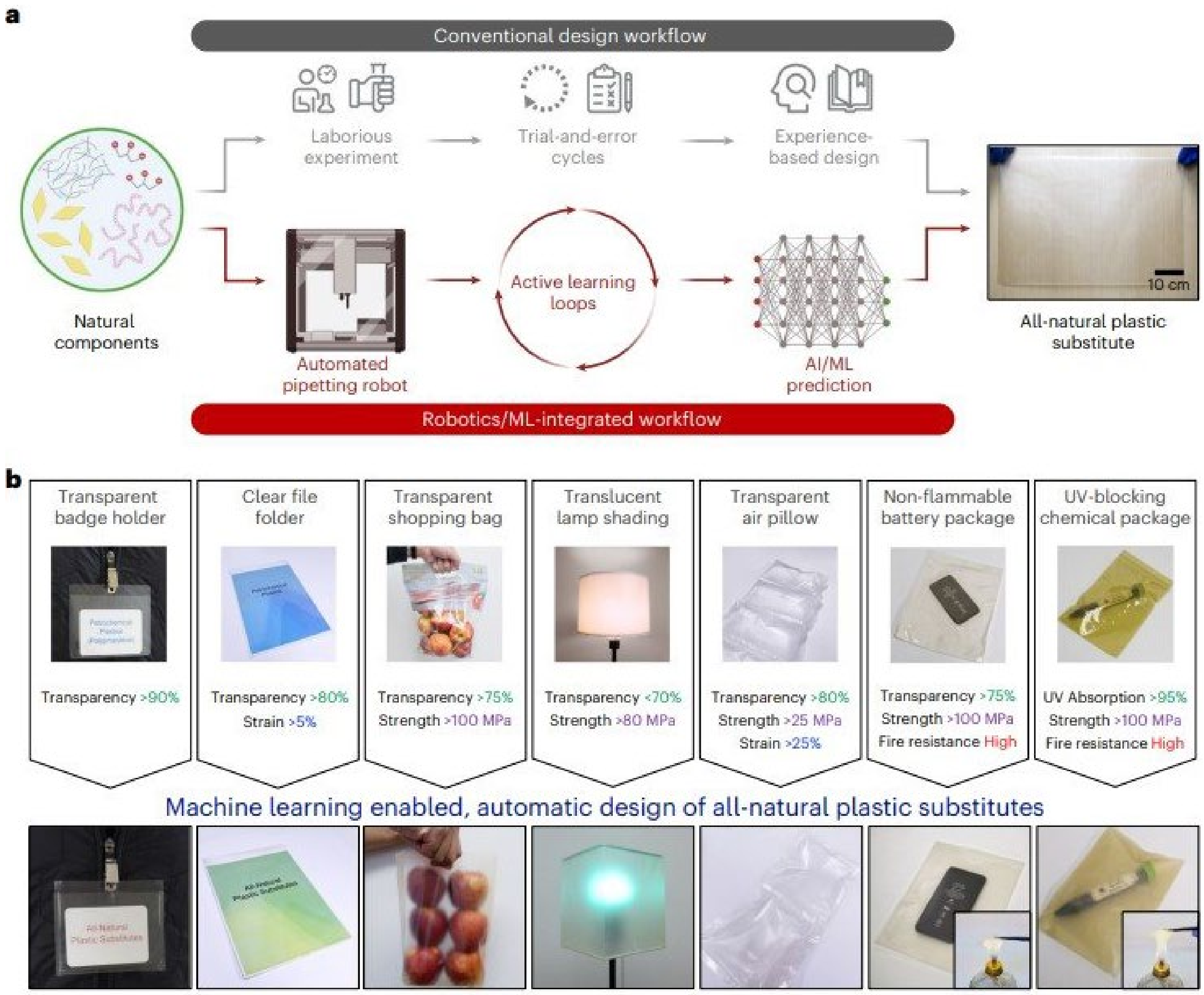


Figure 17. Machine intelligence-accelerated discovery of all-natural plastic substitutes with programmable properties (Chen et al., 2024).

Integrated workflow using robotics and AI/ML predictions to construct a high-accuracy prediction model. Pictures of non-biodegradable plastic products and their property criteria (top row) and biodegradable, all-natural substitutes suggested by the prediction model (bottom row).

There are several ongoing challenges and limitations associated with the AI/ML-integrated workflow for the accelerated design of all-natural plastic substitutes (Chen et al. 2024):

- No available collaborative robotics systems can automate the entire preparation and characterization processes for all-natural nanocomposites. Therefore, manual operations are still required to connect each stage for sample preparation and/or characterization. When more building blocks and structural/chemical features are included, the time and manpower needed for constructing an accurate AI/ML model will be inflated without robot-automated experimentation.

- The quality of natural building blocks may vary from batch to batch. Therefore, stringent quality controls for each building block are crucial, especially for large-scale production and manufacturing.
- Data fusion with cost analyses and life cycle analyses into the champion model would be highly beneficial, allowing for identifying the optimal all-natural plastic substitutes that meet desired properties as well as provide the benefits of cost saving and environmental impact reduction.
- The end-of-life processing of all-natural plastic substitutes has not been considered, which could be converted into biofuels or other valuable chemicals.

4.6 BIO-BASED BIODEGRADABLE PLASTICS

One of the many possible solutions to alleviating plastic waste is the development and production of bioplastics (i.e., biodegradable plastics and bio-based plastics) that can be degraded biologically in both controlled settings such as composting facilities (Samir et al., 2022) or when discarded in the environment. More and more biodegradable and compostable polymers are being produced to replace conventional non-biological based polymers. Indeed, the bioplastics market in Canada is expected to reach a projected revenue of US$ 870.0 million by 2030 with a compound annual growth rate of 18.7% from 2024 to 2030[67].

The ever-increasing production and consumption of bioplastics requires a large-scale processing scheme such as high-heat industrial composting facilities that only a few cities have (Zimmerman, et al., 2020). Additionally, most material recycling facilities (MRFs) do not accept these plastics as they are often contaminated with organic matter. This means that a large amount of bioplastic go to landfills and incinerators, or enter the environment (Narancic and O'Connor, 2019). Other issues related to bioplastics end-of-life and, more specifically, to their biodegradability in natural and industrial environments are described below.

4.6.1 Uncertainties Around the Biodegradability of Bioplastics

Biodegradation of bioplastics depend on the complexity of the chemical structure (e.g., functional groups such as –COO–, –OH, and –COOH) and the crystallinity of polymers. Research has shown that most biodegradable plastics can be biodegraded under specific (i.e., ideal) conditions but less is known of their biodegradability under natural conditions. (Morohoshi et al., 2018; Napper and Thompson, 2019; Nazareth et al., 2019). The current biodegradation standards and test methods are insufficient to predict the biodegradability of bioplastics in the natural environment (Zhu and Wang, 2020).

4.6.2 Confusion over Terminology and Labelling

The word bioplastics does not have a standardized definition and is often used to refer to plastic that is either bio-based, biodegradable or compostable and can even include up to 80% fossil fuel-based plastic[68]. Several different definitions of a biodegradable and/or compostable plastic exist that mean different things. The American Society for Testing and Materials (ASTM), defines bio-based plastic as ”a plastic containing organic carbon of renewable origin such as agricultural, plant, animal, fungi, microorganisms, marine, or forestry materials living in a natural environment in equilibrium with the atmosphere”, while biodegradable plastic is ”a degradable plastic in which the degradation results from the action of naturally-

[67] https://www.grandviewresearch.com/horizon/outlook/biodegradable-plastic-market/canada
[68] https://www.beyondplastics.org/fact-sheets/bad-news-about-bioplastics

occurring microorganisms such as bacteria, fungi, and algae" (Pires et al., 2022). This definition of biodegradable polymer encompasses a broad spectrum, from partially to completely biodegradable polymers (Albright and Chai, 2021). The European Bioplastics Association identifies bioplastics as a diverse family of materials, which can be bio-based, biodegradable, or both[69]. A compostable plastic is a type of biodegradable plastic which breaks down in specific composting conditions (e.g. home or industrial composting facilities) into biomass, organic and inorganic compounds, CO_2 and water[70].

These different definitions can lead to confusion around recycling and end-of-life options for bioplastics. It can also lead to greenwashing by plastic producers, as claims of biodegradability may not actually be true. For this report, the term "bioplastic" was used to represent materials that are bio-based, biodegradable or both.

4.6.3 Unintended Consequences of Bio-Polymers Degradation

Many existing standards and test methods for the biodegradability of bioplastics in different environments do not involve toxicity tests, nor do they consider the potentially adverse ecological effects of bioplastics or micro bioplastics particles that may be produced by crushing and weathering. The health and environmental impacts of micro(nano) plastics (MNPs) from the partial and/or incomplete breakdown of plastics in the environment are becoming increasingly known. These include accumulation within the digestive tract or filtering system of small animals, causing blockage and damage to the proper functioning of their organs and the adsorption of pathogens and chemicals, becoming transporters of persistent organic pollutants (POPs) into animal tissues at concentrations higher than those usually found in the environment (Bertocchini and Arias, 2023). Bioplastics, if not fully biodegradable, can also generate MNPs.

Furthermore, although bioplastics use a "natural" feedstock (such as corn or sugar beets) as compared to conventional, petroleum-based plastics, most still have additives such as plasticizers, stabilizers, flame retardants, biocides, and antioxidants to ensure the end product contains certain plastic-like characteristics and achieve industrial functionality. A recent study on the toxicity and chemical composition of bioplastics (Zimmermann et al., 2020) determined that:

- Most bioplastics and plant-based materials contain toxic chemicals.
- Cellulose and starch-based products induced the strongest *in vitro* toxicity response.
- Most samples contain more than 1,000 chemical features; the maximum found was 20,000 features.
- Bio-based/biodegradable plastics and conventional plastics are similarly toxic.

Some composting facilities do not accept bioplastics and compostable foodware due to a variety of reasons such as the items not composting fast enough or the presence of toxic chemicals like PFAs (pre and polyfluroalkyl substances). There is often conventional plastic mixed in with compostable foodware due to confusion around what is compost-accepting food packaging and service ware. This results in a lot of unwanted, non biodegradable items getting tossed in with actual compostable plastic causing them to be sent to the landfill or incinerator.

[69]https://www.european-bioplastics.org/bioplastics/

[70]https://www.rsc.org/globalassets/22-new-perspectives/sustainability/progressive-plastics/explainers/rsc-explainer-2---compostable-and-biodegradable-plastics.pdf

Based on these concerns around bioplastics, it is imperative to ensure there are adequate and reliable biodegradation testing standards to provide consumers confidence that the bioplastic is truly biodegradable under a variety of environmental conditions and to avoid “green washing” by polymer-producing companies.

4.7 DESIGNING PLASTICS FOR RECYCLABILITY SUMMARY

Designing plastics for enhanced recyclability is a strategic opportunity for building a more circular economy. The way plastic is formulated and integrated into products greatly impacts how easily it can be recovered and reused at the end of its life.

There are several challenges and hurdles to designing for recyclability including ensuring material performance (e.g., durability, heat resistance, or flexibility) is not compromised and reducing risk of contamination from incompatible materials and polymers. Other than Golden Design recommendations, there is also no standard regulation for designing recyclable plastics, leading to inconsistencies across manufacturers and sectors. Overshadowing all these challenges is the fact that virgin plastic is still cheaper than recycled alternatives, reducing financial incentives for recyclable design.

Design for recyclability approach is best applied to niche plastics that require very specific function and applications such as the contact of food or in medical applications. Re-designing plastic whether through traditional chemistry or through AI/ML is an expensive endeavor considering the mass production of polyolefin-based plastics. Thus, these new plastics should target high-end applications – but also ensure they can be easily integrated into existing MRFs or dissolve/biodegrade rapidly in the environment with no negative impacts. An easy target is redesigning inks that can be easily incorporated into various plastics and that are easily removed or degraded at end-of-life.

As with new recycling technologies, new designs for recyclability approaches and technologies should undergo a complete LCA to ensure their cost-effectiveness and sustainability.

5.0 RECYCLING PLASTIC FROM ELECTRONIC WASTE: GAPS AND OPPORTUNITIES

5.1 BACKGROUND INFORMATION ON PLASTICS IN ELECTRONIC WASTE

5.1.1 Types of Plastics used in Electronics

Electronic waste, or e-waste, comprises everything containing an electrical cord: from large household appliances, personal computers (e.g., circuit boards, waste computer casing, waste keyboard keys, electronic display housing plastic, and random-access memory), monitors, laptops, to consumer equipment. The global generation of e-waste was approximately 53.6 million tons in 2019, and it is expected to reach 74 million tons by 2030 (Elgarahy et al., 2024).

E-waste is mainly composed of metals such as copper, gold, silver, palladium, aluminum, and iron (60% of all material), plastics (15%), and metal-plastic mixtures (5%) (Elgarahy et al., 2024). Plastics in electronics are used as connectors, switches, coil formers, relays, capacitors and resistors. Almost all engineering thermoplastics (a group of plastic materials that have better mechanical or thermal properties than the more widely used commodity plastics (such as PS, PVC, PP and PE) are used in some form of electronics component, but standard nylons (polyamides) and thermoplastic polyesters (typically polybutylene terephthalate) are the two most common polymer families (Figure 18). This is particularly true among connectors, which make up the majority of the market for electronic components.

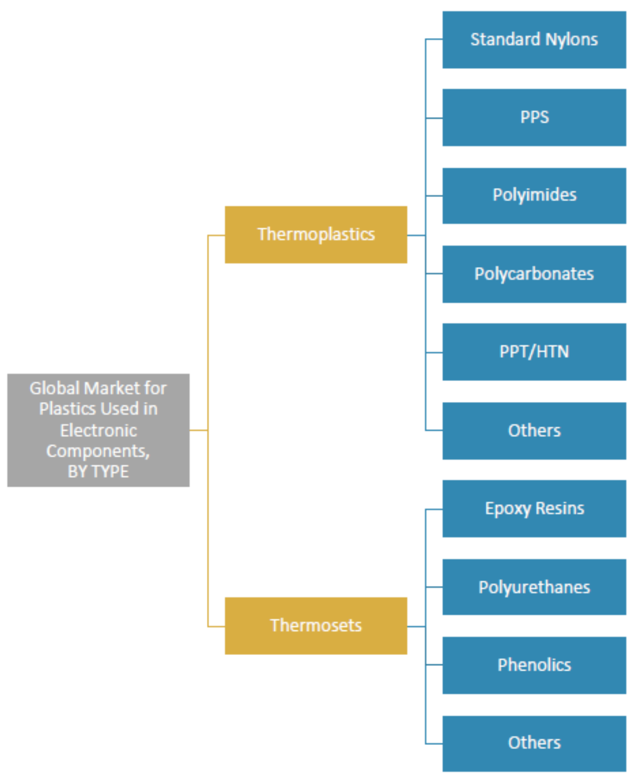


Figure 18. Types of plastics used in electronic components (BBC Research, 2023).

PPS, polyphenylene sulfide. PPT/HTN (high temperature nylon) is a range of materials based on polyphthalamide semi-aromatic nylons.

Even though the average size of each plastic component used in electronics continues to shrink and wall thicknesses are reduced due to advancements in polymer processability and end-use performance, the consumption of engineering thermoplastics in electronics is rising. Indeed, with a CAGR of 5.5%, the global market for plastics in electronic components are forecasted to increase in size from $7.9 billion in 2022 to $10.3 billion in 2027[71].

5.1.2 Current Recycling Practices and Challenges of E-Waste Plastic

Currently, less than 20% of all e-waste is recycled[72]. This low fraction can be attributed to the economic infeasibility of current processes to effectively produce high quality material for end-use markets. Mechanical recycling (e.g., sorting, shredding, and melt processing) is a widely used method to recycle e-waste (Riise, 2020). However, the process cannot handle mixed plastics or remove hazardous additives such as flame retardants or pollutants (e.g., ceramics and metals from printed circuit boards) (Hopewell et al., 2009). The sorting costs associated with separating out the metals and polymers are too high for the process to be economically viable for companies to adopt (Kang and Schoenung, 2006). In terms of process economic viability, it is acknowledged that the value of metals is much higher than the polymers (Anderson et al., 2021, and Sahajwalla and Gaikwad, 2018). Moreover, plastics containing certain additives like brominated flame retardants at concentrations above set values cannot be used in new products due to regulations and consumer concerns (Anderson et al., 2021).

Flame retardants are additives such as alumina trihydrate, antimony oxides, and halogenated compounds, used in plastics to increase the thermal stability of flammable materials (Anderson et al., 2021). In the electronics market, flame retardants are used in key electrical and electronic components such as electronic housings, cables, connectors, and switches. More specifically, phosphorus and brominated flame retardants (BFRs) are often used in plastic components in and around electronics. These flame retardants have been found to be toxic and highly persistent in the environment when released (Evangelopoulos et al., 2019). Therefore, effective recycling technologies should be developed to prevent the future release of flame retardants into the environment (Anderson et al., 2021). The processing of plastics containing certain types of BFRs and/or persistent organic pollutants (POP) is governed by the Stockholm convention[73]. In general, the guidelines from the Stockholm convention state that the recycling or final disposal of articles containing BFRs and/or POPs covered under convention is to be carried out in an environmentally sound manner and should not lead to the recovery of the BFRs or POPs for reuse (Sahajwalla and Gaikwad, 2018).

Whole plastic from single sources such as the disassembly of televisions or cathode ray tubes are the easiest to recycle. Since most of these plastics are clearly labeled and still whole when segregated, they are easy to sort, though the danger of flame retardant-contaminated products remains. Most plastics recycling lines use four complicated, capital-intensive processes: float sink, granulation, electrostatic separation and palletization. Quantum Lifecycle Partners[74] are the major e-waste recycling company in

[71] The Challenges of Recycling Plastic - Quantum | ITAD & E-Waste Recycling
[72] Electronic waste (e-waste)
[73] Stockholm Convention - Home page
[74] Quantum - Electronics Recycling, Enhanced Data Destruction and ITAD

Canada. At Quantum, the shredder line accepts more than half the company's overall volume of processed recyclables. It mechanically breaks apart products for sorting and co-mingled plastics emerge from the shredder in a single stream. Solvent extraction pre-treatment is used to remove BFRs not chemically linked to the polymer chain, while thermal degradation can eliminate chemically linked bromine in polymers (Pivnenko, 2017).

5.2 INNOVATIVE RECYCLING TECHNOLOGIES

5.2.1 Pyrolysis Technology

One of the most extensively researched methods of chemical recycling is pyrolysis (Xayachak et al., 2022). It is based on decomposing long-chain polymers into smaller molecules in an oxygen-free atmosphere. These molecules are then converted into high-value products (Elgarahy et al., 2024), for plastic waste these include oil, char, and syngas, which can be utilized as a source of energy or a chemical feedstock.

Thermochemical conversion is also used to convert the plastic fractions of e-waste into energy or fuels. However, it typically requires high temperatures and results in products that if remanufactured into their original state are of lower quality and value (i.e., down-cycling) than the products made from virgin material (Chandrasekaran et al., 2018).

5.2.2 Supercritical Fluid Technology

Supercritical fluids are considered an appealing and viable solution for processing e-waste plastic since it provides quick kinetics, a rapid rate of reaction, and an effective yield (Li and Xu, 2019). Supercritical water has been used to decompose epoxy resin from integrated circuit waste based on a complex free radical reaction. The process resulted in a high decomposition efficiency (95.5 %) of epoxy resin, releasing H_2O, CO_2, and phenol as products (Li et al., 2019). Additionally, supercritical CO_2 was used for effective extraction of bromine and chlorine from electronic display housing plastic containing BFRs and chlorine (Zhang and Zhang, 2020). Similarly, debromination was followed for extracting the BFR compound, tetrabromobisphenol A, from e-waste containing acrylonitrile butadiene styrene (ABS) using supercritical ethanol (Gripon et al., 2021), and the depolymerization of PVC from PCB and Random-Access Memory wastes by supercritical water and methanol have been conducted (Preetam et al., 2022). The depolymerization of ABS and dechlorination of PVC from electrical appliances were achieved using supercritical CO_2 (Zhang et al., 2023).

5.2.3 Dissolution-Precipitation Technology

To preserve the polymeric structure of plastics used in electronics, dissolution-precipitation, which involves dissolving a polymer in a solvent and then reclaiming it through precipitation (either by cooling, evaporation of solvent, or addition of anti-solvent/non-solvent as described in Section 3.3.2.1), has been explored (Achilias et al., 2007, Ügdüler et al., 2020). In general, dissolution-precipitation is applicable to a wide variety of polymers and can preserve the high molecular-weight compounds from plastic waste (Ügdüler et al., 2020).

A study by Anderson et al. (2022) demonstrated the potential of a solvent-based dissolution-precipitation process to simultaneously recover and purify the plastic fraction from e-waste (Figure 19).

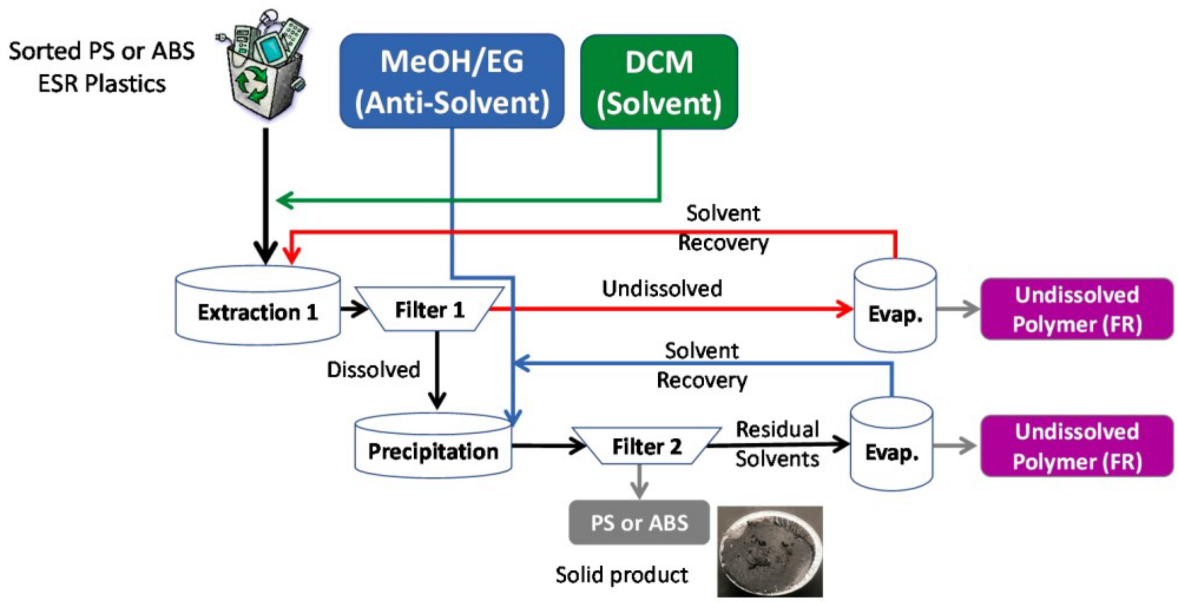


Figure 19. The dissolution-precipitation process used for recovering polymers and removing flame retardants from electronic shredder residue, ESR (Anderson et al., 2022).

In this process, pre-sorted PS or ABS and electronic shredder residue (ESR) plastics with all the metal components removed are put through a series of dissolution and precipitation steps. The pre-sorted heterogeneous ESR feedstock collected by an e-waste recycling facility was analyzed and found to contain 25 wt.% plastics. Using Fourier transform infrared spectroscopy, PS (40 wt%), ABS (25 wt%), and styrene-acrylonitrile (SAN, 9 wt%) were identified as the major components within the plastic fraction (Figure 20).

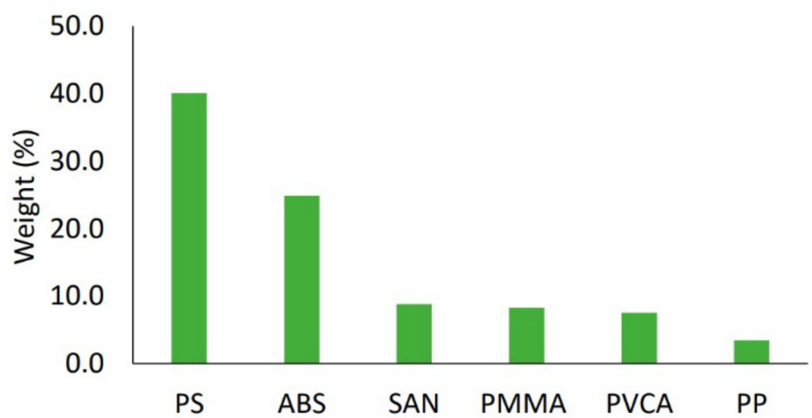
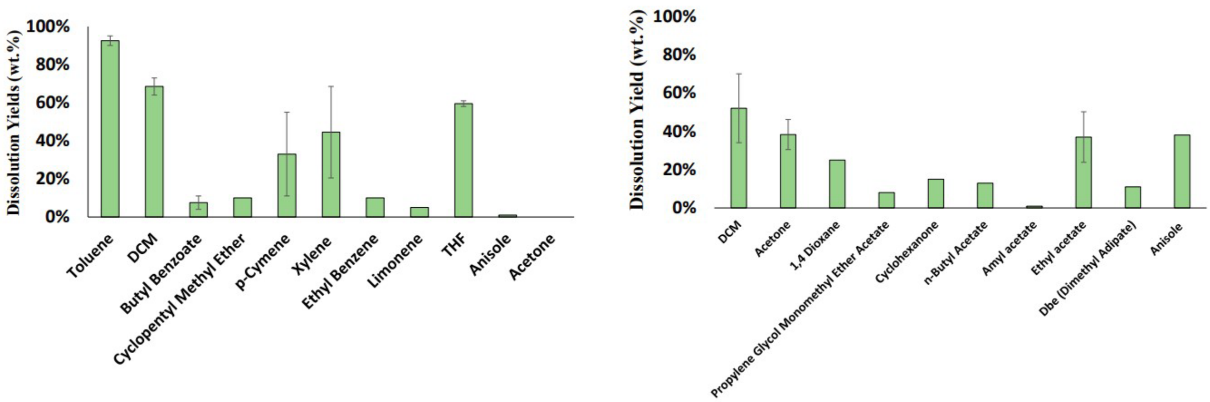


Figure 20. The weight percentage of different plastics found in the ESR plastic waste used in the Anderson et al., 2022 study.

PS, polystyrene; ABS, acrylonitrile butadiene styrene; SAN, styrene acrylonitrile; PMMA, poly(methyl methacrylate); PVCA, polyvinyl chloride acetate; PP, polypropylene.

The researchers demonstrated that methylene chloride (dichloromethane, DCM) and tetrahydrofuran (THF) could dissolve the most PS and ABS, while methanol (MeOH) could precipitate the most PS and ABS (Figure 21). By optimizing the dissolution time and the solvents used, the highest polymer dissolution yield

(99 wt.%) was achieved by using DCM for 48 h. Both MeOH and ethylene glycol showed a precipitation yield of 71 wt.%.



(a) (b)

Figure 21. Dissolution yield of sorted plastics from ESR: (a) dissolution yield of PS-based plastics and (b) dissolution yield of ABS-based plastics.

Ethylene glycol had the highest phosphorus-containing flame retardant removal rate (up to 98%). Subsequent characterization showed that the proposed solvent-based processing could preserve the high molecular weight fraction of the polymers and effectively remove flame retardants. The energy analysis indicated that the proposed solvent-based processes could save 60% of the embodied energy used to manufacture electronics plastics. This research proved the potential of solvent-based processing to produce secondary materials recovered from e-waste for cross-industry reuse. Using the solvent-based recycling process, a recycler obtains the value of the plastics and a more-concentrated mixture of metals for refining.

5.2.4 Examples of Companies Recycling E-Waste Plastic

There are numerous e-waste recyclers in Canada, including Quantum Life Cycle as already mentioned, but very few recyclers indicate on their websites that they also recover and recycle the e-waste plastics. Two Canadian companies that do are GreeNovel and Excir. GreeNovel[75] (Quebec) has developed a microwave-based prototype that selectively heats and breaks down non-recyclable (i.e., contaminated) plastics, enabling them to be extracted more efficiently. The company is also conducting research on recycling the non-contaminated plastic in electronic waste. Excir[76] (Calgary) developed a process to quickly, safely and selectively extract precious metals from e-waste. They are also developing patented technology that will be used to transform separate e-waste into three streams: precious metals, base metals, and plastics.

Stena Recycling[77] (Sweden) recycles plastic from hundreds of thousands of tons of electronic waste. The company uses a sink-float technology to separate out the pure plastic that is recirculated to plastic manufacturers and can become new products while the contaminated plastic containing BFRs, chlorine and other dangerous substances are incinerated under safe conditions. The contaminated part of the plastic still contains a significant amount of pure plastic that cannot be extracted with sink-float

[75] GreeNovel Inc. | Cleantech Recycling in Canada

[76] Excir | Recycling | Precious Metals | Circular Economy

[77] Stena Recycling - Sustainable waste management & recycling

technology. Stena Recycling is therefore a part of the SenSorRe research project[78] where different refined technologies are being tested to extract the remaining pure plastic. The goal with the technology is to be able to identify and separate out halogens such as chlorine and bromine.

5.2.5 Upcycling of Recycled E-Waste Plastic

To increase the value and sustainability of recovered e-waste plastics, some researchers are looking at upcycling the plastic. One such example is adding e-waste to concrete to enhance its durability features (Elgarahy et al., 2024, Ullah et al, 2024). The strength of concrete is affected by the kind and size of the plastic as well as the amount of dose. Plastics containing polybrominated biphenyls and polybrominated diphenyl ethers, available in electronic devices such as circuit boards, have been tested in concrete. It was found that the stress-carrying ability of e-waste plastic substitutes for natural aggregates was greater than that of traditional concrete (Kumar et al., 2021). Also, replacing coarse aggregates with e-plastic wastes enhanced compressive strength (Suleman and Needhidasan, 2020) and reduced the dry unit weight of the concrete. Concrete mixtures with a 40% e-waste plastic substitution showed the greatest decrease in dry unit weight (Evram et al., 2020). Moreover, the concrete containing 25% e-waste plastic and 5 % nano graphite platelets exhibited maximized compressive, tensile, and flexural strength (Ahmad et al., 2022).

The upcycling of e-waste plastic to make supercapacitors has been undertaken (Elgarahy et al., 2024). Because of their high-power transfer capacity, quick ability to charge, high power density, extensive operating temperature range, and extended cycle life, supercapacitors have recently received a lot of attention (Gao et al., 2023). The chemically recycled e-waste plastic materials as a source of 2D porous carbon may be used for constructing supercapacitor electrodes (Bhat et al., 2023; Kumar et al., 2022) Activated carbon materials made from printed circuit board (PCB) waste after pyrolysis showed double-layer capacitive behavior, making it appropriate for constructing supercapacitor electrodes (Rajagopal, et al., 2016).

5.3 DESIGN FOR RECYCLING OF ELECTRONIC PLASTICS

There have been some innovations in designing electronic plastics for enhanced recyclability have been reported. This includes designing electronics with their full lifespan in mind with modular components that can be more easily disassembled for repair or recycling. For example, Fairphone[79], a Dutch company, is creating smartphones that can be upgraded or repaired piece by piece.

5.3.1 Reversible Adhesives

Traditional electronics often use adhesives that make recycling difficult; new reversible adhesives allow components to be detached without damaging them, facilitating easier recycling and reuse. This is also referred to as "debonding on demand".

[78] Recycling of plastic in electronic waste | Stena Recycling
[79] We are Fairphone. Our journey so far

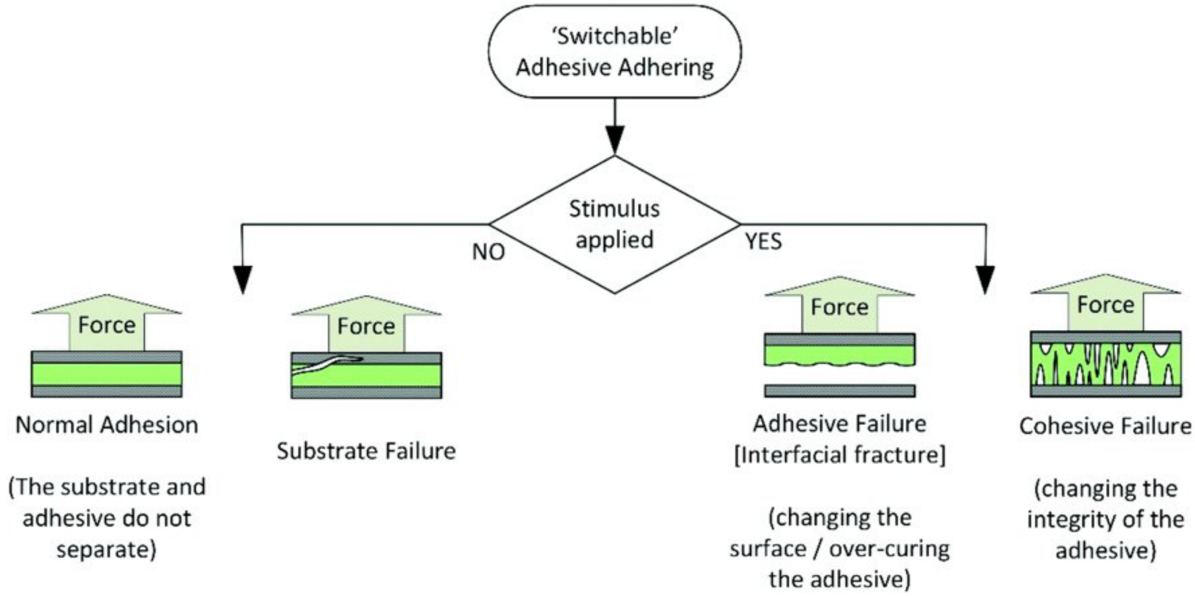


Figure 22. Alternate mechanisms of debonding adhesives (Mulchay et al., 2022).

Adhesive debonding can occur via one of two basic mechanisms as shown in Figure 22 (Mulchay et al., 2022). The first is cohesive failure, where there is loss of mechanical strength in the bulk adhesive for example, on depolymerization or melting. The second is adhesive failure, where the interactions between the adhesive and substrate are influenced, for example on formation of gas bubbles at the interface. The choice of stimulus for debonding is a key design consideration, as it constrains the potential applications and lifetime of the final adhesive. Stimuli may be physical or chemical, but must allow on-demand debonding, within a commercially viable timeframe (typically 1 to 100 minutes), without damaging the adhered substrates. The ideal stimuli is one that is highly specific to reduce the likelihood of exposure during product lifetime, where unwanted debonding could lead to catastrophic failures. Thus, preferred debonding stimuli are those not ordinarily experienced during adhesive service, such as ultrasound or microwaves. Aside from mechanical separating joints, currently ultraviolet (UV) radiation and elevated temperatures are the most utilized debonding stimuli. However, these face many limitations with respect to the accessibility of bonded regions and high probability of unintended exposure. Other debonding mechanisms utilize electrical, magnetic, ultrasonic, or chemical stimuli, which each pose their own challenges.

The economics of a debondable adhesive system must be comparable to commercial structural adhesives. Consequently, debondable adhesives based on novel monomers will be unlikely for anything other than niche, low volume applications. Simple additives, such as graphite, zinc, or iron oxide, are more affordable with prices in the range of $200–800 per tonne, in relatively pure states. Therefore, from a practical and economic perspective, the addition of small quantities of additives, to known structural adhesives is more likely.

Other low-cost fillers could also be used as debonding agents, for example, carbonates and bicarbonates react with mild acid, producing gaseous products which aid physical debonding. In addition, composites, involving biopolymers, such as starch or alginates, could enable low cost-fillers which are water soluble (low molecular weight starches) or digestible by enzymes.

5.3.2 *Alternate Flame Retardants*

While several alternatives to the more hazardous halogenated and phosphorus-based flame retardants have been identified, only a limited number have been implemented: many are not desirable from an environmental and health perspective.

Several natural waste materials, in particular eggshells (chicken, oyster eggs, etc.) have been found to have high flame retardant potential due to their high protein levels, calcium carbonate, phosphorous, potassium, and zinc (Mensah et al., 2022). A novel intumescent coating (a substance that swells from heat exposure) using chicken eggshells and several different additives was synthesized (Yew et al., 2015).. Other natural materials such as Oyster eggshell (Chong et al., 2006) and chicken feathers (Wang et al., 2014) have been used as bio fillers in flame retardants. Other potential flame retardants made from natural materials include linseed oil (Chang et al., 2019) and phosphorylated corn oil with epoxidized corn oil, formic acid, and aqueous H2O2 solution in the presence of sulfuric acid (Mensah et al., 2022). Some sustainable biobased FRs for plastic applications are phytic acid, tannic acid, isosorbide, diphenolic acid, deoxyribonucleic acid (DNA), metallic phytates, and natural fibres such as coffee waste, eggshell.

Sample size influences the results of fire experiments as it was noticed that small samples undergo rapid volatilization which reduces the ignition time of the FR plastics. Leaching of FRs from the polymeric matrix is a great challenge especially at the end-of-life of polymer composites. Finer plastic particles have a higher leaching rate due to the higher surface contact. In addition, the finer particles are easily ingested by humans and animals causing the high content of brominated FRs in the blood, tissue, and milk. The compounds can dissolve in both humic and organic matter. More knowledge is needed about which alternatives are preferable, to assist efforts in finding appropriate substitutes.

5.4 SUMMARY

Recycling plastic from e-waste is an emerging area in sustainable resource management. As the global volume of e-waste continues to increase every year—driven by rapid technological turnover and consumption habits—recovering the plastic components offers both environmental and economic potential. But there are barriers to a recycling e-waste plastics including complex material compositions (e-waste plastic is often mixed with metals, glass, flame retardants, and other additives, making separation and purification challenging) and toxic additives (e.g., BFRs) restricting recyclability due to health and regulatory concerns. Other important barriers include a lack of universal design standards so that each electronic waste device may require a different recycling approach, adding time and cost. There is also limited infrastructure equipped to handle the intricacies of e-waste plastics.

Many of the gaps identified for conventional waste plastics apply to e-waste plastics. There is an urgent need for scalable chemical and mechanical recycling technologies tailored to mixed and contaminated plastic streams. Inadequate tracking of plastic content and composition across product lifecycles hampers efficient material recovery. Gaps in regulation and enforcement reduce incentives for manufacturers and recyclers to prioritize plastic recovery. Finally, public understanding of how to properly dispose of electronics remains low in many areas.

To overcome these challenges and gaps in recycling e-waste plastics, research is focusing on both redesigning products with easy disassembly (e.g., reversible debonding of layers) to enhance plastic recovery as well as advanced recycling technologies such as pyrolysis and solvent-based separation.

6.0 CONCLUSIONS

Because plastics come in many types and are often mixed or contaminated, sorting, processing, and recycling is difficult and inefficient. The complexity and contamination of mixed plastics significantly hinder efficient and cost-effective recycling, leading to high recycling costs. Indeed, only approximately 16% of plastic waste in Canada was recycled in Canada in 2022. Although recycling is important, it cannot keep pace with the volume of plastic being produced. A circular economy approach that would reduce production, reuse materials, and design products for longevity and recyclability would help address many of the issues and concerns associated with plastic waste.

This technology gap review focused on FPP which is difficult to recycle, designing plastics for recyclability and recycling plastic from e-waste as areas where innovative solutions would lead to greater recycling rates, plastic circularity and reduction of waste.

FPP Recycling

FPP, such as plastic bags, pouches, and wraps, are prevalent in various industries because of their lightweight and versatile nature. Recycling rates are low due to difficulties in sorting and separating FPP containing multiple layers of different types of plastics and other materials. Contamination of FPP hinders its recycling into high quality recyclates that plastic producers will purchase.

Another major obstacle is the lack of comprehensive data regarding the production and recycling rates of FPP. Unlike rigid plastics, there is no standardized method to measure how much FPP is generated or successfully recycled. This data gap hinders the development of effective recycling strategies and the ability to track progress over time. Investments in advanced sorting and processing technologies coupled with expanded collection systems can increase recycling rates and reduce landfill waste. Germany's dual system for collecting, sorting, and recycling plastic packaging which has resulted in one of the world's highest plastics recycling rates (approximately 65%) can serve as model system for Canada to follow.

Even when flexible films are collected and sorted, there is a scarcity of end markets to process and repurpose the PCR material. The limited demand for recycled flexible films discourages investment in recycling infrastructure and technologies, creating a bottleneck in the recycling process. At the same time, there is a growing demand for high-quality PCR material to meet the new Canadian PCR content regulations. Therefore, a consistent supply of high-quality recycled material is crucial for product quality and sustainability and, therefore, innovations in pre-processing FPP waste at recycling facilities through decontamination technologies are crucial. Generating high quality recyclates could also address the shortage of food-grade PCR materials suitable for flexible packaging.

There are commercially ready technologies, particularly for deinking of FPP, that are being piloted at selected recycling facilities. But there are many other contaminants such as odorous VOCs, mixed polymers, and multilayers of different polymer types, that require treatment and removal as well. Given the vast number of different types of FPP, one decontamination technology cannot address all the possible contaminants present in the FPP waste. This is why sorting is so important; FPP with similar properties and contaminants can be grouped together and effectively decontaminated with specific approaches optimized for different polymers. Dissolution-reprecipitation processes have been shown to effectively decontaminate and delaminate FPP, with the focus mainly on PE, LDPE, PP, EVOH-containing plastics. Optimization of processes is required, as it has been demonstrated that different ratios of solvent to antisolvent can be effective for one type of FPP but not for others resulting in unusable gel-like substances. Environmental concerns around the use of hazardous solvents have driven research into so-called green solvents. Emerging technologies using supercritical fluids extraction and hydrophobic deep eutectic solvents show promise in producing high-quality PCR materials. LCA of these emerging technologies would ensure that they are indeed sustainable and do not have any negative impacts on the environment.

Designing for Recyclability

Designing plastics for recyclability is a pivotal step toward fostering a circular economy and mitigating plastic waste. By integrating recyclability principles during the design phase, manufacturers can enhance material recovery, reduce contamination, and streamline recycling processes.

Flexible packaging often consists of multilayer films combining different materials like plastics, aluminum, and paper to achieve specific barrier properties. These multilayer structures are difficult to recycle because the layers are challenging to separate, and their varying melting points complicate the recycling process. Utilizing single-polymer materials, such as mono-material PE or PP, facilitates easier recycling compared to multi-layered or composite plastics. Simplifying material composition reduces the complexity of sorting and processing, thereby increasing the efficiency of recycling systems.

Innovations in high-barrier materials for food preservation and durable eCommerce packaging solutions are imperative. Multilayer monomaterial plastic packaging products or monolayer products with barrier properties would help to increase recycling rates of FPP. Some interesting innovations in this area are additives such as nanoclays that not only create the required moisture and oxygen barriers but are also recyclable. Continued optimization and improvements are needed such as ensuring even distribution of the additives, lowering costs and ensuring the nanocomposite materials meet food safety and environmental regulations.

Perhaps less costly and easier to incorporate into existing FPP production lines are inks that are designed for enhanced recyclability. The inks can range from using natural and thus biodegradable materials to novel synthesized additives that serve a dual function; as an ink that can be easily removed by alkaline washing and as a delamination mechanism to separate polymer layers. These novel approaches still require optimization, testing and validation but are promising mechanisms to readily and efficiently deink FPP and create high quality PCR material.

The focus on sustainability is pressuring packaging and upstream material manufacturers to introduce products with less environmental impact. Using chemistry and AI to generate mimics and novel polymers that are sustainable, and recyclable is one way for companies to develop materials that fulfill packaging requirements. Plastic items that are single-use or for medical purposes would benefit the most from AI design and generation.

Overall, there should be standard regulations developed for designing recyclable plastics and a decision tree for best applications of plastics, bioplastics, and mimics.

Recycling E-Waste Plastics

Effective e-waste plastic management involves a combination of reducing consumption, promoting reuse and repair, and implementing robust recycling and responsible disposal strategies. This includes designing for durability and recyclability, educating consumers, and ensuring proper collection and processing of e-waste.

The same techniques being used or developed for chemically recycling regular plastics can be used for e-waste plastics. The main difference is that hazardous components, in particular the BFRs, found in electronic plastics must be removed and treated. Thus, there is a great opportunity to develop alternative flame retardants that are non-toxic, effective, and biodegradable.

In the area of redesigning e-plastics for recyclability, there is potential for novel adhesives development that can readily detach or debond upon exposure to specific stimuli such as ultrasound, electrical currents or chemical reactions. This would greatly aid in the separation and recovery of different plastics used in electronics.

Due to the current poor economics of recycling e-waste plastics, however, the best approach to deal with this type of waste would be to upcycle the plastics into new products. A great example of this is the work being done on incorporating e-waste plastics or e-waste aggregates (includes plastics and metals) into concrete. Studies have shown enhanced concrete performance in terms of durability and workability. Thus e-waste-modified concrete has some promise in terms of reliable and secure dumping of an increasing volume of e-waste.

7.0 RECOMMENDATIONS

This technology gap review has demonstrated that there are many technologies being developed to enhance the recycling rates of plastics. The following is a list of recommendations to help optimize, scale up and accelerate adoption of these technologies for plastic circularity.

Advanced Sorting and Tracking Technologies

- While already well established, there is potential for further refinement and validation of digital tracking such as new sorting technologies to enable better separation of thin films.
- Digital tracking technology as well as use AI for data analysis, tracking and smart labels design should be optimized.

Enhancing Recycling Rates

- Washing processes used in mechanical recycling should be optimized, and where possible develop process that reduce water usage and/or reuse the water for other activities such as concrete manufacturing.
- Validation on novel decontamination processes that enhance the generation of high-quality PCR. (e.g., deinking, testing efficacy of “green” solvents to replace conventional solvents) should be carried out.
- Advance recycling processes using supercritical fluids that can enhance the decomposition and delamination of polymers and flexible plastic as well as debromination/dichlorination of bromine and chlorine from e-waste.

Material Design to Enhance Recyclability and Upcycling

- Expand in the area of self reinforced or oriented PE films research activities for development of monomaterial plastics.
- Conduct research in creating thinner yet stronger materials using small amounts of nano-reinforcement. This would reduce material usage, and the carbon footprint associated with packaging production and transportation.
- There are opportunities to formulate and process novel compatibilizers and additives for testing in new materials and products from recycled plastics and components.
    - This includes developing novel compatibilizers and additives that allow multilayer films to be recycled together, improving compatibility between different polymer types as well as developing or designing additives that do not interfere with recycling or can be easily separated during processing.
- There is a great opportunity to develop alternative flame retardants that are non-toxic, effective, and biodegradable.
- There are opportunities to help industry in repurposing recovered e-waste plastics into durable goods (e.g., automotive components, construction materials).
- There is potential to investigate the transformation of waste plastic such as flexible film, hard to recycle plastic and waste composites to new materials such as carbon fiber, carbon nanotubes, and activated carbon using pyrolysis and chemical processing methods.

- Although not always recyclable in traditional systems, biodegradable and compostable polymeric materials reduce long-term plastic accumulation.

Life-Cycle Analysis

- Use LCA to help identify opportunities to reduce plastic waste, conserve resources, and improve sustainability.
- Quantify energy, materials, emissions, and waste flows throughout the life cycle.
- Evaluate environmental impacts (e.g., carbon footprint, water use, toxicity).
- Analyze results to guide decisions and identify areas for improvement.

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APPENDIX 1: TECHNOLOGY GAP REVIEW METHODOLOGY

Inclusion criteria: Specific key words used for literature searches included: plastic waste, plastic recycling, plastic reuse, plastic circularity, plastic technology gaps, plastic innovation, plastic regeneration, plastic regenerative technologies, plastic resin, resins, plastic types, plastic economy, plastic problem, plastic life cycle assessment (LCA), plastic greenhouse gases (GHG), plastic in municipal solid waste (MSW), plastic waste mgmt. practices, plastic future, plastics, recycled plastics, circular plastics, landfill, mechanical sorting, thermosets, thermoplastics, plastic composites, reinforced plastics, biological plastic recycling, biological degradation, biological processes, mechanical-, biological-, chemical-, thermomechanical-, thermochemical- recycling.

Peer-reviewed papers, policy papers, and white papers were reviewed. In addition, company, government, and non-government organization websites were researched. Comprehensive market searches were done using IBI, Lux, Frost and Sullivan, and market data bases for virgin (raw) plastic quantification (in Canadian/Albertan Context), and waste plastic diversion, recycling, reuse, regeneration, circularity, reduction.

Exclusion criteria: The following search criteria were excluded as they fell out of scope of the project's objectives: biopolymers/bio-plastics production and recycling, negative environmental impacts such as microplastics in water and soil, silicone, natural and synthetic rubber, and conversion of plastics into fuels. Documents that were not in English were also excluded.

APPENDIX 2: FPP EXAMPLES

Table 5 provides an overview of the types and characteristics of FPP used in the market today.

Table 5. Types of FPP in the market[80].

Material/Type	Description/Uses
BOPA Biaxially-oriented polyamide	• Most commonly used for distilled goods, perishable food, and some agricultural products. • Exceptionally durable and puncture-resistant while still retaining a high level of transparency.
BOPP Bi-axially orientated polypropylene polymer	• Used in snack food packages, especially because it can hold weight without easily breaking. • Locks out moisture, thus used for pesticide, hygiene, dairy, or confectionery packing. • High resilience and clarity.
BOPET Biaxially-oriented polyethylene terephthalate	• Desirable properties included their transparency, reflectivity, high chemical and dimensional stability, gas and aroma barrier properties, and electrical insulation. • High tensile strength combined with added heat resistance allows it to withstand modifications without compromising the food's aroma or flavor.
BOPE Biaxially-oriented polyethylene	• Relatively low cost. • Properties include great heat-seal strength, excellent moisture barrier, and durability. • Used in packaging of products that require a high degree of stiffness
LLDPE Linear low-density polyethylene	• One of the strongest and most flexible plastic films and can absorb impact without puncturing or tearing. • Desirable properties include durability and chemical resistance. • Maintains the flavor and quality of the contents within each package, prolonging shelf life.
LDPE Low-density polyethylene	• Most common type of plastic polymer used. • Desirable properties include low temperature flexibility, durability, corrosion resistance, chemical and impact resistance. • They are lightweight but lack the strength of LLDPE.
HDPE High-density polyethylene	• Known for exceptional strength and clarity. • Common uses include beverage bottles, personal care products such as shampoo, and household products, bread and thin plastic produce bags, and cereal box liners.
High-Density Co-Ex Blend Polyethylene Film	• Additive-free bag material with exceptional strength and clarity. • Used for vacuum packaging applications such as food packaging.
Polypropylene Film	• Properties include excellent strength and clarity. • Used for retail packaging.
Foil Packaging	• Typically used by food, medical, and pharmaceutical industries due to their protective solid barrier. • Keeps food fresh, blocks harmful contaminants, and prolongs shelf life.
Laminates	• Multi-layered structures incorporating polymer films and paper to an aluminum or metalized film.

[80] https://www.thepkglab.com/blog/61/packaging-film-types, https://www.ecoplastindia.com/flexible-packaging-film-types/, https://www.rubeeflexpackaging.com/different-types-flexible-packaging-films/

Material/Type	Description/Uses
	• Multi-layered protection ensures that food stays fresher, and no external odors make their way into products (e.g., polyester laminated to linear low-density polyethylene). • Laminates are highly stiff and glossy.
Anti-Fog Film	• Allows the inner contents of the packaging to be seen or remain visible from condensation.
Barrier or Co-Extruded Films	• Designed and manufactured to protect the bagged contents from solvents, gases, aroma, and other flavors. They are very much resistive and strong films.
Opaque Films **UV Protective Films**	• Fully opaque and considered UV-resistant films. They are great for protecting and concealing the bagged contents from UV rays.
Static Dissipative Films	• They are designed for dissipating the static build-up in the bag.
Rust or Corrosion Inhibitor Films	• They are designed to protect the bagged content against rust both during the shipment and in the store shelves.